

SIMRAC

Final Project Report

Title: METHANE PREDICTION IN COLLIERIES

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Research
Agency: WARDELL ARMSTRONG

Project No: COL 303

Date: JUNE 1996

EXECUTIVE SUMMARY

The current status of research on methane emission prediction for collieries in South Africa has been assessed in comparison with methods used and advances achieved elsewhere in the world. Seam gas content, pressure and permeability measurement methods used in various countries have also been reviewed, key research institutions identified and a bibliography of relevant references produced. Recommendations are made as to the direction and content of future research needed in South Africa to develop a practical gas emission prediction approach consistent with the prevailing mining methods and geological conditions.

South African research on methane prediction has lacked a clarity of direction, probably as a result of insufficient contact with the research programmes of other major coal mining nations, too few researchers and a shortage of research expertise. Considerable effort has been devoted to measuring gas-related properties of coal seams at a few, unusually high gas emission, sites using both in-situ and laboratory techniques. Underground methane emission investigations have been generally limited in scope with a strong, but misplaced, emphasis on studies of the effect of barometric pressure on gas emission rates indicative of a lack of appreciation of fundamental principles. Nevertheless, useful work has been done on the characterisation of the reservoir properties of South African coals, an advanced gas flow simulator has been developed, and a range of underground investigation tools designed and tested.

Gas emission problems in South African coal mines seem to arise mostly as a result of locally disrupted ventilation systems, accumulations of gas in the cutting zone of continuous miners where adequate local ventilation is difficult to sustain with the methods in common use and also when mining in proximity to igneous intrusions or faults when unusually high gas flows may be encountered. Initial indications are that methane gas concentrations in the return airways of South African bord and pillar workings are relatively low, and generally not a constraint on coal production rates, whereas on a few longwalls gas emissions could attain critical levels due to the high coal extraction rates sometimes achieved. High, steady methane emissions experienced in the past were associated with collieries in the Natal

coalfield area that are no longer being worked.

Practical methane emission prediction methods have been developed in countries where longwall methods of mining are predominant; gas emission problems tend to be more acute on longwalls than in room and pillar mines due to the greater volume of strata disturbed by mining operations. As a result of improved mechanisation of longwalls, gas emission rates have increased commensurate with the increases in coal production rates achieved. In these circumstances, gas prediction tools have proved invaluable for planning ventilation and gas control requirements to ensure coal production targets can be met.

Most of the established gas emission prediction methods used at collieries elsewhere in the world are empirical, few having a sound theoretical basis but all apparently successful in their countries of origin. Some models are also applicable to bord and pillar methods of mining but have not been proven outside their country of origin. In general, these models are relatively simple to use, attuned to local conditions and needs, have known limitations and are based on physical principles understood by the user. Consultation with the end user has played an important part in ensuring practical requirements are understood and met.

Research and academic institutions in various coal mining countries are actively engaged in work relating to the prediction of methane emissions in coal mines. Improvements in communications technology and opportunities for international collaboration should reduce duplication of effort which has been evident in the past. Most of the current research on methane flow modelling is aimed at improving the accuracy of simulations and enhancing understanding of strata behaviour, gas transport and emission processes. The studies are generally aimed at longwall mining methods, or gas drainage practices, although the principles are applicable to all methods of mining. The methane prediction models being developed are likely to be more general and less empirical than existing practical models but too complex for day to day colliery ventilation planning purposes. However, they could have a role in centralised planning and problem solving within major mining houses. The CSIR Miningtek model could fit such a category.

No commercially available software has been identified which could be readily applied to

South African coal mines to satisfy the practical needs of environmental engineers. However, an existing, soundly based, empirical gas prediction model could be adapted for application to South African longwalls. Development of a more sophisticated gas flow simulator could not be justified given the relatively few longwall operations in South Africa.

A recommendation of the report is that a survey should be conducted of methane flows and coal production rates in South African underground coal mines, differentiating between longwall and bord and pillar sections where appropriate. Thus, the true scale of the gas emission problem would be established to guide future gas prediction modelling research and development requirements. Only if a significant proportion of bord and pillar workings exhibited specific emissions greater than, say 11 m³/t would there be justification for developing the CSIR Mining prediction model into a practical form for use by collieries, otherwise a greatly simplified empirical version would suffice for general ventilation planning. However, even where gas emissions are low, hazardous methane concentrations can occur in mechanised bord and pillar headings when the local ventilation systems are unable to provide adequate fresh air flows. A method for estimating the methane flow into the cutting zone would assist the design of satisfactory gas control measures. Provided duct or brattice systems of ventilation are not excluded from consideration, the prediction method could make a significant contribution to the reduction of gas ignition risks in continuous miner headings.

A greater understanding is needed of the processes which can give rise to exceptional gas emissions in the vicinity of igneous dykes, sills and other geological features. If such emission events prove to be of widespread significance then there would be a strong argument for investigating knowledge based approaches to emission prediction to assist the identification of appropriate precautionary gas control measures.

Most gas emission prediction methods require a knowledge of the in-situ gas content of a coal seam. No reliable method has yet been established in South Africa for measuring the methane content of coal seams. As a consequence, an understanding of the variations in seam gas content from place to place and possible natural causes of such variations has not been obtained. Knowledge of in-situ methane contents and access to a reliable measurement

method would assist quantification of the methane hazard facing a development from an existing mine into a virgin area of coal or a new underground mine.

While methane prediction methods can be of great assistance in determining the proper ventilation requirements, they cannot in themselves prevent incidents of ignitions or explosions when local or temporary failures of ventilation occur. Greater use should, therefore, be made of remote monitoring systems at collieries for recording variations in specific emission, examining effects of varying coal production and for analysing methane problems. Continuously monitored methane concentrations combined with airflow data to yield pure methane flow can be correlated with coal production data to provide specific emissions and also to assist in identification of unusual emission events.

South African research should be stimulated by encouraging international collaboration, regular peer review of progress and, training and recruitment of additional research professionals. A more focused and pragmatic approach is needed to direct existing research resources towards achieving rapid, practical solutions to the identified problems of the industry.

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SAFETY IN MINES RESEARCH ADVISORY COMMITTEE
METHANE PREDICTION IN COLLIERIES
Project No. COL 303

1 INTRODUCTION

1.1 This report was prepared by Wardell Armstrong with the assistance of the Universities of Nottingham and the Witwatersrand in accordance with a contract issued by the Director-General : Mineral and Energy Affairs dated 18 December 1995.

1.2 The primary aim of the project was to assess the current status of research on methane emission prediction for collieries in South Africa in comparison with methods used and advances achieved elsewhere in the world. This aim was to be fulfilled by the following outputs:

- a review of methane measurement and gas¹ emission prediction research as currently applied in South African geological and mining conditions;
- a worldwide review of methods for measuring seam gas content, gas pressure and coal seam permeability for use in gas emission predictions;
- a worldwide review of gas emission prediction models;
- a bibliography of relevant technical papers and reports;
- identification of key institutions undertaking relevant research into new or improved techniques;
- recommendations as to the direction and content of further research and testing required to develop a practical gas emission prediction approach which takes full account of geological and mining conditions in South Africa.

¹ "Methane" and "gas" are used interchangeably in this report.

1.3 Material for the review of South African methane prediction research, knowledge of the industry's practical problems and an understanding of the specific requirements of SIMRAC were obtained during a visit to South Africa which took place between 27 February and 9 March 1996. During the visit contact was made with members of SIMRAC advisory and special interest groups, and discussions were held with various representatives of CSIR Miningtek, University of Witwatersrand, Ingwe, Sasol, Amcoal and the Department of Mineral and Energy Affairs. Details of the visit programme are summarised in Appendix 1.

1.4 A literature search was subsequently undertaken to identify methane measurement and emission prediction methods used in various coal mining countries throughout the world. The research was assisted by an existing gas control database developed by the Department of Mineral Resources Engineering of the University of Nottingham. At the commencement of this project the "user-interface" was upgraded using Microsoft Access and the database brought up to date using the following information sources:

- Compendex Plus: a major engineering literature database covering about 2,600 international journals, conference proceedings and technical reports. It includes citations from tables of contents from over 5,400 journals, conference proceedings, technical reports and trade publications.
- BIDS (Bath Information & Data Services): a UK-based provider of bibliographic data services which operates from the campus of the University of Bath. Although primarily established to serve the academic community in the UK, some of the databases are available to non-UK academic institutions, and a few are available to commercial organisations.
- 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 to 1994.
- The Internet: searches for information on prediction software and current methane research activities especially among academic institutions.
- Wardell Armstrong library: reports and publications on gas content measurement, gas emission prediction, gas control in underground mines and coalbed methane.

1.5 Literature specific to South Africa, supplementary to the above sources, was sought from:

- University of the Witwatersrand: theses and publications relating to methane investigations and research undertaken within the Department of Mining Engineering.
- CSIR Kloppersbos library: reports on methane emissions in South African collieries by the Fuel Research Institute.

1.6 Publications to which specific items of information are attributed in this report are incorporated in the list of references. These references together with additional relevant literature sources are presented as a classified bibliography in Appendix 2.

The bibliography is divided into the following areas:

- methane measurement methods and technologies
- methane emission prediction methods and gas flow modelling
- geological aspects
- miscellaneous.

Background

1.7 Small-scale organised exploitation of coal started in 1864 in Eastern Cape, expanding later into KwaZulu Natal with only about 47,000 tons per annum being produced between 1885 and 1889. Today, coal provides about 72% of South Africa's primary

energy needs (Minerals Bureau, 1995). The identified reserves of 55,300Mt in 1994 represent almost 11% of the world hard coal reserves. In 1994, South Africa mined 242.6Mt of which 195.8Mt was of saleable quality making it the fourth largest producer in the world. Exports of 54.6Mt in the same year result in a ranking of third largest exporter of coal in the world. Of the total saleable coal produced, about 81% was supplied by the four major mining groups viz., Ingwe, Amcoal, Sasol and Iscor. A steady rise in coal production and export capacity is forecast over the next decade. Current methane prediction work is therefore aimed at a growing industry seeking to maintain a competitive position.

- 1.8 There are 18 principal coalfields in the main coal bearing regions of South Africa. The seams generally thin and become less numerous to the east whilst their rank tends to increase. The coals are predominantly of Permian age and are usually rich in inertinite and hard with high ash contents compared with the more friable, "bright" coals of relatively low ash content found in the northern hemisphere. The coal bearing strata in many of the South Africa coalfields have been invaded by igneous sills and dykes which, in addition to causing problems for coal production, also locally affect the gas bearing and emission properties of the coal.
- 1.9 Currently, most of the coal production in South Africa is from shallow-lying seams, generally less than 300m in depth. The seams are relatively thick and undisturbed over large areas. Roughly half of the coal production is obtained by surface mining methods, the remainder almost entirely by mechanised underground methods. In 1994, 9% of underground run-of-mine coal came from longwalls, 67% from room and pillar workings and the remaining 24% from pillar recovery (stooping). Longwall outputs in excess of 7,000 tonnes/shift and continuous miner outputs of 3,000 tonnes/shift have been reported (Walker, 1995).
- 1.10 A Commission of Inquiry in 1994 reviewed the health and safety record of the South African mining industries and recommended ways that improvement could be made (Leon, 1995). Phillips (1996) has shown that fatality and injury rates in South African mines, in general, are high by international standards and have not changed

significantly in the past decade. The incidence of explosions in coal mines is considered to be unacceptably high and contrary to the trends in advanced coal mining countries elsewhere. Since the first recorded explosion at Elandslaagte Colliery in Natal in 1891, more than 330 further explosions have been recorded causing 1036 fatalities and 532 injuries (Phillips and Brandt, 1995).

- 1.11 In addition to in-house or extra-mural mine safety research funded by the major mining companies, the South African mining industry has, since 1993, financed safety research through a statutory levy. The research programme is determined by SIMRAC who also have responsibility for the effective transfer of research findings to the users at the mines (SIMRAC Annual Report, 1994). An urgent need has been identified in South Africa to improve methane control in underground coal mines. A practical method for predicting methane flows is viewed as an essential precursor which would assist in planning to minimise risks.

Control of Methane in Coal Mine Workings

- 1.12 In its naturally occurring state in a coal seam, methane does not constitute an explosive risk. However, at various locations in the mine, significant quantities of methane may mix with ventilation air and pass through the explosive range of 5% to 15% by volume. These are:
- (i) where methane released from roof and floor meets "fresh-air" in goafs;
 - (ii) in the coalface cutting zone where freshly cut coal and freshly exposed coal on the face releases a proportion of its gas;
 - (iii) at the discharge point of a methane drainage system (if present) which may be on the surface or underground.
- 1.13 Control measures are implemented in every mine to minimise the likelihood of an explosive mixture and an ignition source being simultaneously present. These may involve a range of ventilation techniques or a combination of ventilation and methane drainage techniques depending on the gas flows experienced. The main criterion for establishing the efficacy of methane control measures is usually the methane concentration in the general body of the air in return airways. Statutorily maximum

allowable methane concentrations vary from country to country usually with a value somewhere between 1% and 2%.

Methane Prediction

- 1.14 Methane prediction methods are planning tools for estimating gas flows into mine workings which have been developed in various countries to enable gas problems to be forestalled and, in particular, to facilitate achievement of coal production targets without safe, statutory methane concentrations being exceeded. All methods involve a model, which may be very simple or highly complex, which represents how mine workings interact with the natural geological environment causing gas to be released into the workings.

Methane predictions are useful for:

- determination of primary and auxiliary ventilation air quantities;
- assessing need for methane drainage;
- planning gas monitoring and control strategies;
- establishing limitations on coal production due to gas emissions for the mining method to be employed;
- assessing the implications of failures of ventilation systems, other gas control measures or gas monitoring;
- examining prospects for methane utilisation.

The need for methane prediction

- 1.15 The need for methane prediction methods arose in Europe because rising coal production rates resulting from increasingly effective mechanisation programmes were leading to increasingly higher concentrations of gas being experienced in underground coal workings. Methane drainage techniques which removed a proportion of the gas

before it could be released into the mine airways assisted in controlling the problem in most instances. Eventually, coal production levels were attained on some longwall coalfaces which, despite methane drainage, began to experience methane control problems necessitating the introduction of new ventilation configurations. Methane prediction programs provided a means of planning the ventilation and methane drainage of these mechanised longwall coalfaces to ensure that coal production would not be unexpectedly curtailed by excessive methane concentrations.

- 1.16 The specific emissions of methane from UK coal mines which benefitted from advance planning of ventilation and methane drainage was typically in the range 15 to 40m³ per tonne of coal extracted. Information from the USA (Kruger, 1994) indicates that some form of methane control additional to ventilation is generally required once emissions exceed around 11m³ per tonne of coal extracted (Feddock, 1996). Mines with specific methane emissions of less than about 5m³/t would not usually be considered particularly gassy. The advantages of methane emission prediction to these low gas emission mines are limited as calculations are likely to indicate a minimum air requirement for gas dilution which is lower than that required for other underground environmental control reasons.
- 1.17 From the above, it would seem that there are unquestionable benefits to safety, ventilation and coal production planning for mines with specific emissions of 10m³/t or more. It would also seem reasonable to suggest that some benefits would become apparent at lower emission levels, of around 5 to 8m³/t to take account of the possibility of extending working to deeper seams with higher methane contents.

Statutory approaches to gas emission in coal mines

- 1.18 Different countries have different approaches to gas control regulations for coal mines. In some countries the need for at least a simple form of methane prediction method is implicit in the legislation. Gas emission regulations may make reference to:

- flammable gas concentrations in airways which should not be allowed to exceed a prescribed value which may be 2% or lower depending on the country or specific circumstances;
- a "gassiness" or emission severity classification derived from some combination of methane concentration, specific emission and seam gas content measurements. The mining legislation in some countries is more prescriptive than others. For example, Polish mining regulations require the gas content of worked seams to be measured in hard coal mines (Hampton and Schwochow, 1994).

1.19 The occurrence of methane explosions in low gas emission mines in, for example, USA, UK, India, France (Chugh, 1983; Jeger, 1992) and South Africa suggests that all coal mines may be subject to gas emission risks irrespective of seam gas contents and gas emission quantities. Whilst a philosophy that all coal mines ought to be considered "gassy" is being increasingly widely recognised in the international community, some countries classify workings according to the severity of emissions to assist in the selection of control measures appropriate to the magnitude of the perceived problems. Indian Coal Mines Regulations 1957, require all seams worked underground to be classified according to their "gassiness" and the situation reviewed regularly (Chugh, 1983). A comparison between the Indian and some other overseas classifications is shown in Table 1.

Table 1
Categorisation of the gassiness of coal mines in various countries
 (adapted from Chugh, 1983)

Country	Category	Indices for categorisation		Basis for indices
		General body CH ₄ conc.	Specific emission m ³ /tonne	
India	I	less than 0.1%	less than one	Statistical record of spot measurements of general body methane concentrations and air quantities
	II	more than 0.1%	1 to 10	
	III	-	More than 10	
Poland	Non-gassy	-	Less than 5	Continuous monitoring and also by laboratory determination of seam gas content.
	Slightly gassy	-	5 - 10	
	Gassy	-	10 - 15	
	Very gassy	-	More than 15	
Former USSR	I	-	Less than 5	Statistical analysis of records of methane concentrations, air quantity & coal production and by in situ & laboratory determinations.
	II	-	5 - 10	
	III	-	10 - 15	
	Super category	-	More than 15, seams prone to out-burst of gas & coal. Gas flows 1.5m ³ per min per tonne of coal	
Germany	Very strongly gassy	-	50 - 120	Continuous records of methane concentrations together with coal production and 'in situ' and laboratory methods of seam gas content determination.
	Strongly gassy	-	20 - 60	
	Moderately strong	-	8 - 25	
	Gassy	-	4 - 12	
	Slightly gassy	-	2 - 6	
	Insignificantly gassy	-	0.3 to 3.0	
U.K.	There is no formal classification of the gassiness of coal seams. All coal seams are considered gassy. Generally, the methane concentration of the mine air in return airways is the guiding parameters for safety. When it is difficult to maintain the general body methane contents within or below the statutorily prescribed limits (1.25% or less of methane) firedamp drainage is usually practised if the geology is appropriate.			

Quantification of the Methane Emission Problem in South Africa

- 1.20 The scope of a methane prediction method for South Africa is difficult to define without some knowledge of the overall magnitude of methane emissions in the coal mines. The shortage of data on emissions has necessitated a preliminary assessment of the extent of the current problem using:
- highly empirical estimates based on a simple greenhouse gas emission model;
 - consideration of available current and historical data in the context of ventilation limitations on methane control.
- 1.21 A coarse estimate of methane emissions from South African coal mines can be made by an indirect method intended for calculating probable greenhouse gas emission quantities (OECD/IEA, 1994). The method relies on an apparent linear relationship between specific emissions (ie. the volume of methane emitted per unit mass of coal extracted) and the average mine depth for eight major coal producing countries for which reliable information is available. The countries are the USA, Australia, the UK, Germany, the CIS, Poland, China and Czechoslovakia. The relationship can be expressed as follows:

$$Q = 0.023 d + 4.1$$

where Q is the specific methane emission in m³/t and d is the average mine depth in metres. The correlation coefficient was 0.81 (8 data points).

- 1.22 The above correlation has little physical significance and neglects any geological differences between countries. Nevertheless, assuming an average underground mine depth of 200m in South Africa, an average specific emission of 8.7m³/t is obtained. The above relationship presumably incorporates substantial data both from longwall, and, room and pillar operations. As longwalls cause more extensive disturbance of the ground than room and pillar mining, and hence release more methane, any estimate made for South Africa where room and pillar methods predominate might be expected to be too high.

1.23 Methane prediction calculations are often used overseas to determine whether methane drainage is likely to be required in addition to ventilation to ensure methane is controlled satisfactorily, allowing coal production targets to be achieved. Some simple calculations can be made to determine the likely level of specific emission at which control of methane emissions by ventilation alone may become problematic in South African coal mines.

Allowing for dilution of peak methane concentrations 1½ times higher than the average methane concentrations in return airways², statutory 1.4% flammable gas concentration will not be exceeded if the following relationship holds true:

$$1.5f / 1000Q \leq 1.4/100$$

where f is the pure methane flow rate (l/s) and Q the section air quantity (m³/s).

The maximum methane flow (f_m) controllable with ventilation is:

$$f_m = \frac{1000 Q \times 1.4}{1.5 \times 100} = 9.3Q$$

It is a reasonable approximation to assume that methane flow is proportional to coal production, and hence:

$$f_m = W \times 0.00193 \times E_c$$

where W is weekly output (tonnes) and E_c the maximum controllable specific emission (m³/t). Note that 0.00193 is the approximate multiplying factor to convert mean coal production from tonnes/week to tonne/s and methane flow from m³/s to l/s. This is based on a 6 day week, thus making an allowance for non coal production periods.

²A common method of accounting for the variability of methane concentrations in underground airways which is discussed in more detail later in this report.

Combining and rearranging the above equations:

$$\begin{aligned} E_c &= 9.3Q / (W \times 0.00193) \\ &= 4819 Q/W \end{aligned}$$

- 1.24 For a typical air quantity of 35m³/s on a high-production South African longwall face producing 70,000 tonnes of coal per week, the critical specific emission, using the above equation is about 2.4m³/t. A continuous miner section producing 20,000 tonnes of coal per week, with 60m³/s of air available, would have a limiting specific emission of 14.5m³/t.
- 1.25 Figure 1 shows the maximum specific emission which is theoretically controllable with ventilation air for selected air quantities at any rate of coal production (based on a 6-day production week). Specific emission data for some South African collieries (Table 2) have been plotted on the diagram together with estimated coal production rates. There are too few data to be conclusive but indications from the very limited information available are that the methane problems historically experienced, mainly in Natal, are not being encountered in mines currently being worked. The implication is that air quantities in main ventilation circuits may be sufficient to dilute most methane emissions without recourse to more elaborate control measures. Gas emission problems are more likely to be encountered on longwalls than in the returns of room and pillar mines due to the greater strata disturbance and lower air quantities associated with the former.
- 1.26 Comments that recorded methane concentrations in return airways were relatively constant (Joubert, 1966) in a particularly gassy mine in Natal shows that highly permeable coal or a gas source additional to the coal seams may occasionally be encountered possibly associated with structural entrapment of gas against igneous intrusions.

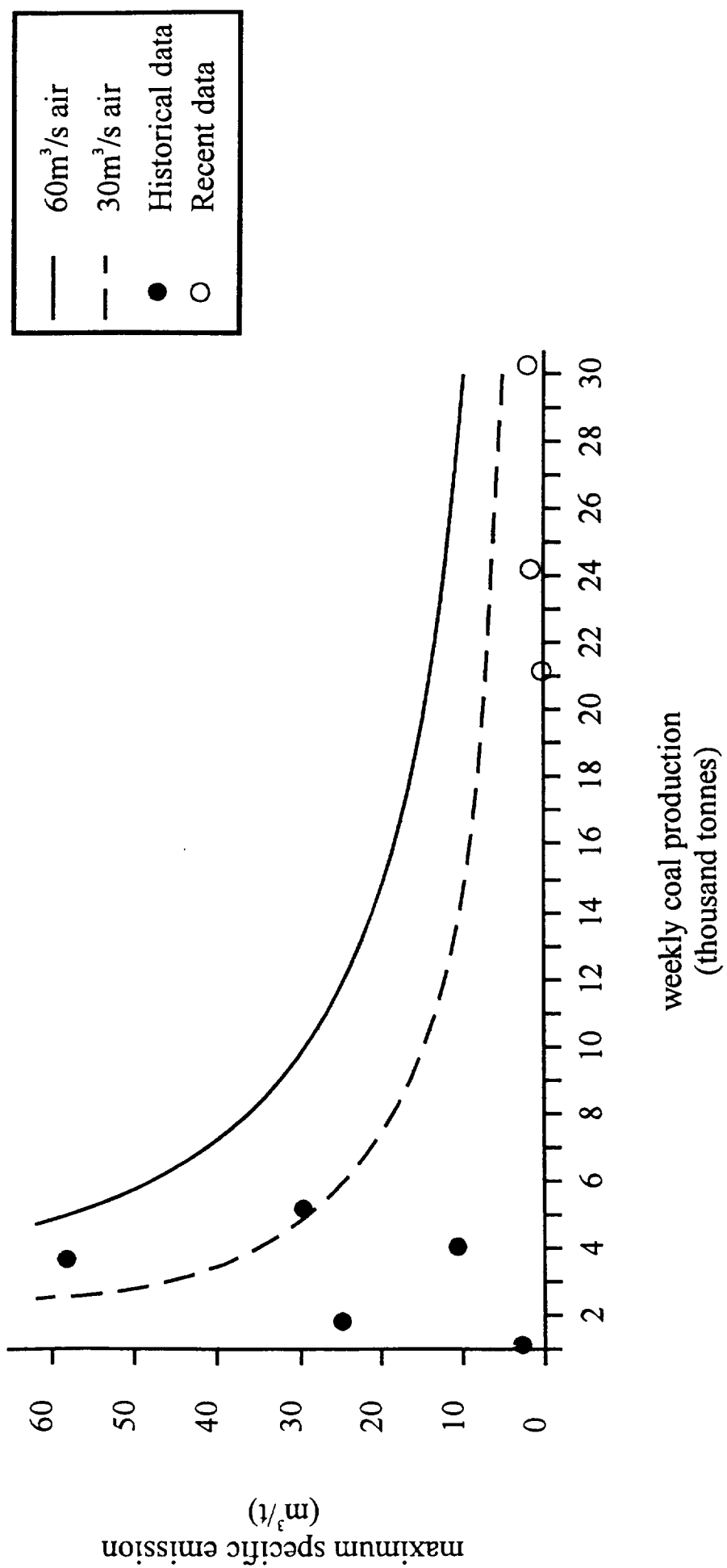


Figure 1 The maximum specific emission controllable with ventilation air against coal production for selected air quantities (historical and recent data from individual South African collieries plotted for comparative purposes).

Table 2
Specific methane emissions from working sections
in some South African collieries from 1966 to the present

Name of Colliery	Approximate year of study	Type of working	Weekly coal production (tonnes)	Specific emission (m ³ /t)	Reference source
Durban Navigation	1966	Development	4000 ⁽¹⁾	10.6	Joubert, 1966
		Development	1800 ⁽¹⁾	24.8	
		Development	1100 ⁽¹⁾	2.8	
		Longwall	5100 ⁽¹⁾	29.6	
Indumeni	1969	Bord and pillar	3625	58.6	Joubert, 1969
Majuba	1990	Bord and pillar	not worked	11 ⁽²⁾	Kavonic, 1990
Middelbult	1993	Pillar extraction	24000	1.6	Eicker, 1993
New Denmark	1996	Shortwall	30000 ⁽²⁾	2 ⁽²⁾	This study
Brandspruit	1996	Bord and pillar	21000 ⁽²⁾	0.2 ⁽²⁾	This study

- ⁽¹⁾ Estimated from Joubert's (1966) single shift data assuming 11 similar coal production shifts per week.
- ⁽²⁾ Estimated values using generalised data.

1.27 Experience of gas emissions in the Indian coalfields is relevant to South Africa due to geological similarities. Chugh (1979) found that the usual relationship between coal production and methane emission was not always evident. This appears to be particularly the case in mines where gas emissions are associated with dykes and faults. Chugh does not state the method of mining used but it is likely that room and pillar, pillar recovery and longwall systems are represented in his study.

1.28 It is uncertain from the few data available whether or not current gas emission levels in South African coal mines exceed the nominal threshold where significant advantage can be gained from a conventional methane prediction method similar to those employed in gassy coalfields overseas. Routine underground environment monitoring records and coal production data gathered from operating mines are clearly needed to clarify the current situation.

1.29 The South African perspective is particularly well expressed by Holding (1987) of Anglovaal who, in proposing ventilation guidelines for the managers of South African coal mines, stated:

" if abnormal conditions occur the ventilation requirements must be raised accordingly. There is a need to be able to predict, with a greater degree of certainty than at present, when such abnormal conditions are likely to occur, and this could be based on the prediction of methane emission. Several mining groups are working on the problem, some with the collaboration of the University of the Witwatersrand, and it is recommended that these efforts be co-ordinated and expanded to produce more meaningful results".

2 METHANE PREDICTION RESEARCH IN SOUTH AFRICA

- 2.1 In 1985 the Chamber of Mines decided that there was a need for fundamental research into the mechanisms of methane retention and migration in coal seams which would lead to the development of a methane emission prediction method for South African collieries. Information on the in situ gas content, permeability and gas pressures of coal seams was scarce.
- 2.2 Studies of methane emissions in the preceding 15 years by the Fuel Research Institute of South Africa (FRI) had demonstrated that high methane flows could occur in South African collieries. Joubert (1965, 1966, 1967, 1968, 1969, 1980, 1981) described various underground investigations undertaken by the FRI. Spot gas concentrations and later continuous recordings were made on the return side of operational sections. Combined with air quantity readings these data yielded flows of emitted methane. Methane flows divided by coal production gave an indication of specific emissions. Specific emissions of $29.6\text{m}^3/\text{t}$ were calculated for a longwall at Durban Navigation Colliery in 1966 and $58.6\text{m}^3/\text{t}$ from bord and pillar workings at Indumeni Colliery in 1969.
- 2.3 In addition, surface exploration boreholes for the proposed new Majuba Colliery encountered gas and water under pressure giving rise to concerns regarding the potential gassiness of future underground workings at depths of around 300m and more. Prior to this time, underground coal mining in South Africa rarely progressed deeper than 150m below the surface.
- 2.4 A national programme of research was initiated involving collaboration between the Chamber of Mines Research Organisation (COMRO) and the Department of Mining Engineering at the University of the Witwatersrand with the support of Gencor. When COMRO was acquired by CSIR in 1993 the research was continued under the auspices of CSIR Miningtek. Most of the methane emission research undertaken between 1992 and 1995 is encompassed by the SIMRAC project COL 030 "*Reduce the Methane Hazard in Collieries*".

- 2.5 Details of the findings have been published in reports to the Chamber of Mines, SIMRAC, mining journals, conference proceedings and University theses.
- 2.6 The achievements recorded in the above documents are briefly discussed under the following headings:
- (i) development of measurement and monitoring apparatus
 - (ii) development and evaluation of measurement techniques
 - (iii) results of laboratory measurements, in situ testing and underground investigations;
 - (iv) development of methane flow models;
 - (v) summary of research results.

Development of measurement and monitoring apparatus

- 2.7 Methane prediction studies require data to aid the understanding of gas emission processes in the underground environment and also to enable the accuracy of emission forecasts to be tested. It is, therefore, important to have a means of obtaining sufficient, accurate and reliable data. For this reason two intrinsically safe, independently powered, portable monitoring and data logging units have been produced at CSIR Miningtek (Kononov and Cooke, 1995):
- (i) a two-channel barometric pressure and methane monitoring station incorporating a 65Kb data logger capable of providing more than 10 days of periodic data collection;
 - (ii) a multi-channel monitoring station for use with up to six methane monitors or various other sensor combinations as required. This unit was designed to facilitate real time monitoring of methane distributions around an operating continuous miner.

- 2.8 Infra-red gas detectors have been investigated on behalf of SIMRAC as a possible alternative to the catalytic detectors in current use, which are particularly susceptible to poisoning by various trace gases and also damage by water and excessive hydrocarbon concentrations. Research established that no suitable infra-red system has yet been developed for use in coal mines (Kononov, 1993).
- 2.9 Borehole instrumentation has been developed at the University of the Witwatersrand in order to improve the reliability of in situ seam gas pressure measurement (Stripp, 1989). Several types of borehole packer were also developed by COMRO for in seam gas pressure and in situ permeability determination (Cooke, 1993).
- 2.10 Volumetric apparatus was devised and constructed at the University of Witwatersrand for measuring the quantity of methane adsorbed on South African coals at a range of pressures, at constant temperature ie., methane adsorption isotherms. Gravimetric apparatus was established at COMRO to facilitate additional laboratory methane adsorption and desorption studies. The gravimetric equipment is now located at the CSIR Kloppersbos testing facility to provide a commercial service to collieries but has not been used for some time.
- 2.11 Colliery environmental monitoring systems which provide comprehensive on-line data at a surface computer have been developed in-house by various mining companies in South Africa. These systems have the potential to contribute significantly to methane measurement and also provide a valuable means of obtaining data for research. The full benefits of these systems have yet to be exploited.

Development and evaluation of measurement techniques

- 2.12 Laboratory techniques have been established for measuring methane adsorption isotherms and also for investigating stress-permeability relationships in coal and other types of rock. Specific test procedures have been devised for quantifying both methane diffusion coefficients and also the typical natural fracture spacing (fracture network size) in coal samples (Cook, 1992). The latter involved measuring rates of

sorption and desorption of methane from crushed coal of a known size distribution. A similar process has previously been described by Daines (1972).

- 2.13 Experimental techniques have been demonstrated by Leibowitz and Cook (1992) for measuring in situ coal seam permeability. One method involves measuring the transit time of a pulse of tracer gas (sulphur hexafluoride) between two sealed boreholes maintained at different pressures. Another method uses a single borehole in which multiple packers are placed. Pressure decays are then matched against theoretical curves to derive a permeability value. A further technique also appears to have been applied with success in which coal seam permeability was measured by determining the rate of pressure drop in seven 80mm diameter boreholes, one of which had its packer removed after gas pressures had stabilised. Details of the method which involves optimising values in a mathematical model of radial gas flow to a sink are described by Cook (1989).
- 2.14 A technique for investigating the effect of coalface stress on the permeability of a seam in the roof of room and pillar workings was demonstrated at Ermelo Colliery (Leibowitz and Cook, 1992). Tracer gas was injected into the roof seam via a borehole drilled through an intervening sandstone bed. Arrival times of the gas detected in a grid of boreholes provided an indication of the directional dependence of permeability in the vicinity of coal workings. The value of this type of experiment is that it provides information on the potential mobility of gas beyond the seam actually being worked.
- 2.15 A limited amount of work has been done in developing a method of directly measuring seam gas content from coal cores. The general principles of the US Bureau of Mines approach have been adopted, but no standardised method appears to have been described.
- 2.16 Due to lack of confidence in direct methods of seam gas content measurement and doubts as to their practicality in South Africa, an indirect method has generally been preferred which involves measuring in situ gas pressures and using methane

adsorption isotherms to estimate the quantity of gas held in the coal at the measured pressure.

Results of laboratory measurements, in situ testing and underground investigations

- 2.17 Sampling, in situ testing, and investigations have mainly been concentrated on relatively few, unusually high gas emission sites. Table 3 shows the principal locations at which methane emission research has been undertaken since 1980 along with the type of study made. Majuba, in particular, was potentially the gassiest mine ever developed in South Africa but it was abandoned before coal production was established due to problems of dykes and gas emissions.

Laboratory results

- 2.18 A considerable number of methane adsorption isotherm measurements have been made at the University of the Witwatersrand. By June 1987, isotherms had been determined on some 90 coal samples taken from 20 different mines (Phillips, Wait et al, 1987).
- 2.19 In collaboration with COMRO, Billenkamp (1988) gathered coal samples representing 12 different colliery locations. Methane adsorption determinations were made on some 30 samples, most of which were conducted at three different temperatures, 10°C, 20°C and 30°C. No reliable seam gas pressure data are provided which enable the results to be interpreted in terms of seam gas content values. However, temperature data obtained from measurements in exploration boreholes confirmed that for usual seam depths in the region of 150m to 200m, isotherm temperatures of 20°C are reasonably representative.
- 2.20 A considerable amount of methane adsorption data on South African coals was produced by Stripp (1989) and Billenkamp (1988) but the full measurement details are not particularly clear. No special precautions regarding the retention of moisture are recorded although during the period of the research "*a procedure of testing undried coal samples was adopted for further experimentation*" (Stripp, 1989, p94).

Table 3
Major Methane Emission Studies at Colliery Sites in South Africa (post 1980)

Location	Mining Company	Method of Mining	Nature of study and reference for further details
Klippsruit	Anglovaal Ltd	-	<p>Measurement of coal seam temperatures</p> <p>Direct measurement of seam gas content on exploration borehole cores (Billenkamp, 1988)</p>
Ermelo	TransNatal Coal Corporation	Bord and pillar	<p>Methane adsorption measurements on coal samples</p> <p>Measurement of in situ gas pressures in existing underground exploration boreholes and a roof seam (Stripp, 1989)</p> <p>Tracer gas study of gas migration patterns in a coal seam in the immediate roof of the worked seam (Leibowitz and Cook, 1992)</p> <p>Laboratory permeability tests on samples of coal, sandstone, carbonaceous shale and igneous rock (Stripp, 1989)</p> <p>Measurement of methane emission rates in bord and pillar workings using a combination of electronic recording and manual equipment (Stripp, 1989)</p>
Majuba	Rand Mines (Mining and Services) Ltd	Bord and pillar (proposed)	<p>Methane adsorption isotherm measurements on coal samples</p> <p>Direct measurement of seam methane contents (but no residual gas content determination) on coal cores (Kavonic et al, 1987)</p> <p>In situ gas pressure measurement (Kavonic, 1990)</p> <p>Measurement of methane flow rates from in-seam drainage boreholes without the application of suction (Cook, 1993)</p> <p>In situ permeability determination by analysis of measures rates of pressure drop in boreholes (Cook, 1989)</p>

Table 3 (continued)
Major Methane Emission Studies at Colliery Sites in South Africa (post 1980)

Location	Mining Company	Method of Mining	Nature of study and reference for further details
Secunda (4 collieries)	Sasol	Bord and pillar	<p>Occurrences of methane in the mine workings and their correlations with mining and geological factors (van der Merwe, 1993)</p> <p>Analysis of gas compositions and determination of the probable origins of the gas encountered in the underground workings (Botha, 1995)</p>
New Denmark	Amcoal	Longwall	Methane drainage of goafs (Roman, 1996; da Silva, 1996)

The quantity of methane adsorbed by coal at a particular pressure is affected by the moisture content of the coal. The in-situ moisture content must be maintained during the measurement process if results representative of natural conditions are to be obtained, or an appropriate correction applied. Isotherms can be expressed in the form of two constants obtained from a mathematical representation of the results. The Langmuir constants obtained at 20°C from the above studies are reproduced in Tables 4 and 5. Table 4 also shows the adsorbed methane content of coal (dry, ash-free basis) for a seam gas pressure of 800kPa considered to be reasonably typical of South African conditions. The volumetric laboratory method used takes no account of any gas held in fracture space within the coal. A poor correlation between methane adsorption capacity and rank was reported which contrasts with European results but this may have been due to error resulting from large corrections due to the high ash contents of the South African coals and lack of standardisation of moisture conditions.

- 2.21 Experience in current coal mine workings where methane is detected in roof dewatering boreholes and the occurrence of methane emission problems in gold mines is a reminder that, at elevated pressures, significant methane can be dissolved in water. Stripp (1989), adapted the methane adsorption apparatus to determine the solubility of methane in mine water (from a gold mine shaft) at 30°C over a range of pressures up to 5MPa; approximately equivalent to a hydrostatic head of 490m (see Table 6). In coals seams of low gas content at moderate depths, gas in solution may represent a significant hazard in some circumstances.
- 2.22 The permeabilities of various rocks and coals were measured in the laboratory at the University of the Witwatersrand under different degrees of confinement to simulate strata stresses (Stripp, 1989). For reasons of safety, air was used instead of methane. The difference in viscosities was not considered to be important at the low permeabilities typically exhibited by coals. Experiments were conducted to establish the effect of the following on permeability:
- gas pressure ("Klinkenburg Effect");
 - repeated gas pressurisation and de-pressurisation at constant stress;
 - sensitivity to repeat loading and unloading of hydrostatic stress at constant gas pressure;
 - non-hydrostatic stress environments representative of mining conditions.

Table 4

Langmuir constants at 20°C measured on coal samples from various South African collieries (NTP, daf basis)

Colliery and Seam (1)	Sample Number	A (m ³ /t)	b (MPa ⁻¹)	Q (2) (m ³ /t)
Tshikondeni, (product)	s25	17.34	0.79	6.7
Tshikondeni (ROM)	s26	20.62	0.51	6.0
Hlobane, Gus	s27	12.52	0.88	5.2
Hlobane, Dundas	s28	13.46	0.76	5.1
Ermelo, C seam lower	s29	13.04	0.80	5.1
Ermelo, C seam lower	s30	11.67	0.89	4.9
Hlobane, Dundas top	s31	13.14	0.75	4.9
Umgala, Alfred middle	s32	13.30	0.70	4.8
Kilbarchan, Main seam	s33	12.74	0.76	4.8
D.N.C, Bottom seam	s34	18.25	0.43	4.7
N.A.C, (discard)	s35	17.12	0.47	4.7
T.N.C, 2 seam	s36	12.67	0.73	4.7
Hlobane, Dundas bottom	s37	13.14	0.62	4.4
Umgala, Gus seam	s38	12.71	0.66	4.4
Hlobane, Dundas bottom	s39	11.26	0.76	4.3
Kilbarchan, Main seam	s40	13.07	0.55	4.0
Ermelo, C seam upper	s41	13.85	0.50	4.0
Greenside, 5 seam, (R.O.M)	s42	12.88	0.40	3.1
Greenside, 5 seam, (product)	s43	9.26	0.59	3.0
Greenside, 2 seam, (product)	s44	9.01	0.61	3.0
Prinshof, 2 seam	s45	10.24	0.50	2.9
Delmas, 2 seam	s46	7.38	0.83	2.9
Springfield, 4 seam	s47	7.30	0.47	2.0
Matla, 4 seam	s48	6.41	0.54	1.9
Sigma, 2b seam	s49	7.75	0.41	1.9
Delmas, 2 seam	s50	5.96	0.52	1.8
Matla, 4 seam	s51	5.71	0.53	1.7
Sigma, 3 seam	s52	7.69	0.28	1.4
	Mean	11.77	0.62	
	S.d	3.79	0.16	

After Stripp (1989).

(1)

Type of sample used shown in brackets

(2)

Estimated methane content assuming a mean gas pressure of 800kPa

Table 5

Langmuir constants at 20°C measured on coal samples
from a range of collieries in South Africa (NTP)

Colliery	Sample Number	Isotherm			
		As received		Dry ash free	
		A (m ³ /t)	b (MPa ⁻¹)	A (m ³ /t)	b (MPa ⁻¹)
Ermelo	23	14.827	0.686	19.621	0.683
	24	9.313	0.874	12.222	0.869
	25	8.770	0.921	11.842	0.915
Majuba	2	6.473	1.128	10.196	1.128
	3	15.188	0.470	25.634	0.470
Hlobane	4	8.320	1.608	11.390	1.608
	5	11.567	0.402	15.536	0.402
	6	8.995	1.241	12.468	1.241
Bosjesspruit	7	10.216	0.927	14.395	0.927
	8	12.369	0.894	17.539	0.895
	9	10.544	0.927	17.635	0.927
Springfield	10	3.878	1.473	6.126	1.473
	11	5.550	0.781	9.037	0.781
	12	7.638	0.975	10.886	0.975
Phoenix	13	11.262	0.813	15.705	0.805
	14	11.533	0.823	15.966	0.816
	15	11.984	0.753	16.407	0.746
Umgala	16	20.725	0.534	28.067	0.531
	17	20.260	0.319	28.642	0.316
Utrecht	18	22.025	0.629	28.489	0.625
Klipspruit	19	9.899	0.554	12.960	0.562
	20	11.634	0.863	19.407	0.877
	21	8.465	1.032	12.631	1.040
	22	10.732	0.366	14.001	0.369
	26	20.837	0.585	29.483	0.578
Piet Retief	27	19.606	0.833	28.024	0.823
	28	20.802	0.544	30.087	0.537
	29	14.504	0.402	20.369	0.398
Blinkpan	30	14.857	0.428	19.223	0.424
	31	20.052	0.233	26.934	0.231

After Billenkamp (1988)

- sensitivity to repeated loading and unloading of hydrostatic stresses at constant gas pressure;
- non-hydrostatic stress environments representative of mining conditions.

Table 6

Solubility of methane in a mine water sample at 30°C

Gas Pressure (MPa gauge)	Methane solubility (m³/t of water)
0.5	0.113
1.0	0.291
1.5	0.534
2.0	0.680
2.5	0.874
3.0	1.036
3.5	1.149
4.0	1.214
4.5	1.375
5.0	1.570

After Stripp (1989)

- 2.23 Samples of coal, sandstone, carbonaceous shale and igneous rock were obtained from Ermelo Colliery. Additional coal samples came from Piet Retief, Phoenix and Durban Navigation Collieries. The experimental techniques were found to be unsuitable for examining permeability characteristics at low stress confinements (<3MPa) such as may be expected near coalfaces. Friable samples and extreme variations in visible fracturing inevitably meant a scatter of results for each test.
- 2.24 The results appeared to show a reduction in apparent permeability with increase in pressure (the Klinkenberg effect). Reversals of the effect observed at low confining stresses may have been a result of the experimental method rather than a manifestation of a characteristics of the material. Decrease in permeability with increase in stress was demonstrated as expected with sandstones generally showing

less stress dependence than coals. All sample types exhibited permeability hysteresis effects.

- 2.25 The wide variability of permeability parameters obtained indicates that laboratory determined characteristics may not be helpful for predicting in situ conditions. Due to difficulties in reproducing natural stress conditions in coal samples, a lack of parity between laboratory and in situ measurements is not unusual. For instance, in-situ tests at one location produced a permeability value of 250 microdarcies whereas laboratory tests yielded permeabilities from 1 to 10 microdarcies (Cook, 1989).
- 2.26 The results of laboratory methane adsorption isotherm measurements made using a gravimetric method on 28 coal samples from eight different coalfields are described by Erwee and Cook (1991). Within the expected gas pressure range of 0 to 1 MPa most collieries are considered to have gas contents below $10\text{m}^3/\text{t}$.
- 2.27 Laboratory rate of desorption measurements on samples of crushed coal of known size distribution are also reported. Diffusion constants were estimated from the data. Values obtained during the initial emission of compressed gas are meaningless, therefore only the values measured at the lower desorption rates should be used. The method is also sensitive to size distribution variations between samples. Nevertheless, provided samples are of similar petrographic composition and treated consistently, the emission behaviour of coals at the micro structure scale can be characterised. Most of the samples (Cook, 1992) exhibit diffusion coefficients within the range 1 to $5 \times 10^{-9} \text{ cm}^2/\text{s}$. These values compare favourably with those measured by other workers eg. $10^{-12} \text{ cm}^2/\text{s}$ (van Krevelen and Schuyer 1957), $\leq 10^{-9} \text{ cm}^2/\text{s}$ (Nandi and Walker 1970) and $10^{-10} \text{ cm}^2/\text{s}$ (Creedy, 1985). Cook (1992) also refers to values of 10^{-4} to $10^{-7} \text{ cm}^2/\text{s}$ quoted for Australian coals (Lama and Nguyen, 1987) and US coals (Kissel and Bielicki, 1972).
- 2.28 The emission characteristics of samples of a South African coal seam which had been affected by proximity to an igneous intrusion have been studied (Cook, 1992). The diffusion coefficient of burnt coal increased as did the methane adsorption capacity

on approach to the dolerite as shown in Table 7 below. The increase in the latter may be partly a response to the reduction in moisture content and partly due to an increase in micropore surface area as a result of the "coking" process.

Table 7
Effect on coal properties of proximity to an intrusion

Parameter	Contact	2m distance	75m distance
Bulk density (g/cm ³)	1.37	1.38	1.25
Moisture (%)	2.2	2.8	4.3
Volatile matter (%)	13.0	14.5	32.0
Ash (%)	18.8	11.7	11.1
Calorific value (MJ/kg)	26.5	29.4	27.1
Diffusion coefficient (cm ² /s)	2.0x10 ⁻⁹	4.2x10 ⁻⁹	5.0x10 ⁻⁹
Estimated methane content at 1MPa pressure (m ³ /t)	12	18	19

2.29 An important parameter in many methane prediction models is the initial methane content of the coal seam to be worked. Accurate gas content measurements are also needed to determine the magnitude of local variations in seam gas content which could affect the reliability of methane prediction calculations. There are two basic approaches to seam gas content measurement, "direct" (or desorption) and "indirect", the details of which are discussed in a later Chapter. Researchers in South Africa have used and compared both methods but not with particular rigour.

2.30 Samples of coal for direct measurement were obtained from Anglovaal exploration boreholes at Klipspruit. There was a 2 day delay before the first desorption test was made. Desorption measurements were continued for 17 days and the cumulative volume of gas emitted plotted against the square root of time in accordance with the USBM method. Thus, the initial gas loss prior to sealing was estimated and added to the total desorbed gas volume. No measurement was made of the gas remaining in the coal core once the desorption measurements were completed. The highest

methane content value obtained was $0.55\text{m}^3/\text{t}$ on an 'as received' basis. The expected gas content using the indirect method for an assumed gas pressure of 1.1MPa was $3.7\text{m}^3/\text{t}$ (as received). As a result of the apparent discrepancy between the two gas content results, no further direct tests were done. The reason for the discrepancy was not satisfactorily explained by the researchers.

- 2.31 Seam methane contents were measured on coal cores at Majuba using the USBM direct method (Kavonic et al, 1987). However, only desorbed quantities and estimated gas losses prior to sampling were measured. No facility was initially available for determining residual gas left in cores on completion of desorption testing. Measured gas contents varied from $1.03\text{m}^3/\text{t}$ to $10.8\text{m}^3/\text{t}$ (ash-free basis). Samples from neighbouring mines, again without measurement of residual gas contents, were reported to vary from $1.1\text{m}^3/\text{t}$ to $8.6\text{m}^3/\text{t}$.
- 2.32 The results were considered to be erratic with no observable trends, boreholes separated by about 100m at one locality showing highly variable results. However, it seemed reasonable to assume that the highest gas content samples were those which desorbed the most rapidly and hence would have the lowest residual gas contents. The variability was ascribed to lack of residual gas content measurements and operator error.
- 2.33 Direct gas content measurements were discontinued as it was felt that the accuracy of results relied too heavily on field operatives. Instead, efforts were concentrated on indirect measurements involving laboratory methane adsorption isotherms conducted at a temperature of 20°C and in situ gas pressure determinations in underground boreholes. The highest gas pressure measured was 1.6MPa . A mean seam gas content of $6.6\text{m}^3/\text{t}$ was obtained from a series of adsorption isotherms (the reference does not indicate whether the results were adjusted to an ash-free basis). No allowance was made for gas compressed in fracture space. The seam temperature was 23°C but this was considered sufficiently close to the 20°C used for the methane isotherm measurements (Cook, 1989).

- 2.34 Research to date in South Africa has, therefore, shown an apparent high variability of seam gas content even from sampling sites in close proximity to each other. Some of the variation has been attributed to measurement uncertainty where a direct method of gas content determination has been employed. In the proximity of underground mine workings, methane content variations would be expected due to desorption of gas from the de-stressed ground, the residual gas content depending strongly on the time elapsed since the ground was first disturbed. However, there are also geological factors which are likely to have caused regional variations and local perturbations in gas content. These do not appear to have received much attention.
- 2.35 The quantity of gas generated within a coal seam depends on the degree of coalification (coal rank), but the amount of gas retained is determined by the sorption capacity of the coal, together with gains and losses due to later geothermal events and migration losses during any erosion periods.
- 2.36 Coals of various ranks are recognised in South Africa from low rank bituminous in the Orange Free State through medium-rank bituminous in the Transvaal to high-rank bituminous and anthracite in Natal (Falcon, 1977). The general trend is of coal rank increasing westwards. However, superimposed on this pattern are effects which have implications for gas content variations in individual coal seams due to the existence of many major and minor dykes and sills. According to Falcon (1977) the range of influence of a dyke can vary within wide limits depending upon temperature, its chemical composition, the thermal conductivity of surrounding rocks and the water content.
- 2.37 South African coal mines have experienced elevated gas emissions on occasions on approaching igneous dykes. Outbursts of coal and methane have also been reported. During operations to access a new area of coal through a dolerite intrusion at Twistdraai Colliery, Secunda, five outbursts occurred over a period of about one year (Anderson, 1995). Dolerite intrusions had been mined through without incidents during the preceding fifteen years at the mine. Whereas the changes in the emission

characteristics of coal in proximity to a dyke have been studied (Cook, 1992), no direct gas content measurements have been reported.

2.38 Geothermal events can exert a strong influence locally on seam gas contents resulting in an increase or decrease depending on the proximity of the seam to heat sources such as igneous dykes. Table 8 shows the seam gas contents measured on coal cores from an exploration borehole in the North East of England which intersected an igneous dyke close to a coal seam.

Table 8
Gas contents of coal seams in the vicinity of an igneous dyke in the UK

Seam	Depth (m)	Gas content m ³ /t ash-free		In situ moisture content (%)
		Methane	Ethane	
Yard	397.3	7.56	0.49	2.9
Low Main	440.9	6.20	0.63	5.9
Thin coal	545.5	1.41	0.06	3.6
Igneous dyke	555.0	-	-	-

2.39 In the same region of the UK an unusual seam gas content phenomenon has been observed, possibly connected with a regional geothermal event. Above a certain depth, ranging from about 350m to 500m below sea-bed level, seams were found to be almost wholly degassed over an extensive area. Beneath the degassed zone, methane contents increased with vertical depth commensurate with trends elsewhere. This feature has yet to be satisfactorily explained. Similar geological circumstances may become evident in South Africa. Unusual methane content variations amongst measurements made on South African coals should, therefore, not necessarily be dismissed as wholly due to experimental uncertainty. A reliable gas content measurement method will enable such features, if they exist in South Africa, to be detected and the implications for underground methane emission levels assessed.

- 2.40 The relationship between coal rank and gas bearing characteristics of South African coal seams has not been studied in any detail. Work that has been done has generally relied on parameters such as carbon and volatile matter contents as an indicator of the thermal maturity of the coal substance. Due to the variability of the petrographic composition of South African coals, chemical and physico-chemical analyses are not suitable for representing the degree of coalification. The most appropriate method, which is largely independent of the variability of the coal composition is vitrinite reflectance (Falcon, 1978). As both seam gas content and vitrinite reflectance (in particular the anisotropy) are sensitive to thermal events, it may be possible, on the basis of such measurements, to predict the presence of a dyke before it is intersected by mineworkings.
- 2.41 The petrographic compositions of South African coals differ substantially from European coals. The petrographic components of coal are known as macerals which can be considered analogous to the minerals of other rocks. On the basis of their similarity in petrographic properties, three principal maceral groups are recognised: vitrinite, exinite and inertinite. European coals are generally high in vitrinite and South African coals rich in inertinite. Laboratory work has demonstrated that the sorption and emission properties of coal samples in the laboratory depend on the petrographic composition of the coal. Differences between the gas bearing characteristics of South African coals compared with European coals are therefore to be expected.
- 2.42 In comparing gas contents of South African coal seams with those from other countries, especially those in the northern hemisphere, consideration should be given to the following:
- the inertinite rich seams of South Africa might be expected to have lower gas contents than vitrinite rich European coal seams at similar gas pressures because inertinite appears to have a lower adsorption capacity than vitrinite and also inertinite produces less gas than vitrinite coals during coalification (Creedy, 1979). Beamish and O'Donnell (1992) have also demonstrated that "dull" coal has a lower sorption capacity than "bright" coal;

- the present gas content of a seam is the difference between the quantity of gas produced by coalification and the net quantity lost over geological time - the geological history of the South African coalfields has some differences from those elsewhere;
- the retention and transmission properties of coal in its natural state are strongly temperature dependent - ubiquitous, localised thermal events due to igneous intrusions are likely to have significantly affected seam gas contents in their vicinity.

In-situ testing

- 2.43 Measurements of gas pressure at Majuba Colliery were made early in the life of the mine. Boreholes were purpose drilled. After insertion of the packers, maximum gas pressures were recorded within 24 to 48 hours, 1600 kPa being the highest attained in the Gus seam. Fluctuations in recorded gas pressures over time indicate the possibility of gas leakages from the boreholes. The highest measured pressures should, therefore, be considered minimum estimates of in situ conditions, provided the holes were dry; waterlogged boreholes would provide a measure of hydrostatic rather than gas pressure.
- 2.44 Underground investigations were also carried out at Ermelo where the working section was separated from an upper coal by a low permeability sandstone parting. Gas pressures up to 215kPa were measured. From Stripp's (1989) methane isotherm data an in situ gas content of 1.6 m³/t is therefore indicated.
- 2.45 This work indicates the importance of taking possible gas contributions from immediate roof seams into account when modelling gas emissions. The usual practice at Ermelo was to drill 2 to 3m vertical drainage holes through the sandstone parting.
- 2.46 The range of maximum seam gas pressures recorded at various locations are shown in Table 9. Some directly measured seam gas contents are compared with indirectly measured values, where available, in Table 10. The direct measurements are of the

desorbable gas content which is the quantity of the gas released into an atmosphere of pure methane at 0.1MPa. This does not represent the total absolute methane content.

Methane emission investigations

2.47 Methane emission rates were measured at Ermelo Colliery in bord and pillar workings using specially developed instrumentation designed and constructed by Gencor's Group Electronics Department.

Table 9
Reported in situ gas pressures
in some South African coal seams

Location	Seam	Maximum recorded gas pressure (kPa)	Reference
Durban Navigation	Gus	920	Joubert (1967)
Indumeni	Gus	320	Graves et al (1975)
Ermelo	Lower C	70 ⁽¹⁾	Stripp (1989)
Ermelo	Upper C	215	Stripp (1989)
Majuba	Gus	1600	Kavonic (1990)
Majuba	Alfred (2)	1900	Cook (1993)

Notes

- (1) Measured in existing underground exploration boreholes with ages ranging from 2 months to 2 years
- (2) Affected by dolerite sill according to Kavonic et al (1987) and therefore may not be typical.

Table 10
Reported seam methane contents (desorbable)
of some South African coal seams

Location	Seam	Methane content (m ³ /t)		Reference
		Direct Method	Indirect Method	
Klipspruit	Alfred or Gus	0.55	3.7 ⁽¹⁾	Billenkamp (1988)
Majuba	Gus	1.03 to 10.8 ⁽²⁾	6.6	Kavonic et al (1987) Kavonic (1990)
Ermelo	Upper C	-	1.6	Stripp (1989)
Middelbult	No.4	1.7 to 2.1 ⁽³⁾	-	Eicker (1993)
	4 Upper	0.6 to 1.2 ⁽³⁾	-	Eicker (1993)
New Denmark	No.4	0.95 to 1.7 ⁽⁴⁾	-	Roman (1996)

Notes:

- (1) A gas pressure of 1.1MPa was assumed
- (2) Quoted to dry ash-free basis
- (3) As received basis at 101.3kPa, 273K
- (4) As received basis.

The equipment recorded absolute ambient pressure, methane concentration in the ventilating air and the time and date of readings. Air quantity was measured manually. Although ostensibly located in a historically gassy area of the mine, little gas was detected at a working coalface. The mean flow rates of methane varied from about 260 to 450 l/s in one return. An intersected in-seam borehole contributed most of the methane make to a drill and blast section. No obvious build-up of gas was recorded overnight when no production was taking place yet concentrations increased rapidly following ventilation failures, presumably due to gas migration from previously unventilated areas.

2.48 Barometric pressure variations have attracted considerable attention as a possible cause of underground gas emission problems in South Africa. Sufficient research has now been done in South Africa to enable the phenomenon to be properly understood. Research findings have been very clear. Gas emission into bord and pillar workings at Ermelo colliery in the Eastern Transvaal (Stripp 1989) was not significantly

affected by barometric pressure. Neither was any correlation evident between drained methane and barometric pressure at Majuba colliery (Kavonic, 1990).

- 2.49 Fauconnier (1992) analysed barometric pressure patterns preceding 59 major explosions in South African gold and coal mines which had occurred over a period of 20 years. All the cases considered in coal mines related to bord and pillar operations, no major explosion having been associated with a longwall operation in the period studied. The author argues that medium term (longer than one day) downward trends in barometric pressure rather than diurnal variations are the main contributory factor to explosions of flammable gas in underground coal and gold workings. A hypothesis that rate of pressure drop is not an important criterion is inconsistent with observations on abandoned mineworkings in the UK which indicate that the magnitude and direction of flow strongly depends on the rate of pressure drop and the period over which it occurs.
- 2.50 The data provided by Fauconnier (1992) indicates that rates of pressure drop immediately prior to explosions ranged from zero to 65Pa/hr. Where pressure drops coincide with explosions in coal mines, the rates of fall vary from 10.8 to 65.0 Pa/hr and in gold mines from 7.1 to 58.6 Pa/hr. These rates of fall apply to 54% of the coal mine explosions and 48% of the gold mine explosions which suggests a random effect.
- 2.51 Van Zyl and Cook (1994) reviewed the relationship between barometric pressure and 35 methane related explosion incidents. They concluded that there was a tendency for gas related incidents to occur during downward pressure trends but were unable to identify a causal link. A subsequent study reported by da Silva (1995) used underground measurements to investigate the effects of barometric change on gas emissions. A general inverse relationship between barometric pressure and methane concentration was detected. Possible methane sources cited, but not proven in the investigation, included goafs, sealed areas and "fault systems" in the coal.

2.52 In practice it is recognised that a number of factors contribute to an explosion, essential prerequisites being an ignition source and an accumulation of gas to migrate over the ignition source. The quantities of gas held in fracture space within exposed coal and rock faces in normally ventilated workings, which would be released as a result of relatively small reductions in absolute pressure, cannot usually account for the volumes of gas involved in explosions. Goafs and sealed-off areas are, however, widely recognised as sensitive to variations in barometric pressure.

Development of Methane Flow Models

2.53 One of the first methane flow models to be produced was described by Stripp (1989). A simple uni-directional flow of gas in a semi-infinite, porous medium was modelled analytically. Due to the generally unsatisfactory nature of laboratory results, reliance was placed on the in-situ permeability and porosity data of others. In predicting gas flows, no account was taken of diffusion and desorption processes either in the coalface or mined coal. For the model to predict realistic flow rates it was found necessary to increase the porosity value to empirically take into account the adsorbed gas in the coal. The model was therefore inherently limited in that neither porosity and permeability input data could be determined adequately.

The CSIR Miningtek Gas Flow Model

2.54 Several years of literature and technical research have culminated in the development of a gas flow model by CSIR Miningtek (Linzer and Cook, 1995).

2.55 The model represents coal as a micropore matrix from which gas diffuses and a fissure network within which laminar flow of gas occurs (Liebowitz and Cook, 1992). The fissure network size is determined from rate of sorption or rate of desorption analyses. Measurements on two coal samples from South Africa indicated a fissure spacing of about 3mm (Cook, 1992). In order to fully characterise the coal, the model requires the following additional inputs (van Zyl, 1995):

- coal density determined using standard laboratory procedures;
- gas diffusion coefficients from laboratory desorption measurements;

- free gas temperature which can be measured in situ or estimated from available geothermal data;
- principal intrinsic permeabilities;
- Klinkenberg constants which enable the effects of gas pressure on apparent permeability to be described;
- normal incumbent stresses from rock mechanics analyses;
- Young's modulus and Poisson's ratio from standard rock testing procedures;
- virgin seam gas pressure which can be measured directly, estimated as a function of depth using an empirical formula, or calculated from the methane isotherm data already entered by supplying a seam gas content value.

2.56 Sensitivity tests are now needed to determine which of the above parameters are the most critical and the precision to which they need to be known. There is some doubt as to the relevance of the Klinkenberg effect in describing coal permeability and this is discussed further in Chapter 3. Kim's (1977) formula, which was derived to represent some US coal seam conditions, has been used to estimate gas pressures in South African coal seams (Stripp, 1989) as too few in situ measurements were available. Neither were sufficient methane content values available from which gas pressure could be calculated via methane adsorption data.

2.57 There is clearly some scope for reducing the input requirements of the current model by assigning typical values to some parameters and introducing empirical relationships to facilitate reasonable estimation of others. It would be of considerable practical benefit to users if the input variables were reduced to, say, gas content and depth.

2.58 There is little doubt that the gas emission model described by Linzer (1994) would provide a suitable basis from which to construct a methane prediction program for

application to South African coal mines. The model is probably more advanced than any method in regular use at collieries. However, in its current state it is a research tool and is likely to remain so if not rationalised substantially. Like many of the advanced simulation models elsewhere in the world it has yet to be validated. The work involved in developing a practical prediction method from a theoretical model should not be underestimated. For example, Airey published his theory of gas emission from coal mining in 1971. Initial computations sometimes involved days of processing time on a mainframe computer. Only by introducing simplifying empirical relationships was the model made manageable. Almost 10 years elapsed before a practical method was available for, and the technology accepted by, collieries. During this period the prediction method evolved as a result of testing and consultation with colliery engineers. Early versions were constrained in their scope by the memory and graphical limitations of portable computers. A hand-worked graphical method was superseded by an APL computer program which in turn was overtaken by a compiled BASIC version for modern PC's.

- 2.59 Development of an application version of the Miningtek model would not be as protracted, but it will require a combination of mathematical, computing and practical engineering expertise.
- 2.60 During the course of SIMRAC project COL 030 Mr Linzer of CSIR sought the views of European peers on the developing gas flow model. The Miningtek gas flow model was considered to be comprehensive by those consulted but there was concern that computerisation may prove difficult due to the large number of calculations required by the model. The experts from Germany, Poland, France and Belgium who were approached were not aware of any similar work currently being undertaken in Europe.
- 2.61 For this particular project, Dr T X Ren of Nottingham University was asked to express his expert opinion of the Miningtek model. His comments are summarised below:

- The mathematical model, although complex, has been clearly defined. The underlying mechanism of gas diffusion and subsequent transport and migration behaviour has been well explained and understood.
- The treatment of permeability is important in any methane prediction model. In the Miningtek's model, permeability is related to the element dimensions (void space) which is dependent on the in-situ permeability and the state of mining activities, in particular, stress distributions around the working faces. A mathematical or empirical link may be needed between stress prediction and permeability determinations. The effect of fracture, and hence fracture permeability, needs to be understood and incorporated into the model. Strata permeability not only depends on the element dimensions (void space) but also on the interconnections of these void spaces say, by micro-fractures.
- The introduction of the concept of the random variations (random number generator) to cope with 'natural fluctuations' is quite unique.
- The parameters considered within the model are comprehensive and this may present some computerisation difficulty for a PC. The idea of considering "*an elemental region composed of a collection of elements that all behave in a similar manner*" may prove helpful when considering a mining layout. Nottingham University have adopted a similar approach with their CFD model currently under development.

Modelling of gas flow in the cutting zone

2.62 Incendive sparking caused by picks on continuous miners, roadheaders, shearers and coal cutters striking quartzitic rock is a dominant source of gas ignition. In the period 1984 to 1993 frictional ignitions in the cutting zone accounted for 56% of the recorded ignition and explosion incidents in South Africa in which the source of ignition was known (Phillips and Brandt, 1995). There is, therefore, an urgent need for fail-safe mechanisms to minimise gas ignition risks in the cutting zone. The

principal means of defence is fresh air ventilation. Appropriate ventilation techniques and other precautionary measures have been identified by Phillips (1996).

- 2.63 Measurements have been made of methane concentrations around continuous miners whilst cutting coal during room and pillar operations (Cook, 1995). These data have been used to validate computational fluid dynamics (CFD) models. CFD simulations have proved extremely useful for evaluating heading ventilation configurations (van Zyl, 1994; Meyer and van Zyl, 1995; Meyer, 1995). Variables on which the effectiveness of methane control depends include water flow and pressures applied to directional sprays, spray locations and orientations, the position of the machine within the roadway, airflow through machine mounted dust scrubbers, gas emission from the coal, air velocity and fresh air provisions.
- 2.64 Research in South Africa has shown that most of the methane emissions in headings occur in the cutting zone, gas flows from cut coal once loaded into shuttle cars being negligible. A primary ingredient of a ventilation design process is therefore a prediction of the likely methane flow during cutting. An empirical method for predicting ventilation requirements on longwall coalface shearers has been developed elsewhere (Creedy and Clarke, 1991), and is regularly used by ventilation engineers in the UK. The method estimates likely gas emission quantities and suggests an appropriate specification for a machine ventilation device depending on the fresh air needed to achieve satisfactory dilution of the gas. A similar approach has not yet been attempted for continuous miners. However, irrespective of the efficacy of planning aids, it is difficult to envisage a reliable solution for situations where ducts or brattices are not used to provide an uninterrupted supply of fresh air to the system.

Summary of Research Results

- 2.65 The research has provided a substantial volume of information on the occurrence and nature of gas emissions in South African coal mines. As a result of this work a number of pertinent interpretations and observations can be made and these are summarised below:

- (i) High methane flows are rarely encountered in current underground operations in South Africa irrespective of the method of coal extraction. In the past, gas emission problems occurred mainly in collieries within the Natal coalfield area.
- (ii) Steady gas emissions from seams currently being worked appear to be generally low and easily diluted by the quantities of air usually provided in the mine ventilation circuits.
- (iii) The processes which give rise to occasional hazardous gas emissions in South African collieries are complex and may not lend themselves to conventional mathematical treatment. Hazardous gas emissions should be distinguished from accumulations of methane that occur at times when the normal, designed ventilation of a section is interrupted or reduced, either accidentally or by the deliberate action of personnel with little understanding of the effects such actions may have.
- (iv) Most potentially hazardous methane emissions probably occur during the cutting process in mechanised room and pillar workings (Cook, 1995).
- (v) A significant proportion, but not all, of the methane occurrences in the relatively low gas emission mines at Secunda are associated with dolerite dykes or associated geological disturbances (van der Merwe, 1993). On a wider scale, unexpectedly high release rates of methane in underground workings are often associated with faults, igneous intrusions and areas of devolatilized or burnt coal.
- (vi) Methane is emitted into room and pillar workings from the seam being worked and also from immediately adjacent seams in the roof (Leibowitz and Cook, 1992) and floor. Strata failure above longwall panels may extend much higher. Strata disturbance has been reported up to about 100m above the worked seam (Piterek et al 1991).

- (vii) Gas emission from the solid coal into room and pillar workings is not significantly affected by barometric pressure variations (Stripp, 1989).
- (viii) A predilection for barometric variation as an important gas emission control is misplaced other than where goafs or sealed areas of a mine are being considered.
- (ix) Much of the research undertaken to date has concentrated on sites associated with specific methane problems. Insufficient information is available from "normal" sites which would allow the overall scale of methane emission risks to be assessed.
- (x) Gases emitted from coal seams and other strata in the coal measures consist predominantly of methane. Low concentrations of hydrogen, carbon dioxide (Sevenster and Mentjies, 1964; Mentjies, 1965) and helium have also been reported (Botha, 1995).
- (xi) At elevated pressures, significant volumes of methane can be dissolved in groundwater (Stripp, 1989) which under certain conditions may constitute a hazard additional to gas released from coal seams.
- (xii) A practical, reliable and accurate gas content measurement procedure has yet to be established in South Africa. Seam gas contents have been measured using a direct method but the results treated with suspicion due to the wide scatter of values determined on core samples from boreholes with separations as close as 100m (Kavonic et al, 1987). No explanation has been found but geological factors, such as the heating effects of dykes may be relevant.
- (xiii) Seam gas pressures have been measured in underground boreholes and the results used to obtain a "generalised" seam gas content value from methane adsorption isotherm curves. These data are no more reliable than direct

measurements due to the uncertainty as to whether test boreholes are adequately sealed. The measurements are also costly and time consuming.

- (xiv) Coal seam permeability is strongly stress-dependent and therefore rates at which gas is released into mine workings depend heavily on the degree of disturbance of gas sources caused by the mining activity.
- (xv) Coal seam permeabilities determined in the laboratory are unreliable for predicting in situ conditions.
- (xvi) The South African coal seams examined to date exhibit low permeability compared with coal seams in other countries. Evidence for this statement comes from observations that:
 - diffusion coefficients are generally less than those reported for Australian and US coals (Cook, 1992);
 - relatively low methane flow rates were measured in in-seam boreholes at Majuba compared with flow rates from boreholes drilled into coal overseas (see Table 11);
 - significant gas pressures were still detected in underground in-seam boreholes at Majuba which had been drilled from 2 months to 2 years prior to being sealed for measurement purposes
 - desorption measurements (Billenkamp, 1988) on borehole core from Klipspruit indicate that about 0.11m³/t of methane is emitted in the first 10 hours after sampling. By way of comparison, the average methane emission quantity from a UK coal over a similar period of time is 0.346m³/t; UK coals are considered to be typically low-permeability.
- (xvii) The applicability to South African collieries of research findings, methods and technologies from overseas should be considered in the context of the following profile.
 - shallow, generally thick, flat lying coal seams;

- strong, durain rich, generally high ash content coals;
- pervasive igneous intrusions;
- predominance of mechanised room and pillar operations;
- high rates of coal production.

Table 11
Comparative methane flows from in-seam boreholes in various countries

Country	Location	Seam	Suction	Methane flow rate m ³ /day/m	Comment	Reference
South Africa	Majuba	-	N	0.2 to 2.5	-	Cook (1995b)
UK	Silverdale	Great Row	Y	0.1 to 0.7	Abutment gas	-
UK	Point of Ayr	Three Yard	Y	4 to 62	Abnormal site	-
Germany	Rhineland	-	Y	0.1 to 3.5	-	Noack (1982)
Europe	General	-	-	3.2 to 6.8	-	Boxho et al (1980)
USA	Sunnyside	-	N	13 to 35	-	Finfinger et al (1982)
USA	Federal No.2	Pittsburgh	N	15	Average value	Fields et al (1976)
USA	Alabama	Mary Lee	N	6 to 18	-	Perry et al (1982)
Australia	Westcliff	Bulli	N	3	-	Hayes (1982)
Australia	Westcliff	Bulli	-	26	-	Hebblewhite et al (1982)
Australia	Central	German Creek	N	1.4 to 12	-	Robertson et al (undated)

3 WORLDWIDE REVIEW OF METHANE MEASUREMENT METHODS FOR COAL SEAMS

- 3.1 Estimates of the ability of a coal seam to relinquish its gas are strongly influenced by measurements of seam gas content, fracture permeability, gas desorption and gas diffusion characteristics. Pratt and Close (1993) state that many accepted procedures for collecting and interpreting these data are still incomplete. In this Chapter, various methods which are currently used to determine the methane bearing and emission characteristics of coal seams are reviewed.

Measurement of Seam Gas Content

- 3.2 Methane prediction methods require a measure of the quantity of gas stored in all the coal seams likely to be disturbed by mining operations. There are two principal measurement approaches:
- (i) "Indirect" methods involving adsorption isotherm and in situ gas pressure measurements; correlation of gas content with coal rank, depth and other factors; and statistical sampling.
 - (ii) "Direct" methods which involve measuring the gas released from fresh coal seam samples of known degassing history.
- 3.3 The gas content of a coal seam is usually expressed in units of metres cubed of methane, under standard conditions of temperature and pressure, per tonne of coal on an as-received basis or corrected to ash-free, dry ash-free or dry mineral matter free.

Indirect Gas Content Measurement

Adsorption isotherm - gas pressure method

- 3.4 This method involves measuring the in situ gas pressure within a coal seam and then calculating the gas content from an adsorption isotherm determined in the laboratory. The approach was first developed by Ettinger (1958) and of the indirect methods has been the most widely used. There are two parts to the method which can be examined separately:
- (i) adsorption isotherm determination;
 - (ii) measurement of the in-situ gas pressure.

Adsorption isotherms

3.5 The process by which the gas is retained in coal is termed adsorption. Methane is bonded to the vast internal surfaces within the coal by weak intermolecular forces and is in equilibrium with a relatively small proportion of free gas within the pores. At a constant temperature, the quantity of gas held increases with pressure until no more methane can be accommodated. This maximum quantity is known as the adsorption or methane capacity and the relationship between gas pressure and gas content as the "adsorption" isotherm. Some methods for measuring this relationship also take account of gas compressed in pore and microfracture spaces within the coal, the derived curve then being termed a "sorption" isotherm.

3.6 The quantity of methane (q) adsorbed at a pressure P, for a particular temperature, can be represented mathematically by the Langmuir isotherm:

$$q = AbP/(1+bP)$$

where A and b are Langmuir constants; A is the maximum methane capacity.

3.7 The additional quantity of methane (m^3/t) compressed in fracture space is given by:

$$P \left(\frac{1}{\rho_1} - \frac{1}{\rho_2} \right) \times 9.527 / (1 - 0.01552P)$$

where P is the methane pressure (MPa); ρ_1 and ρ_2 are the bulk density and the helium density respectively of the coal (tonne/m^3).

3.8 The Langmuir isotherm describes the adsorption behaviour of methane on coal (Ruppel et al, 1974) and provides a satisfactory mathematical representation of the sorption behaviour over the range of gas pressures normally expected in coal seams (Creedy, 1979). The Freundlich isotherm is also adequate (Patching and Mikhail, 1975) but less often used. The equation is written:

$$q = kP^{1/n}$$

where k and n are constants

- 3.9 The capacity of a coal to adsorb methane increases with coal rank but is reduced with increase in moisture content and increase in temperature. The adsorption properties of coal also depend on petrographic composition (Creedy, 1979).
- 3.10 The sorption characteristics of the coal substance fundamentally influence seam gas content explaining why similar ranks of coal exhibit similar ranges of gas content in different countries and different geological environments.
- 3.11 The methane sorption capacity (A) of a coal effectively places an upper limit on the gas content of the seam; excessively high gas pressures would result if the value was exceeded, far beyond any recorded in practice. The limiting capacity is probably that obtained at the maximum temperature reached during burial.
- 3.12 Various methods for measuring adsorption isotherms have been described. The methods commonly used for coal seam studies involve bringing a coal sample into contact with methane at different pressures under controlled temperature conditions and allowing a period of time for equilibrium to be attained. The quantity of gas adsorbed is measured either by weighing (gravimetric method) or by releasing the gas and collecting it over water in a calibrated burette (volumetric method). A gravimetric method developed by Daines (Daines, 1968) was used by British Coal for many years (Creedy, 1985) and subsequently in modified form by COMRO in South Africa (Erwee and Cook, 1991). Daines' method was also used by Mikhail (1971) in an extensive study of Canadian coals as reported by Patching and Mikhail (1975). Billenkamp (1988) has described a volumetric apparatus used for measuring adsorption properties of South African coal seams.
- 3.13 The gravimetric method involves removing the sample capsules from the pressurisation manifold once equilibrium is attained and conditioning the capsules to ensure temperature stability before weighing them on an accurate balance. At the same time a control capsule containing a non-adsorbent volume equivalent to that of the coal is weighed to provide a correction for the free gas in the sample capsule. The volumetric method involves desorbing the gas into a burette and recording the

total volume released. The process is repeated with helium, which is not adsorbed by coal, to determine the sample volume occupied by compressed gas, the difference representing the volume of adsorbed methane.

- 3.14 A more recent form of the gravimetric technique has been developed simultaneously in the USA (Levine, 1991) and Australia (Beamish et al, 1992) in which a high pressure microbalance is used. These are available commercially and are capable of accurate measurements of weight changes under a wide range of pressure and temperature conditions. Approximately 1g of sample is required thus enabling investigation of the sorption properties of individual coal macerals.
- 3.15 Levy et al (1992) used a sophisticated pressure-volume method to measure methane isotherms for Australian coals. The method was based on a system initially described by Mavor et al (1990). The apparatus consists essentially of a sample cell of about 80 cm³ and a reference cell of 320 cm³ which are immersed in a temperature controlled bath. A weighed sample of up to 100g of powdered coal is placed in the sample cell. After leak testing to 12MPa, helium expansion from the reference cell of known volume is used to calculate the dead space volume. The system is then evacuated. The reference cell is filled with methane at a selected pressure. The sample cell valve is then opened to admit methane from the reference cell and then closed after 3 seconds. The decrease in pressure as the gas is adsorbed is logged until equilibrium is attained and maintained for 40 minutes. The reference pressure is then increased and the cycle repeated over 8 to 10 pressure points. The system uses high precision variable pressure transducers connected to each cell and is fully automated allowing un-manned 24 hour operation.
- 3.16 Coal in its natural state is moisture saturated. To be relevant to in-situ conditions, isotherms should be measured on coal which retains its natural moisture content. The moisture content of a crushed coal sample can be restored after preparation by placing it in a saturated atmosphere under controlled temperature conditions. Standard methods have been described eg., ASTM D 1412-89 (Storer, 1990).

Effect of moisture content variation

- 3.17 Addition of moisture above a certain critical level to a coal sample causes no further change in the methane adsorption capacity within the 0 to 4MPa pressure range. The critical moisture content appears to correspond to the adsorbed water capacity of the coal (Joubert et al, 1974). Any isotherm measured on coal containing moisture at or above the critical moisture level should be almost identical and representative of coal in the natural state. The effects of small moisture losses, below the critical moisture level, can be corrected for using the empirical relationships after Ettinger (1958):

$$A_w/A_d = 1 / (1 + cm)$$

where A_w and A_d are the methane capacities of moist and dry coal respectively, m is the coal moisture content (%) and c is an experimental constant.

- 3.18 A value of the constant c applicable to US coals has been derived by Joubert et al (1974) and for UK coals and individual macerals by Creedy (1979).

Equilibrium temperature

- 3.19 For practical application it is desirable to make the sorption measurements at a temperature representative of the strata at the depth of interest. However, to facilitate comparative studies it is sometimes convenient to choose a common temperature. Sorbed quantities can then be estimated for different temperatures using Ettingers (1958) empirical equation:

$$Q \propto 1/e^b$$

where Q is the sorbed methane capacity (m^3/t) and b is a temperature factor determined from the equation:

$$b = 0.02t/(0.993 + 0.007P)$$

where t is temperature ($^{\circ}C$) and P the methane pressure (bar).

Effect of gas composition on methane adsorption isotherms

- 3.20 Methane of laboratory grade purity is generally used for measuring methane adsorption isotherms. In some countries, Australia for example, high concentrations of carbon dioxide are found in coal seams. Bartosiewicz and Hargraves (1985) have shown that the sorption capacity of coal for carbon dioxide is about 1.7 times that of

methane. However, compositional information on gas from South African coal seams would indicate that isotherms determined with pure methane adequately represent usual conditions.

3.21 The gravimetric methods involve sorption of gas and the volumetric methods desorption. For coal at the normal range of seam pressures these processes appear to be reversible with negligible hysteresis. In a comparative study Daines (1968) demonstrated that both approaches gave generally similar results. However, he considered that the weighing method offered advantages over the volumetric (or desorption) method because:

- the sorbed quantity at atmospheric pressure is more easily measured;
- moisture loss is minimised although a small loss may occur during the initial evacuation;
- there is a possibility of coal powder loss if gas is released suddenly in the desorption method;
- each gas volume measurement requires separate correction for temperature and pressure whereas increases in weight may be directly converted into volumes of methane.

3.22 Adsorption isotherm results are usually quoted at standardised temperatures and pressures, or NTP (273K, 101.325kPa) on an ash-free basis. It is usual to record sample details, moisture content and ash content with the results.

3.23 An isotherm representative of actual seam conditions is determined on coal, sampled from the gas pressure measurement site, under in-situ conditions of moisture and temperature. However, the gas content obtained will depend to some extent on whether sorption or adsorption data are used. The adsorption measurements may slightly underestimate the gas capacity at each pressure whereas sorbed quantities may exceed in-situ capacities; sorption measurements involve initially measuring the bulk density of the coal which will have a greater porosity than when in-situ due to stress relief. As the gas pressures reported for various countries are generally less than 2MPa (Ettinger 1958; Dunmore, 1969; Mucke and Meiners, 1987; Struzlick, 1975;

Cook, 1993a), the differences are not important and are likely to be substantially lower than experimental error.

Measurement of in-situ gas pressure

- 3.24 Seam gas pressures are usually measured in underground boreholes drilled to extend beyond the disturbed ground surrounding the underground excavation. Seals are set deep in the borehole and the build-up of pressure in the isolated volume is monitored. The validity of the results depends on the efficiency of sealing and the integrity of the borehole. Various hydraulic, pneumatic and mechanical seals have been used (Hargraves, 1963, Gray 1982). The petroleum and gas exploration industry have also adapted their techniques to coalbed methane testing which enable formation and seam gas pressures to be monitored in surface boreholes (GRI, 1992).
- 3.25 Gas pressure measurements in coal seams made between the years 1880 (Graham, 1937) and 1969 (Dunmore, 1969) have been reported in the UK. The indirect method was subsequently abandoned due to the practical difficulties of installing gas tight borehole seals, concerns over hydrostatic pressure effects and borehole deformation influences on gas pressure results, and also because no information as to the composition of the seam gas was obtained. In Germany, Paul (1971) has used the shape of pressure-time curves to discriminate between hydrostatic and methane pressure effects in in-seam boreholes. Prior to establishing their Direct Method, the US Bureau of Mines also undertook a programme to measure gas pressures in coal seams by inserting inflatable packers into horizontal boreholes drilled into the working face or a rib pillar (Hadden and Cervik, 1969; Hadden and Sainato, 1969).
- 3.26 Comparative tests have been made in Europe between the Belgian, French and German coal mines of the direct method developed by the former CERCHAR described by Bertard et al (1970) and the indirect or "gas pressure" method of Bergbau-Forschung (Mucke, 1972). Measurements were taken at the same place in each location. Two-thirds of the 51 values measured differed by less than 20% from the results of the other measuring method. On average, values obtained from the gas pressure method were 3.3% higher than those obtained by the direct method. Mucke

(1972) considered the indirect method to give the most precise measure of seam gas content. This conclusion is questionable on the basis of the comparative study as a systematic error in measuring sorption isotherms could easily have occurred.

The Kim method

3.27 Kim (1977) proposed an indirect method for estimating the methane content of bituminous coal seams in the USA. An equation was formulated, combining relationships from various isotherm experiments, to estimate methane content as a function of strata temperature, gas pressure, coal rank and moisture content. Thus, the gas content of a US coal seam could be estimated on a dry, ash free basis from the results of proximate analysis.

3.28 The general equation for estimating gas content (q in m^3/t) is written:

$$q = ((100 - m - a) / 100) (V_w/V_d) [k_o P n_o - b (Gh/100 + t)]$$

where h is depth in metres, m is moisture content (%), a is ash content (%), V_w/V_d is the ratio of adsorbed gas in wet and dry coal (approximated by Kim as 0.75) and b is a temperature constant (m^3/t per degree Centigrade) with an average value of 0.14 for US coals.

In addition, the rank dependent factors $k_o = 0.8 F/V + 5.6$

where F is fixed carbon (%) and V is volatile matter, and

$$n_o = 0.315 - 0.01 F/V$$

P is gas pressure which Kim estimates assuming a gas pressure gradient of 0.63MPa/100m from drill stem test data which showed the actual pressure in US coal seams was often less than hydrostatic. G is the geothermal gradient, (Kim suggests a value of 1.8°C/100m), and t the ground temperature (Kim uses 11°C).

3.29 Due to its purely empirical nature the method is of limited value beyond the coalfield areas for which the relationships were derived. However, similar empirical relationships could be developed elsewhere.

The "Statistical" method

- 3.30 The Statistical method (Creedy, 1986) involves taking fresh coal samples from rapidly advancing coalfaces or headings and measuring their total gas contents by crushing the coal and determining the quantity of gas released. As the working face advances it produces a stress field which will affect different parts of the seam to different degrees due to natural inhomogenities. The degree of cracking will, therefore, vary from place to place. If sufficient lump samples are taken, they will include some that have degassed very little below the initial seam gas content. Whereas maximum measured values themselves may be a good estimate of seam gas content, a more reproducible result is obtained by fitting the data to a suitable statistical distribution and using a particular probability point of the distribution as the best estimate.
- 3.31 The method was initially developed assuming log-normal distribution as most apt on intuitive grounds. Subsequently, the normal distribution was found to satisfactorily represent the spread of gas content values from a particular site. Strict adherence to the sampling procedure is essential if results reproducible within acceptable limits are to be obtained.
- 3.32 Experimental studies on underground coal in the UK indicate that, subject to adherence to the prescribed sampling procedure, methane content values can be satisfactorily represented by a normal distribution and seam gas content Q estimated from:

$$Q = 1.87S_n + q_n$$

where S_n is the standard deviation and q_n is the mean of the gas content values. The reproducibility of Q is given by:

$$\pm 1.66 S_n t / \sqrt{n}$$

where n is the number of samples and t is "Student's" tabulated test statistic for a chosen level of confidence and $n-1$ degrees of freedom.

The preferred sampling method is to remove a large block of freshly cut coal from the working face then remove and immediately seal a solid sub-sample of about 30 mm to 40mm in size.

- 3.33 The sample gas content measurement procedure involves breaking the sealed sample jar in a proprietary air-tight device to release the desorbed gas. This is done in a nitrogen atmosphere. Once the gas composition and pressure have been determined, the still intact coal lump is removed, weighed and placed in a mill barrel for crushing and release of the remaining gas. A correction is applied to the final result to take account of the quantities of the different gaseous components remaining adsorbed on the powdered coal.
- 3.34 Where there has been no previous experience of the method a range of sites should be sampled, taking some 10 to 20 samples from each site. Linearity of the relationship between the maximum gas content minus the mean gas content value against the standard deviation of the gas content values will indicate the potential applicability of the method and the gradient will yield an appropriate estimator.
- 3.35 The method has been widely used in UK collieries since about 1985 in place of the more expensive and technically difficult in-seam diamond-drill coring previously used to obtain underground samples for "Direct" method measurements. The advantage of this approach is that it allows measurement of gas content when the degassing start time is unknown, whereas the Direct methods are only applicable to samples of known degassing history. The disadvantage of the method is that it is only applicable to relatively low permeability coal seams from which coal samples of low fracture density can be obtained.

Additional indirect methods

- 3.36 Methods have been reported which include exhaust ventilation sampling (Lama, 1980), logging of gas emissions into a surface borehole whilst drilling (Lidin, 1965) and use of an empirical relationship between seam methane contents, coal rank and

the gas contents of coal samples taken from the sidewalls of Polish workings (Tarnowski, 1972).

- 3.37 Gas content can also be estimated from calibrated geophysical borehole logs of bulk density (GRI, 1995). An initial gas content value is, however, needed. The method relies on the correlation between ash content and bulk density; as methane is only sorbed on the coal fraction.
- 3.38 Another approach has been described by Yee et al (1991) which assumes a system comprising water filled fracture porosity, pure coal, mineral matter, adsorbed water and adsorbed methane. The densities and equilibrium moistures of the pure coal and mineral matter are determined from laboratory measurements on drill cuttings. Thus, a relationship between the mass fraction of pure coal and bulk density can be obtained.

The Direct Method

- 3.39 The Direct or Desorption Method is used to measure the gas contents of coal seams that have not been sufficiently disturbed by mining to lose significant gas before the sampling process is initiated. The direct measurement methods take account of the adsorption and desorption properties of coal which enable it to hold substantially more gas than surrounding non carbonaceous strata and when sampled to release gas at a relatively low rate. By measurement of the rate of emission, gas losses which occur during sampling can be calculated. Desorption rates increase with decrease in coal particle size. The gas remaining in coal after desorption testing can, therefore, be rapidly released and measured by crushing the samples. The Direct Method, in some form, has been applied to drill cuttings and borehole cores taken from underground boreholes in most European coal producing countries at some time. It is used to measure gas contents of cores recovered from surface boreholes in Europe, the USA and in many other countries especially in connection with coalbed methane exploration. The method was originally developed at the former CERCHAR in France during the 1960's (Bertard et al, 1970). Since that time many variants have

emerged. All the approaches involve consideration, measurement or calculation of three basic elements:

- (i) gas lost from the coal during the sampling process;
- (ii) gas desorbed into a sealed container over a period of time in order to determine (i) and gas accumulations during transport;
- (iii) residual gas in the coal on completion of desorption testing.

Recent developments have sought to improve the accuracy, speed and convenience of use of the method.

Sample containers

- 3.40 Coal samples obtained for gas content measurement are placed in specially made desorption canisters. Desorption canisters are designed to either accommodate specific lengths of whole core, core fragments or drill cuttings. When measurements involve a volumetric method it is important not to allow pressure to build-up in the vessels as this would reduce the desorption rate. In the USA a 30 psi (207kPa) pressure gauge, therefore, is often attached to the lids of these vessels in addition to a gas sampling valve. The US Bureau of Mines preferred a 4-inch (102mm) canister diameter because it will just accommodate a standard 4-inch core, thus minimizing the headspace between the sample and canister walls (Diamond and others, 1986). This helps prevent errors due to expansion or contraction of gas in response to external pressure and temperature differentials (TRW Energy Engineering Division, 1981). In testing a long length of core, use of multiple canisters is recommended so the loss of data is less critical should leakage of gas occur from one canister.
- 3.41 The dimensions of vessels used with concentrations measurement methods are not critical, an internal volume of 700 to 800 ml being suitable. The lids are fitted with two brass sampling taps. Below one of the taps is a nylon tube which, when the lid is bolted in place, reaches the base of the container. Thus, when the container is pressurised with nitrogen through one tap then subsequently sampled for concentration determination through the other tap adequate mixing of nitrogen and firedamp is assured. The nylon tube also ensures efficient flushing after each desorption

measurement when nitrogen is passed through the container to remove the evolved firedamp.

- 3.42 Canisters must be robust and gas-tight when sealed. Leak testing ought to be incorporated in the sampling procedures. The internal volumes of the canister need to be determined accurately to allow head space corrections when using volumetric measurement and for determining gas quantity when measuring concentrations.

Total versus desorbable methane content

- 3.43 Methane content results obtained using the direct method are calculated either in terms of the total methane content or the desorbable methane content. The desorbable methane content as understood in Europe is the methane content of coal in equilibrium with pure methane at a pressure of 0.1 MPa. However, the Australian Standards Association (Williams, Saghafi et al, 1992) has published guidance on gas content measurement which defines:

- (a) "desorbable gas content" as the sum of the lost gas and the gas evolved during desorption testing and
- (b) "**total** desorbable gas content" as the latter sum of quantities plus the residual gas released when the sample is crushed at atmospheric pressure.

The result of an analysis will, therefore, depend on the composition of the gas which in certain parts of Australia can include a significant carbon dioxide component. These concepts suppose that coal within strata will remain surrounded by methane when the degassing of the coal ceases. This, however, is not always the case. In mine roadways, where the partial pressure of methane is virtually zero, desorption of gas from coal will continue, if enough time was allowed, until the gas content was practically zero. Within the strata, at some point, a condition may exist where the coal is in equilibrium with methane at a pressure of 0.1MPa but it is likely to be a transient situation. For the purposes of methane prediction, therefore, total absolute gas content surely provides the most appropriate and least confusing reference value from which to calculate emissions.

3.44 The difference in value between desorbable and total gas content can be calculated from adsorption isotherm data. Preliminary inspection of South African adsorption data and also measurements made for Middelbult Colliery (Eicker, 1993) suggest the difference is of the order of $1\text{m}^3/\text{t}$. Apparatus for determining methane adsorption on coal at atmospheric pressure has been described by Daines (1963).

Gas loss before sampling

3.45 One of the most important elements of the direct method is the determination of gas loss before sampling. Most approaches involve the extrapolation of results and hence an inevitable uncertainty. Errors are minimised by seeking to:

- reduce sampling delays;
- increase the accuracy of emission measurements;
- improve the reliability of gas emission models used to represent the data;
- prevent gas loss.

3.46 Desorption measurements are used as a basis for estimating gas loss during the sampling process. Desorption rate can be measured by volumetric, piezometric, gravimetric or concentration means and the results fitted to empirical emission equations of varying complexity. The gas loss before sampling is obtained by extrapolating the emission curve to time zero when degassing was considered to have started either during retrieval of a coal core or flushing out of drill cuttings. In underground boreholes the delay times are usually short but for deep surface boreholes the time element can be substantial. Core retrieval times can be minimised by using wireline core recovery techniques in preference to conventional coring which requires the drill string to be dismantled to recover the core barrel.

3.47 As the ambient conditions in which desorption takes place in a vertical borehole will be changing as the core is recovered, neither the starting time of desorption nor the emission behaviour is known particularly well. For practical purposes the USBM recommend that time zero is considered equal to the time when the sample has been retrieved halfway to the surface if wet drilling or immediately upon coring in air-drilled wells (McCulloch et al, 1975). In the MRDE method (Creedy, 1986) time is

assumed to be zero at the point during recovery of the core when the drilling fluid pressure equals the estimated sorption gas pressure.

- 3.48 In France and Germany where much of the gas content data has been obtained from measurements made on drill cuttings from underground boreholes, gas emission rates are commonly determined with desorbometers. These are simple, robust devices which enable gas emission rates to be measured underground over short periods of time. The French desorbometer consists of a U-tube manometer connected to a vessel with an internal volume of about 1 litre. Some 10 to 15g of drill cuttings or core fragments are placed into a sampling vessel which is connected to the instrument for the same length of time as the sampling delay and the pressure rise measured. The method of calculation of gas loss is described later. This apparatus is also used in Spain. An automatic bubble flow meter is used in Germany to determine flow rate (Steinkohlenberghauverein, 1987).
- 3.49 The most well known apparatus for measuring desorption rate on whole coal cores from boreholes is that devised by the USBM (Diamond and Levine, 1981). The basic equipment consists of a sample container and an inverted water-filled graduated cylinder into which the gas accumulating in the sample vessel is periodically released. The desorbed gas is measured as the volume of water displaced. In recent years the apparatus has become increasingly sophisticated but the principles remain unchanged (Figure 2). For a detailed description of the methods currently in use in the USA together with details of available borehole core and sampling techniques "*A guide to determining coalbed gas content*" (GRI, 1995), should be consulted. However, it should be borne in mind that the techniques described are aimed at coalbed methane resource evaluation.
- 3.50 The UK version of the direct method (the MRDE method) was developed by Pritchard and first described by Broughton et al (1977). The method was developed to take advantage of an extensive surface borehole exploration programme. It differs from that used in the USA because there was a need to obtain gas content measurements using only fragments of coal core, most of the core being required for

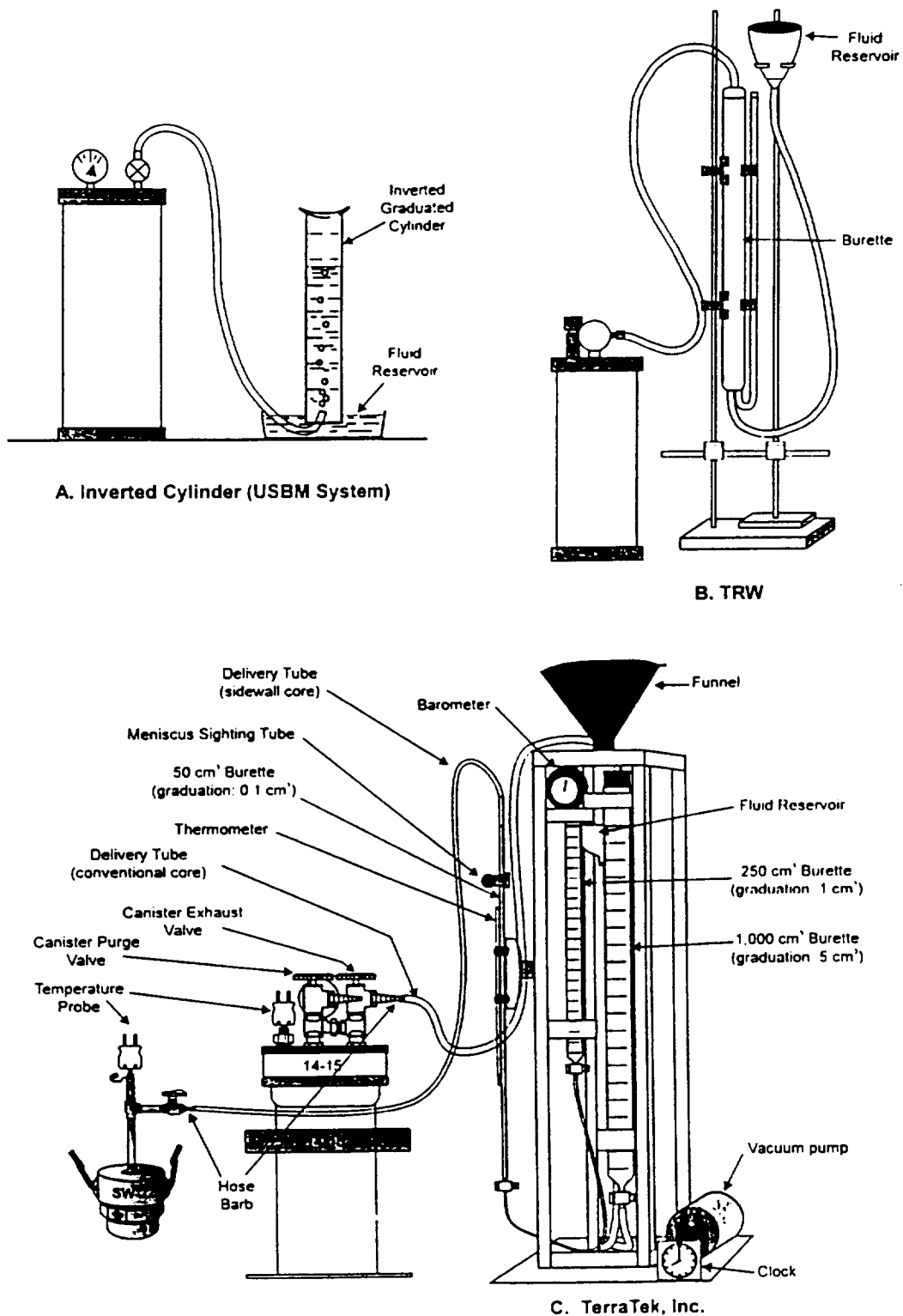


Figure 2
Progressive development of volumetric displacement
apparatus in the United States for measuring gas emission
from samples of coal core (after GRI 1995)

geological and coal quality analysis. A combination of relatively small sample size, typically 40 to 100g and generally low desorption rates precluded accurate volumetric measurements. Instead, a concentration method was used. Coal samples are placed in gas-tight vessels and returned to the laboratory for analysis. Gas concentrations and pressure provide a measure of the quantity of each gaseous component emitted over a period of time. The sample vessel is then flushed with nitrogen and another desorption increment measured over a further period of time. This process is usually repeated three times to provide the necessary data for estimation of the initial gas loss prior to sealing. Field variants of the concentration method have also been used by the author which involved measuring flammable gas concentration with a calibrated, portable gas detector.

- 3.51 Lama and Bartosiewicz (1982) examined the errors that could arise in estimating gas loss with the versions of the Direct Method which relied on volumetric measurements of desorption quantities. In particular they considered the potential for pressure build-up and rapid pressure changes in the sample vessels during the measurement process a source of uncertainty. A gravimetric technique was, therefore, proposed.
- 3.52 The method of gas content measurement they describe involves using an electronic digital balance and data logger to record the weight change over progressively longer periods as the sample is allowed to desorb. When emission rates fall to less than 0.1ml/g/day the sample is transferred to an adsorption bomb then subjected to a fixed pressure, based on an assessment of the expected seam gas pressure, until the weight gain becomes negligible. The sample is then allowed to desorb at constant temperature. Emission constants are calculated which enable the initial gas loss to be estimated.
- 3.53 This method is unnecessarily complicated. Rate of desorption measurements on fresh coal releasing its gas are not easily reproducible on re-pressurised coal lumps due to moisture loss and the long-time required for equilibrium to become re-established with other than powdered coal. The weighing method may also be inaccurate unless

a control capsule is weighed to take account of diurnal and long-term air density variations.

- 3.54 Krzystolik et al (1985) have described a Polish development for underground application to reduce the uncertainty due to gas loss before sampling and also to provide a rapid in situ determination of seam gas content. A probe and microprocessor arrangement allows the quantity of gas released during the drilling operation to be measured directly. The measured volumes of gas are corrected to standard conditions of temperature and pressure. A 100g coal core is obtained which is transferred to a sealed container for residual gas content determination in the laboratory. Although of technological interest, such a method is unlikely to find wide application when simpler less costly methods are available.
- 3.55 Attempts have been made in the past to improve the accuracy of the direct method by preventing gas loss prior to sampling through hermetically sealing coal core prior to recovery, collecting the gas released during core recovery or freezing the sample prior to recovery (Lidin et al, 1965). None appear to have been particularly successful.
- 3.56 The need for lost gas corrections when sampling surface boreholes can be obviated by "pressure coring" (Owen and Sharer, 1992). The pressure core retains samples at in-situ pressures until the barrel is on the surface and measurements can commence (Figure 3). Although more expensive than conventional coring it is sometimes used when drilling new coalbed methane reservoirs. Thus, the accuracy of future lost gas estimates made using a conventional Direct Method can be assessed.
- 3.57 A disadvantage is that the gas must be completely desorbed and measured before the tool can be released. A 3m core can be recovered in a single run. After desorption the core must then be divided into smaller sections say (about 300mm lengths) and quickly transferred to the normal desorption canisters where emissions are measured for a further 1 to 3 weeks - presumably until no further gas is released as no mention is made in the reference of residual gas content measurement.

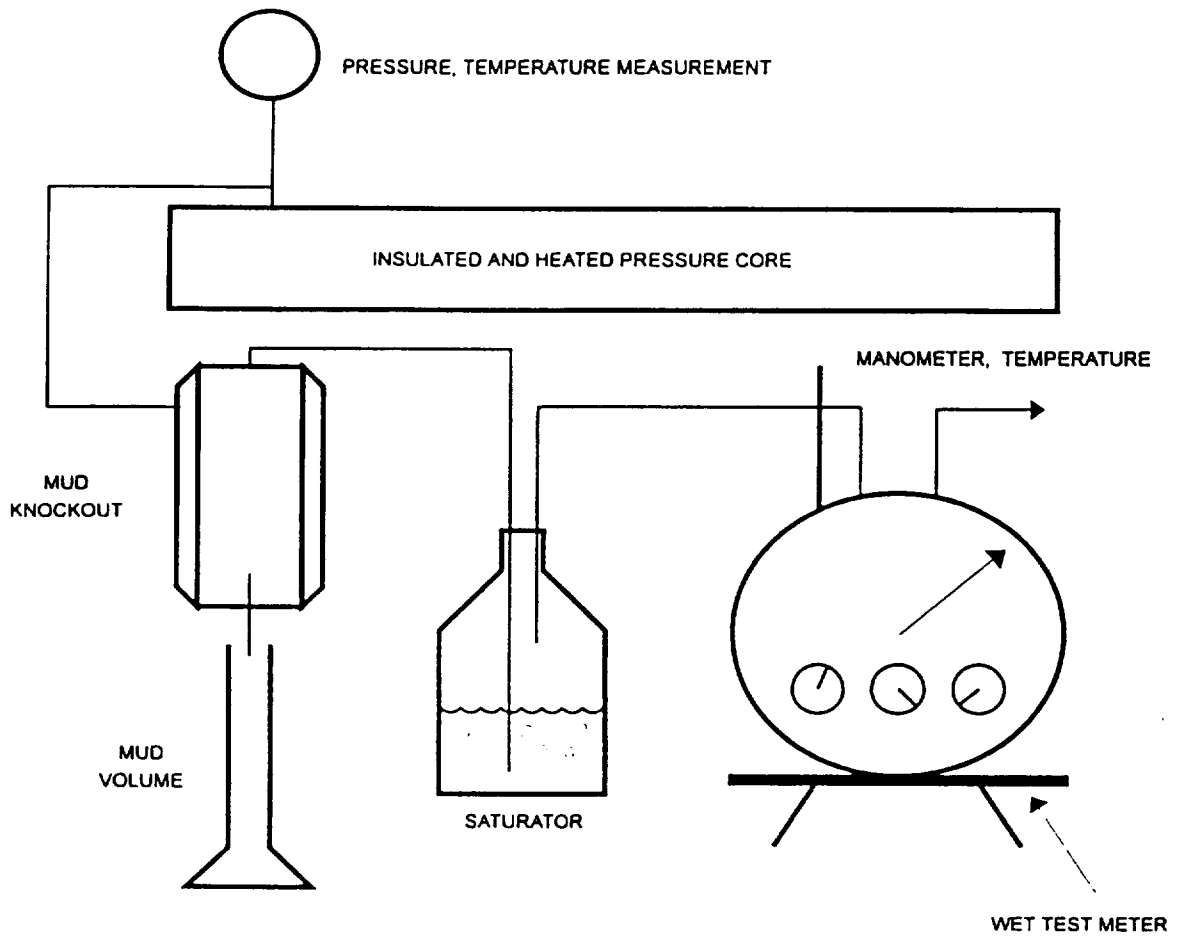


Figure 3
Schematic of a pressure core desorption apparatus
(after GRI 1995)

- 3.58 The above method is more suited to the needs of accurate gas resource evaluation than the gathering of input data for mine gas prediction.
- 3.59 Some authors advise of the importance of conducting the desorption measurements at reservoir temperature if accurate lost gas volumes are to be estimated (GRI, 1995). The magnitude of error will, however, depend on the core retrieval and sampling delay times, the inherent permeability of the coal and the contrast between reservoir and surface conditions. Experiments with UK coals indicate that in normal UK conditions, differences in temperature between field and laboratory are unlikely to be important (Creedy, 1985).

Calculation of the Initial Gas Loss

- 3.60 The emission equation most widely used (Bertard et al, 1970, Kissel et al, 1973, Creedy, 1986) is equivalent to that of a simple spherical diffusion model which can be simply expressed as:

$$V_t = kt^n \quad (1)$$

where n is a constant with value 0.5 and hence the quantity of gas emitted (V_t) is proportional to the square root of the desorption time (t). This relationship appears to hold for surface borehole core samples for desorption periods of up to about 10 hours for US coals (McCulloch et al, 1975) and 15 hours for UK coals which tend to be less permeable than US coals (Creedy, 1986).

- 3.61 Rather than assume a value of 0.5 for n in the above equation, some methods use the measured desorption data to obtain a best fit value which generally lies between 0.2 and 0.7 (Creedy, 1979; Lama and Bartosiewicz, 1982). Examination of various results suggests that best fit values for n are generally around 0.5 for lump samples and about 0.3 for crushed coal samples or drill cuttings. According to Janas (1979) a coal of methane content greater than $9\text{m}^3/\text{t}$ which exhibits a best fit exponent value equivalent to less than $n = 0.25$ is likely to be susceptible to outbursts.

- 3.62 The lost gas quantity in the USBM method is found graphically by plotting the cumulative volume of gas released against the square root of time elapsed since desorption started. For periods of less than 10 hours a linear relationship is generally demonstrated. Extrapolation to time zero enables the lost gas to be read from the ordinate axis.
- 3.63 A more complex solution has been developed by Smith and Williams (1981, 1984) which attempts to take account of the ambient pressure changes occurring during core recovery. This method was aimed at measuring gas content using drill cuttings. However, comparisons made on a research well indicated that the conventional Direct Method (sometimes known as the USBM method) yielded results in close agreement with pressure core measurements whereas the Smith and Williams technique produced a value lower than the other two methods (GRI, 1995).
- 3.64 The Amoco Production Company report an alternative approach (Seidle, 1993) using the first term of the diffusion equation:

$$V_l = V_{ld} \left[1 - \left(\frac{6}{\pi^2} \right) \exp \left(- \pi^2 \left(\frac{D}{r^2} \right) t \right) \right] - V_l \quad (2)$$

where V_l is the gas lost before sampling V_{ld} is the lost plus desorbed gas, V_l the lost gas, D/r^2 the diffusivity and t is time. The data are fitted to the equation using a nonlinear least squares routine. Some authorities, consider this method to yield acceptable results, others suggest they may be too high (GRI, 1995).

- 3.65 In the CERCHAR method, the lost gas is calculated using the relationship in equation (1). The sample is left in the desorbometer for a length of time equivalent to the sampling delay. For this particular case, the lost gas together with the gas emitted into the desorbometer, Q_1 , is given by:

$$Q_1 = (\sqrt{2} + 2) V_l \quad -(3)$$

where V_t is the gas emitted into the desorbometer. The sample is then transferred to another vessel for transport out of the mine to the laboratory where the gas released during transport and the remaining desorbable gas is measured.

3.66 A similar method of measurement was developed in Germany (Winter and Janas, 1975; Janas 1976) but which involved calculating gas loss on the basis of the desorption rate at a time 1 minute after starting the flow of drill cuttings from an underground borehole. The emission for short time intervals is represented by a more general form of equation (1); with the exponent 0.5 replaced by the expression $(1-k_t)$ where k_t is a constant with a value of around 0.65 (StbV, 1987) for most coals, numerically equivalent to a value of 0.35 for Airey's emission constant n .

3.67 The volume of gas lost, Q_1 , up to time t_a after cutting is obtained from:

$$Q_1 = \frac{\dot{V}_1}{n} t_a^n \quad (4)$$

where \dot{V}_1 is the rate of desorption after 1 minute and $n = (1-k_t)$.

3.68 An approximate linear relationship was also established between \dot{V}_1 ($\text{cm}^3/\text{min.g}$) and the desorbable gas content (q_d).

$$q_d = 29.4 \times \dot{V}_1 \quad (\text{m}^3/\text{t})$$

3.69 The MRDE approach is based on use of Airey's empirical gas emission equation (Airey, 1968). The empirical relationship was derived to approximate a theoretical model of gas flow through a solid containing a crack structure which did not attempt to separate diffusion and fracture flow processes. Airey's full empirical emission equation is written thus:

$$V_t = V_o \{ 1 - \exp [-(t/t_o)^n] \} \quad (5)$$

where V_t is the quantity of gas released in time t from coal of initial gas content V_o ; t_o and n are constants.

When V_t is small, the above equation can be simplified:

$$V_t = V_o (t/t_k)^n \quad (6)$$

where t_k is an emission constant, conceptually similar to t_o but in practice yielding a value of roughly twice the magnitude (Creedy, 1985).

3.70 The gas loss before sealing (V_1) is estimated using the simplified emission equation with a value of 0.5 for n :

$$V_s = (V_o / t_k^{0.5}) t^{0.5} - V_1 \quad (7)$$

where V_s represents the cumulative measured quantities of gas evolved into the desorption canister and t is time elapsed since degassing was assumed to commence.

A value for V_1 is obtained as the intercept of a least squares regression line fitted to paired values of t and V_s .

3.71 The method of gas loss estimation using the above equation is identical to that obtained with the USBM Method. However, when unavoidable sampling delays occur a modified approach is used involving, Airey's full equation arranged in the following form:

$$\ln \ln \left(\frac{V_1 + V_m}{V_m - V_t} \right) = n \ln t - n \ln t_o \quad (8)$$

Where V_1 is the lost gas, V_m is the cumulative total quantity of gas desorbed plus the remnant gas and V_t is the quantity desorbed in time t .

The method of calculation involves increasing V_1 incrementally until the least square fit is obtained. If the value of V_1 exceeds 40% of the measured gas quantities the extrapolation is considered too great and the results are discarded.

Gas Desorbed During Transit

- 3.72 On completion of desorption measurements which involve short periods of emission measurement such as with the German and French methods the coal samples are placed into vessels for transportation to the laboratory. The gas accumulated during this time is measured in terms of concentration or by water displacement.
- 3.73 The USBM method which initially involves on-site desorption measurements by volumetric displacement of water is continued in the laboratory until the daily emission is less than 0.05 m³/t for 5 consecutive days (McCulloch et al, 1975) or if it falls below 10ml per day for 7 consecutive days (Diamond and Levine, 1981; Diamond et al, 1986). With some low permeability coals the desorption period may extend beyond 30 weeks whereas high permeability coals such as those from the Fruitland formation in the San Juan Basin, New Mexico, desorb almost all of their gas in 6 to 7 weeks.
- 3.74 Good communications and the relatively short travelling distances usually involved meant that in the UK coal samples could be transported to the laboratory in desorption canisters prior to commencing emission measurements using the concentration method.

Residual Gas

- 3.75 On completion of desorption measurements to provide sufficient emission rate data to estimate the initial gas loss, some gas will remain in the coal. Depending on the measurement method being employed, the desorption characteristics of the coal, the magnitude of the gas content and the required accuracy, various approaches have been adopted:
- (i) desorb to completion assuming any residual gas to be negligible compared with the desorbed quantities;
 - (ii) estimate the residual gas on the basis of a locally established empirical relationship;
 - (iii) crush the coal sample to release and measure the residual gas usually either by volumetric displacement or by the concentration method.

The principal difference between the various methods depends on whether the desorbable or the total gas content is required.

- 3.76 In the CERCHAR method the residual gas measurement stage is accomplished by crushing the coal for 20 to 30 minutes in a vessel containing steel balls and collecting the gas over water in a graduated tube. The desorbable gas content is determined as the sum of the lost gas, gas desorbed during transport and the residual gas. The German method is similar.
- 3.77 The US methods for determining residual gas content have changed considerably over the years. The Bureau's original test method involved operating a jaw crusher within a sealed, clear plastic box to crush the coal. The volume of gas released was determined by measuring the concentration of the gas and combining the reading with the free space volume in the box. This cumbersome and time consuming method was then replaced by a graphical approach which enabled samples to be classified as "blocky" and a slow emitter of gas or "friable" and a rapid emitter of gas. Friable coals emitted nearly 96% of their initial gas during desorption whereas a blocky coal emitted about 60 per cent. Depending on the simple coal classification, residual gas was read off a graph showing lost gas plus desorbed gas versus residual gas. Subsequently, both this method and the previous crushing method were found to be inaccurate and a more conventional sealed ball mill crushing apparatus was introduced (Diamond and Levine, 1981). The method described by Diamond and Levine (1981) yields the desorbable gas content, therefore, care should be taken in interpreting the tabulated "total gas content" values included in their report.
- 3.78 To facilitate residual gas content determination of UK coal samples, "light weight" mill barrels with a simple clamping device to seal the lids were designed (Creedy, 1985) for operation in conjunction with a 'Tema' vibrating mill. The small 'light weight' barrels are placed on the Tema for one minute (considerable heat is generated if crushing is prolonged). A product with a geometric mean size of about 0.04 to 0.06mm is obtained, sufficiently fine for methane to desorb to equilibrium within the allotted time of 2 hours for temperature to stabilise prior to analysis.

- 3.79 Prior to crushing, the mill barrel is pressurised with nitrogen to 40kPa above ambient to provide an inert atmosphere and also to ensure a positive pressure after milling to enable gas to be passed into a gas chromatograph sampling loop for injection and analysis. Before analysing the gas composition, the total gas pressure is measured. The residual gas content is calculated as the sum of two components:
- (i) the free gas in the mill barrel;
 - (ii) gas remaining adsorbed at the final mill pressure.
- 3.80 As the adsorbed volume of methane depends on the partial pressure of the gas rather than the total gas pressure, the correction is generally small, usually less than 4% of the total residual methane content. The overall uncertainty in the remnant gas content determination using the above method is of the order of $\pm 3\%$ (Creedy, 1979).
- 3.81 The gas content measurement method used in Australia is a modification of the USBM Method. Rather than allow desorption to proceed for many weeks as with the USBM method, the process is accelerated by crushing the sample presumably once sufficient desorption data has been obtained for gas loss estimation purposes. Experimental studies (Williams, Saghafi et al, 1992) demonstrated that similar results were obtained irrespective of whether samples of approximately 30g or 300g were used. The samples were crushed in a reciprocating ball mill for a period of 20 to 30 minutes for the small sample container and 1 to 2 hours for the larger container. After these times 70% of the product size was less than 0.09mm.

Total or Desorbable Gas Contents

- 3.82 The final seam gas content values are calculated as the sum of the lost gas, desorbed quantities and the residual gas. The results are generally adjusted to standard conditions of temperature and pressure and corrected to a pure coal basis either in terms of ash or mineral matter. Sometimes moisture is also taken into account. However, as the moisture associated with coal is a coalification product which varies systematically with rank this correction is not essential.

3.83 The total methane contents of most coal seams throughout the world lie in the range 0 to 22m³/t. This indicates similarities in the fundamental geological processes controlling gas generation and gas loss. The limiting factor may be the sorption capacities of the coals of various rank which will be at their minimum during the coalification process when the seams are buried at their maximum depth.

Interpolation of seam gas content results

- 3.84 Seam gas content data bases have been established in the UK (Creedy, 1983) and the USA (Diamond et al, 1986). Where a large number of gas content measurement data are available, the trends can be plotted or represented by empirical equations to facilitate estimation of values at intermediate locations.
- 3.85 General correlations between increase in seam gas content and increase in vertical depth have been demonstrated in UK coals (Davies, 1964; Hinsley et al, 1965; Creedy, 1979, 1985, 1988), US coals (McCulloch and Diamond, 1976; Diamond, 1982) and Canadian coals (Feng and Lu, 1981). Correlations with rank have also been reported. Gas loss in the geological past, for instance at ancient erosion surfaces, can result in some seams having lower than expected gas contents. Seam gas content may increase with vertical depth but significantly different gas contents may obtain at the same depth below the surface in different parts of a coalfield (Creedy, 1991). Occasionally, for reasons not always understood, a borehole sometimes exhibited an unusual gas content trend with depth. In general, however, given the methane content of a seam in the UK, the contents of adjoining seams can be estimated with reasonable accuracy.
- 3.86 Using the 4000 gas content results obtained from exploration boreholes, seam gas content models have been developed for various UK coalfield areas in the form of second-degree polynomials with three independent co-ordinates. This simpler trend model was found to yield similar and possibly marginally better interpolations than a geostatistical approach although it was recognised that the geostatistical model used was relatively unsophisticated and could have been improved (Creedy, 1991).

3.87 Compared with the UK, more complex gas content distributions are evident in the Ruhr district of Germany where data have been obtained from more than 500 wells during the last 20 years of coal exploration (Freudenberg et al, 1966). Analysis of the data in a recent evaluation of coalbed methane potential indicates significant lateral and vertical variations in gas content. The coal seam gas is predominantly methane with minor amounts of carbon dioxide, nitrogen and hydrogen. Immediately beneath the buried unconformity which marks the top of the coal measures, gas compositions and stable carbon isotopes exhibit characteristics possibly indicative of a biogenic origin. At distances greater than about 200m below the unconformity, methane content tends to increase with depth. In some locations, gas contents increase on approaching the unconformity from a depth of about 200m below. In general, therefore, an increasingly complex geological history can lead to more complex gas distributions in coal seams and hence estimation of gas content by interpolation is potentially less reliable.

Permeability of Coal Seams

3.88 The release and flow of methane through coal seams are governed mainly by gas pressure and coal permeability. The experimental determination of gas pressure by in situ measurement or by a combination of methane adsorption isotherm and seam gas content measurement has already been discussed. The permeability of a coal seam is a more difficult property to determine. Movement of gas in a coal seam is through microstructures, cleat and fractures each of which have their own permeability characteristics. Some gas flow models attempt to describe these individual processes and require measurements to enable them to be characterised. The situation is further complicated where the seams are disturbed by mining. Mining induced stresses affect both the matrix and fracture compressibility of coal seams and can increase or decrease the permeability by orders of magnitude. It is impracticable to obtain detailed permeability measurements where mining induced stresses prevail, specific features are monitored instead and used to calibrate laboratory and theoretical stress-permeability studies to produce relationships for incorporation in numerical or empirical gas flow models.

3.89 Much of the current research effort relating to the measurement of the permeability of coal seams undisturbed by mining is connected with reservoir characterisation for evaluation of coalbed methane production potential.

3.90 The following variables affect the permeability of coal seams:

- natural stress variations eg, overburden pressure
- cleat and fracture intensity and size
- degree of water saturation
- gas pressure (Klinkenberg effect)
- coal matrix composition
- physical properties of the coal
- stress history
- mining induced stresses
- post-failure characteristics of the coal

Laboratory Studies of coal permeability to gas

3.91 Laboratory measurements can provide qualitative indication of the effect of the above on permeability but they are not a substitute for in-situ testing.

3.92 The relationship between the permeability of coal seams and effective stress have been studied by various researchers (Somerton et al, 1975; Harpalini and Schraufnagel, 1990) who have considered the competition between two effects:

- (i) a decrease in permeability due to the increase in effective stress as gas is removed from the coal;
- (ii) shrinkage of the coal matrix causing widening of fractures and increase in permeability as methane is desorbed.

3.93 According to Harpalini and Shraufnagel of the above effects, (ii) dominates. Many more experimental results could be described but the important message is that coal seam permeability is a transient rather than a fixed property of a coal seam. Curl (1978) concluded that owing to fractures induced during the sampling of coal the accuracy of any laboratory measurements for other than comparative purposes, is

suspect. According to Curl (1978) the consensus of opinion from the published literature was that the micro-permeability of coal is reduced by increased stress until failure occurs forming fractures which increase the overall permeability.

3.94 At very low pressures and permeability, the mean free path of gas molecules approaches the flow path dimensions. Interactions between mobile molecules and those adhering to surface pores dominate over mobile gas molecular collisions leading to an apparent decrease in permeability known as the Klinkenberg effect (Klinkenberg, 1941). Where this effect is present, a linear relationship between permeability and the reciprocal of the mean gas pressure is expected. Patching (1965) found that at absolute pressures less than about 60 psi (420kPa), coal permeability to gas apparently exhibited a Klinkenberg-type pressure dependence.

3.95 A contradictory result was reported by Yerebasmaz (1981) who found that increasing gas pressure caused an increase in permeability in unstressed coals for pressures of 36 to 80 psi (252 to 560 kPa). He explained the increase in permeability of the coal with increasing gas pressure by the expansion of pore spaces providing wider channels for flow. A similar result was also reported by Harpalani and McPherson (1988). Gawuga (1979) had conducted similar tests but at a variety of stress conditions which suggest that the permeability of coal is independent of the gas pressure when sufficiently high stresses are applied. As the Klinkenberg effect can only be tested for porous media in which no changes in the internal structure take place, it would not seem appropriate to attempt to measure its effect on coal using conventional testing methods and there must be some doubt as to its relevance for inclusion in seam gas flow models.

3.96 Airey (1968, 1971) thought the concept of permeability unhelpful for representing gas emission from coal due to the impracticality of separating Darcy flow and diffusion processes in time and space. He encapsulated his ideas in a general mathematical model in which coal was represented by a large number of homogeneous elements of widely varying sizes. Solutions of Airey's gas flow equations were found to be in good agreement with an empirical emission equation of the type:

$$V_t = V_0 \{1 - \exp(-(t/t_0)^n)\}$$

where V_t is the quantity of gas emitted from coal of initial gas content V_0 in time t : n and t_0 are emission constants.

- 3.97 The time constant t_0 depends on the degree of microfracture within a coal sample and is the time required for 63% of the initial gas content to be emitted. Laboratory experiments have shown that the time constant increases proportionately with the square of the coal size for grains of up to 2mm or 3mm becoming practically independent of sample size for coal in the range 10mm to 30mm. These results imply a fracture network size for UK coal of 2 to 3mm comparable with independently determined values for South African coals (Cook, 1992). The laboratory procedure involves placing samples of size-graded coal in light-weight gas-tight metal containers and saturating the coal with methane at a specific pressure. The gas saturated samples are allowed to desorb via a syringe needle which prevents air diffusing into the containers in the later stages of gas release. Indicated weights are noted at 1-minute intervals for 10 minutes and subsequently at lengthening intervals until most of the gas is released.
- 3.98 The changes in the structure and permeability of a number of British coal seams caused by longwall mining have been investigated through a series of laboratory stress-permeability measurements simulating in situ stress conditions. The work was carried out using a state-of-the-art servo controlled electro hydraulic press which allowed the continuous monitoring of the changes in stress, axial and volumetric strain and permeability of coal before, during and after failure is initiated (Durucan, 1981 and Edwards, Durucan and Riley, 1987). Permeability measurements were made, in a modified triaxial cell, on cores taken from large lumps of coal, drilled perpendicular and parallel to the bedding planes.
- 3.99 The analysis of these results have shown that coal permeability is highly stress-dependent and the permeability of coal seams could decrease by up to two orders of magnitude in the front abutment zone of the longwall coal face. Under triaxial

compression, microfracturing of the coal matrix may take place in the front abutment zone, however, this would not have a significant effect on permeability. The flow of methane in non-fractured coals is mainly governed by the extent to which the applied stress changes the size of inherent fissures and pore channels. This, in fact, is directly related to the structural characteristics of the coal seam concerned (Durucan and Edwards, 1986).

3.100 Fracturing and failing of coal, in and around the seams being worked, is most likely to occur in the yield zone resulting in a significant increase in coal permeability. The failure of coal under triaxial compression and the subsequent changes in volumetric strain corresponds to a marked increase in coal permeability. It is believed that the permeability of coal seams can increase by up to three orders of magnitude in the yield and stress relief zones of longwall faces and the source seams above and below. It is significant that fracture permeability under triaxial compression remains constant once the residual strength of coal is reached. The flow of methane through fractured coal under triaxial stress is controlled mainly by the fracture width which was found to be comparable for most coals tested. The above observations on the effects of stress on permeability of coal seams and the theoretical analysis of stresses around longwall faces enable generalised stress-permeability profiles to be constructed (Figure 4) for coal seams around longwall extractions (Durucan, 1981).

3.101 There is some disagreement on the effect of the high stress abutment zone on coal seam permeability. Some authors believe that the front abutment load reduces the permeability (Patching, 1970, McPherson, 1975; Durucan, 1981) whereas others claim there is no supporting evidence (Price et al, 1973). That such a conflict of ideas can arise is illustrative of the difficulty of making and interpreting measurements. Such differences of opinion tend to be focused on the understanding of stress and its effects on longwall workings. The effects of stress on permeability of coal around room and pillar workings appear to be less controversial.

3.102 Levine (1966) has explored the influence of matrix shrinkage on coal permeability. He questions the validity of conclusions drawn from laboratory simulations and seeks

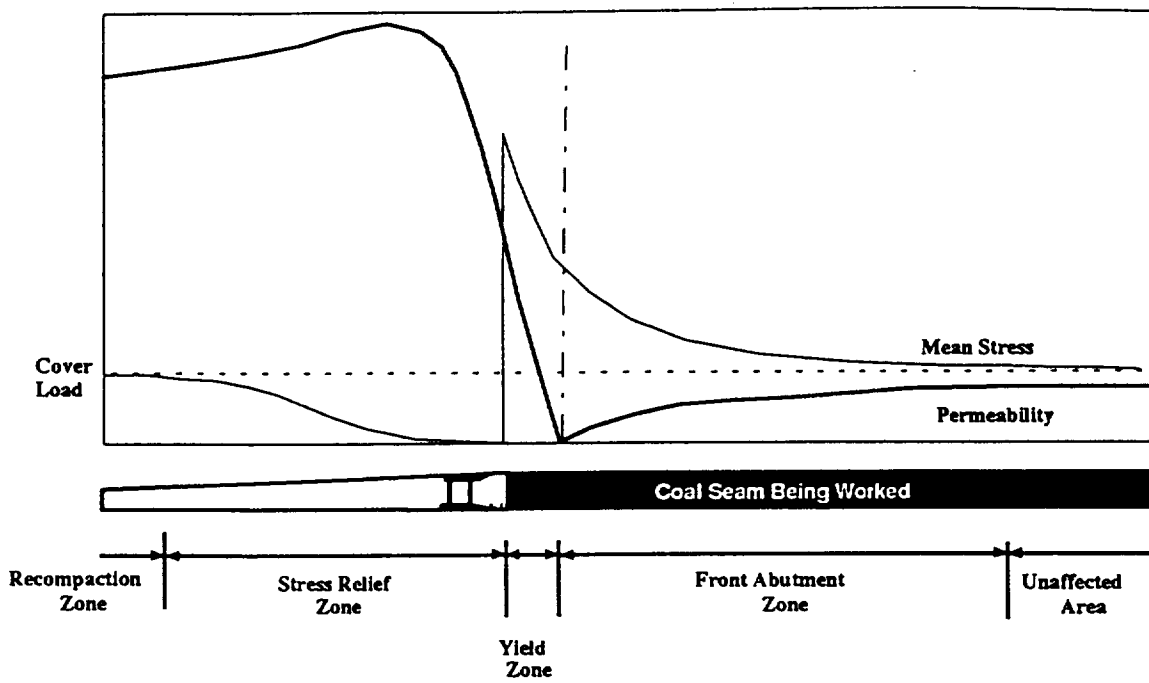


Figure 4
Generalised stress-permeability profile around
a longwall coalface (after Durucan 1981)

to resolve current ambiguities using a rock mechanics model. The coal is assumed to behave elastically which may be reasonable for conditions of low strain where seams are unaffected by mining. The width of fractures is considered to depend on the combined influences of:

- (i) vertical overburden stresses
- (ii) "tectonic stresses" which may be either compressive or tensile across the fracture plane
- (iii) hydraulic fluid pressures within the coal which tend to hold the fractures open
- (iv) the mechanical strength of the coal
- (v) volumetric shrinkage of the coal matrix due to desorption of methane.

3.103 The study indicated that significant changes in permeability could occur due to matrix shrinkage as gas is desorbed but that the magnitude of the effect will depend on coal rank, petrographic composition, mineral matter content and gas composition. Although written in the context of coalbed methane recovery the modelling approach presented by Levine has potential for incorporation into gas flow models for room and pillar mining subject to validation of the theoretical assumptions.

Permeability of goafs

3.104 The permeability of a goaf depends on the size distribution of broken material and the compaction by overlying strata, varying with time and also with distance from the working face. The dynamic nature of the factors which determine the permeability combined with the difficulty of access to undertake measurements precludes direct determination of the distribution of permeabilities with a goaf. Indirect methods are therefore required to characterise the goaf. Tracer gas studies and also observations of methane concentrations and airflow patterns along the edge of the goafs behind longwall retreat coalfaces have recently been used in the UK and France in conjunction with CFD models to develop presentations of permeability distributions in goafs (Creedy and Clarke 1992; Tauziède et al, 1993). The method involved adjusting permeability zones within an idealised goaf in a CFD model until results were obtained that were reasonably consistent with measured underground data.

Characterisation of Methane Emission from Coal Samples

- 3.105 Most gas flow models rely on measurements made on coal samples to provide input relating to emission and transport characteristics of the coal.

Gas emission rate measurements can be made on freshly sampled coal obtained by coring or underground sampling. The gas release rate at constant temperature and pressure will depend mainly on the initial gas content, petrographic composition, and the microfracture structure within the coal. The microfracture structure within the coal will vary with petrographic composition and possibly also as a result of regional and local geologically imposed tectonic disturbance. However, when comparing the emission characteristics of coal samples as determined in the laboratory with the behaviour of in situ coal seams it is important to understand the differences which will arise due to the differences in states of stress. In addition, results can also be influenced by the sampling method (Creedy, 1985). For example, consistently longer time constants of emission have been obtained from measurements on sub-sampled lumps of coal taken from longwall faces compared with core samples of virgin coal. Such a result was unexpected as the coalface samples had been subjected to the high stresses associated with the abutment load. The suggested explanation is that for a block of coal, of a size typically taken for sub-sampling, to emerge intact on the coalface an above average degree of inherent strength is implied and hence a low crack density. Comparisons can therefore be made between samples from different coalfields provided that similar sampling methods have been employed. The corollary is that when measuring input data for empirical gas prediction models, care must be taken to employ appropriate sampling and measurement techniques.

Diffusion parameters

- 3.106 Movement of gas at the microscopic scale, ie where the grain size is less than the natural fracture spacing, occurs by diffusion. Diffusion rates in continuous solid coal are extremely slow, therefore, for gas to be released from the microporous coal structure at a detectable rate a pervasive cleat or fracture network must be present. Due to the difficulty of defining the mean diffusion distance (r) in, for example, Ficks

equation for non-steady state diffusion from a homogeneous sphere (Schilling et al, 1966), the diffusivity D/r^2 is often used in practical gas flow models.

- 3.107 "Sorption time" or estimates of diffusivity are needed in some gas flow models to characterise the rate of gas flow from the coal matrix to the natural fractures. These data can be obtained from Direct Method desorption measurements provided they are undertaken at, or close to, reservoir temperature. "Sorption time" is defined as time required for 63.2% of the total desorbable gas content to be released (Close and Erwin, 1989; GRI, 1995). It is similar in concept and almost equal in magnitude to Airey's time constant of emission t_0 , which is the time taken to desorb 63.2% of the total gas content (Airey, 1968). Sorption time indicates initial gas release rates from coal seams and is used as input in some coal gas reservoir simulators. Airey's time constant is used the MRDE longwall gas emission prediction model.
- 3.108 Sorption times of the bituminous Cretaceous and younger coals in the San Juan basin of the USA lie typically in the range 2 to 50 hours whereas those reported for the bituminous Pennsylvanian coals are generally longer, ie from 1 to over 600 days and are more akin to UK coals.
- 3.109 Kissell and Bielicki (1972) described a unique method for estimating the diffusion parameter from considerations of the desorption history of a hypothetical lump of coal as it was approached by a coalface. Initially, at some depth in the seam the lump will be undisturbed. As mining continues desorption will commence until the lump appears on the coalface when it can be sampled and its residual gas content measured. The difference between the original and residual gas contents is the amount of gas lost which can be inserted into a standard solution for the diffusion equation and hence the diffusion parameter D/r^2 obtained, (where r is the radius of the hypothetical coal fragment). The desorption history of the hypothetical lump at specific test sites was deduced from previous measurements of gas pressure change with distance into the coalface, adsorption isotherms and the mining advance rate. The method takes no account of the dynamics of mining disturbance and the statistical variations in residual gas content and desorption history. Nevertheless, a value for the Pittsburgh seam of

1.3×10^{-8} was estimated, surprisingly close to the 1.4×10^{-8} measured in a laboratory experiment. The in situ estimation method is of limited value due to the uncertainties in the data on which the result depends and the assumption that diffusion and fracture flow can be treated as separate, independent processes; Kissell and Bielicki (1972) argued that because the remnant gas content was relatively high in the Pittsburgh seam, the emission process was essentially diffusion controlled.

Relative "Gassiness"

- 3.110 A gassiness index has been proposed (CEC, 1988) which depends on both the initial gas content of a coal sample and the degree of inherent cracking. The index, defined as the quantity of methane lost in the first 10 hours of exposure, is calculated using the empirical emission equation:

$$V_t = V_0 (t/t_k)^n$$

Where V_t is the volume of gas desorbed (m^3/t) from a sample of initial gas content V_0 in time t ; n is the constant usually with a value of 0.5. Broad comparisons of the "gassiness" of seams in different coalfields can be made and the seams ranked according to potential. The average value for UK coals is $0.346m^3/t$ but indices in excess of 4 times greater are found in some coalfields. However, some seams in the USA have gassiness indices 25 times greater than the UK average.

- 3.111 It is important to note that the index represents the emission behaviour of a single seam which differs significantly in magnitude from gas emissions as encountered in longwall coal mining. The rate of gas release caused by a longwall coalface depends on the gas contents, thickness and proximity of all the seams in the roof and floor disturbed by the extraction process and varies with the rate of working. However, the index could be useful for obtaining an indication of the relative gas emission potential of seams worked by room and pillar-methods.
- 3.112 Another index used to indicate the rate at which gas can be released from coal is the ΔP index (Patching and Mikhail, 1975). The procedure was initially devised by Russian and French investigators for the identification of coals that might be

susceptible to outbursts. Sized, particulate coal samples of about 3g are pressurised with methane. The methane is released into a manifold and the manometer reading produced after 60 seconds, less the result obtained with helium in place of the methane, is taken as the ΔP index. Current gas prediction models do not make direct use of this parameter.

In Situ Determination of Coal Seam Permeability

- 3.113 In the former USSR in-situ measurements of coal seam permeability were made from measurements of gas flow to a borehole beyond the influence of active workings (Kuznetsov and Krigman, 1973). A tracer gas method which involved injecting gas at one borehole and detecting it at another was also used (Krivitskii et al, 1972).
- 3.114 Kissell (1972) used gas pressure curves measured in horizontal boreholes with the aid of inflatable packers to estimate gas permeabilities of a US coal seam exposed for 15 days and 180 days prior to drilling. For the calculation, the coal seam was assumed to be a homogenous slab, to which a simple one-dimensional unsteady state form of the Darcy equation was applied.
- 3.115 A Guide to Coalbed Methane Operations (GRI, 1992) includes details of sources for estimating reservoir properties of coal seams as shown in Table 12 below.

Table 12 Sources for Estimating Reservoir Properties	
Properties	Source
Coal	Core test
Permeability	Well test
Adsorbed gas content	Core test
Desorption isotherm	Core test
Desorption time	Core test
Initial water saturation	Well test
Porosity	Core test, history match with simulator
Ash content	Core test
Initial pressure	Well test

- 3.116 Well tests are used for coalbed reservoir evaluation to provide both permeability and reservoir pressure data. Packers are set before testing to isolate the particular seam

of interest. The most commonly used well tests for obtaining coal reservoir permeability properties are:

- (i) slug tests
- (ii) injection, fall-off tests
- (iii) interference tests

3.117 A slug test involves the instantaneous injection or withdrawal of a volume of water into or from the wellbore. The change in wellbore pressure with time is measured until the original pressure obtains and the results are matched against model curves to determine permeability. Most slug tests used in coalbed methane wells involve water injection rather than withdrawal. Amongst available well test techniques, the advantages of slug tests are their simplicity and low cost. However, the results are not valid for two-phase flow and the method can only be used on underpressured coal seams - not a problem in most instances. The only equipment needed is a means of introducing water, a pressure transducer to install in the wellbore, a pressure data recorder on the surface and tools to analyse the data. Numerical simulators such as COALGAS (Holditch and Associates, 1994) can be used to estimate in-situ coal permeability from slug test data (Shu et al, 1995).

3.118 An injection, fall-off test is a transient test used to estimate permeability. Water is injected at a constant rate for a period of time at a pressure substantially less than the pressure required to fracture the coal. The well is then shut in. The pressure data obtained from a gauge at the base of the well is then analysed.

3.119 Interference tests provide information about directional permeability. A pressure transient is induced in one borehole and the response monitored both in the test well and adjoining observation wells.

3.120 The above tests are provided by oilfield service companies. The parameters measured relate to water rather than gas and will need adjusting accordingly. In coal seams of low permeability response times to the various tests are likely to be long and the results may be inconclusive.

Summary of the Measurement Review

- 3.121 Accuracies varying from 3% to around 20% are claimed for the various gas content measurement methods. It is not helpful to assign a specific accuracy to a particular method as it will depend on factors relating to sampling, measurement technique, choice of apparatus and the emission properties of the coal.
- 3.122 Little use is currently made of sorption isotherm and in-situ gas pressure measurement for seam gas content measurement. In fact, it is often seam gas content and sorption isotherms that are used to estimate seam gas pressure.
- 3.123 Pressure coring with direct desorption measurement appears to provide the most accurate means of determining seam gas content. However, the conventional Direct Method, which involves estimating gas loss before sampling, whether applied to full core using volumetric desorption or to core fragments using a concentration measurement process would seem to yield satisfactory results for practical purposes. Examination of the literature, and practical experience, indicates that the simplest approach to lost gas estimation which assumes a square root law of emission is suitable for most applications.
- 3.124 The seam gas content measurement methods in most common use throughout the world are based on the Direct Method originally developed by CERCHAR. Most of the variations of the method were developed in the 1960's and 1970's. Recent developments have mainly been in connection with the evaluation of coalbed methane resources from surface drilling.
- 3.125 In order to minimise error with direct methods it is important to:
- recover and seal the coal sample as rapidly as possible. When coring surface boreholes, wireline core recovery systems are preferable to conventional;
 - initiate desorption measurements immediately after placing whole core samples in the desorption canisters when using volumetric methods to measure gas flow. Some delay between sealing and the first measurement can be tolerated

with the concentration method provided the canister volume is much greater than the sample volume;

- conduct the desorption measurements in a stable temperature environment which should be as close as practicable to the strata temperature conditions if emission parameters are to be derived for use in gas flow models;
- record ambient pressure and temperature at all stages during the measurement process and correct results to quoted, standard conditions and to a standard basis;
- determine the absolute total gas content rather than the more arbitrary "desorbable" gas content.

3.126 Techniques for determining the in situ permeability of coal seams from surface borehole tests are well developed, their primary application being in the characterisation of the reservoir potential for coalbed methane extraction independently of mining. These methods are not particularly suitable for application to low permeability coals and usually involve measuring permeability to water rather than gas.

3.127 The permeability of a seam disturbed by mining is a complex variable. The magnitude of coal permeability at a particular location within a seam depends on its proximity to the working coalface, which varies with time, and also on the mining method and geological factors which affect the stress distributions around the mine workings. In situ measurements of gas permeability in mined coal seams are therefore only of limited use for methane emission prediction but they can be helpful for calibrating stress-permeability models.

3.128 Various empirical emission indices have been described for coal samples which facilitate comparison of characteristics between different seams or from country to country.

4 PREDICTION OF METHANE EMISSIONS

- 4.1 A considerable volume of material has been published on the development of gas emission prediction models for coal mining applications especially in Europe and the USA. A comprehensive review of methane prediction in coal mines has been conducted by Curl (1978) and of gas flow models by King and Ertekin (1989) and King (1994). This Chapter summarises and updates these studies describing existing models which are considered to be of possible practical use for predicting and modelling gas release in coal mines.
- 4.2 Methane emission prediction models usually involve one or a combination of empirical, numerical, analytical or statistical techniques. Predictions may be applicable over a time basis of a few minutes or a few weeks. They may assume steady coal production or allow for variable rates of advance. Some models are designed specifically to predict emissions in longwall sections, others to predict emissions in headings. There are also a substantial number of coalbed methane simulators which have been developed to assess the gas production potential of virgin coal seams; most of the recent models are of this type. Emissions of gas which occur as a function of the rate of strata disturbance, assuming a fixed geology and mining method, can generally be satisfactorily represented by mathematical equations. Unusual emission events, such as sudden emissions of gas from the floor are often too complex to model although the causal processes may be reasonably well understood. Knowledge - based problem solving approaches sometimes known as Expert Systems have been used to make forecasts associated with these types of phenomena.
- 4.3 It is convenient to divide methane prediction models into four functional categories:
- (i) Short-term forecasting models (pseudo real-time)
 - (ii) Medium to long-term empirical models
 - (iii) Simulation models
 - (iv) Expert systems.

Short-Term Forecasting Models

- 4.4 The aim of short-term forecasting is to identify potential gas problems by predicting likely methane emissions on the basis of intended coalface advance or production rates and comparing expected and actual values. It is essentially a process control system approach which uses continuously monitored mine environmental data as input. The automatic provision of coal production information is also desirable. Whilst colliery computer systems may generate appropriate production data this sometimes involves a separate machine to that used for processing environmental monitoring. A short-term prediction method, using data from environmental transducers, should provide sufficient information to ensure that the source of a methane problem, or potential problem can be correctly identified.
- 4.5 An early example of a model which established useful statistical principles was devised in Germany by Kaffanke (1980). In his model, the gas emission on one day depended not only on that days production but also on gas emissions and coal production on previous days. Due to the statistical technique used, data from some intermediate days was sometimes arbitrarily omitted. Whittaker (1980) and McStravick (1982) experimented in the UK with simple correlations between mean daily methane data and tonnage mined from a longwall on a particular day and the two preceding days but the results were not always satisfactory. Success was eventually achieved by introducing a constraining function to ensure that the weighting contributions due to previous coal production shifts decreased progressively (CEC, 1989). An algorithm was produced to predict "normal" emissions on a shift by shift or day by day basis, unusual data being highlighted as anomalies requiring management attention. The method was tested in pseudo real time mode on a computer simulation but did not reach the colliery trial stage due to difficulties accommodating the algorithm in the mine monitoring computers available at that time.
- 4.6 The statistical approach to gas emission prediction on a weekly basis has also been applied to mines in the Lorraine coalfield of France (Tauziede and Pokryszka (1993). It was found that the volume of methane released depended on the advance during that week and to a lesser extent on those during the previous two weeks. The method

was found to be unsatisfactory during the early life of a face until an advance of about 200m had been attained (ie. the "square" position where the length of goaf produced equals the face length). Apart from this limitation, promising results were produced for a number of faces. However, on some faces where there were interactions with other workings or where intensive gas drainage was taking place, poor correlations were obtained.

- 4.7 Dunmore (1982) described how the MRDE (British Coal) steady-advance methane prediction program for longwall coalfaces might be adapted as a quasi real-time model. The idea was that predictions could be updated weekly, significant differences between actual and predicted emission quantities for the following week being indicative of possible abnormalities requiring attention.
- 4.8 A further development was to devise a short-term prediction capability based on Airey's general theory of gas emission in coal mining operations which takes account of non-steady advance rates. This work was uncompleted when the British Coal project terminated but the report is important in that it provides the only published account of Airey's variable advance model (CEC, 1989).
- 4.9 Barker Read et al (1992a) investigated the application of time series analysis methods to the problem of modelling methane concentration variations in coal mines. Their interest was in examining the effect of changes in methane drainage system performance upon the purity of drained gas and also the effects of interactions between ventilation and drainage systems on methane concentrations in the airway. Conventional time series analysis was found to be inadequate for tracking both slow and rapid fluctuations. However, a recursive estimation technique, which updates parameter values in a reference multi-variate model at each time interval when new information becomes available, was found to show promise. Its possible application would be in methane drainage extraction control systems.
- 4.10 Dixon and Longson (1993) described research undertaken independently of the above in which a multi variate time series model was constructed to predict hourly airway

methane concentrations arising on a longwall section purely from a knowledge of coal production. The model was comprised of components which notionally represented the instantaneous release of methane from coal cutting, release of methane from the coalface and conveyed coal, and subsequent release of methane from adjacent strata over longer periods of time. A 10 minute methane prediction model was also produced. No account was taken of air quantity. As methane concentration is sensitive to fluctuations in airflow this omission limits the practicality of the actual models demonstrated. This method was recently improved by the use of artificial neural networks (Dixon et al, 1995). Data on methane concentration and coal production, obtained from an underground coal mine, were used to train the neural network to 'learn' the underlying patterns of methane emission and hence forecast methane concentrations in the underground workings.

- 4.11 Possible applications for short-term methane prediction models in collieries are for controlling methane quality in drainage systems which provide gas for utilisation or for increasing the sensitivity of methane detectors in high risk locations by using predictions to pre-empt deleterious changes in methane concentration. The former process would require relatively low frequency data whereas for the latter high frequency data collection and processing would be essential. It is doubtful whether short-term prediction methods would aid Environmental Superintendents in South Africa with day to day problem solving any better than the graphical outputs obtained from remote colliery environmental monitoring systems. A printout which shows methane concentration, air quantity and coal production (provided that it is remotely monitored) on a common time base would facilitate diagnosis of most section ventilation problems.

Medium to long-term empirical models

- 4.12 The most common method of methane prediction involves simply using specific emission values obtained from previous experience of a mine, a particular area of a mine or of neighbouring mines where similar mining methods are being used in similar geological conditions. General ventilation planning is often adequately served

by this approach. Sometimes estimates are scaled to take account of known differences in seam methane contents.

- 4.13 For many practical mining purposes this simple method is considered satisfactory provided that factors which may lead to unusual emissions can be identified in advance. Mines with low gas emissions usually rely on this approach. Implementation of the method is assisted by systematic recording and processing of mine environmental data. Use is commonly made of remote monitoring systems linked to surface computers where they are available.
- 4.14 Specific emission is used as a ventilation planning parameter in many collieries throughout the world. Unfortunately, it is also often mis-used by failing to take account of temporal effects. Emission on a particular day depends not only on the rate of advance achieved on that day but also on previous days. Gas continues to flow, albeit in small volumes in some instances, when coal production stops. Thus specific emission assumes an infinitely high, and meaningless value. It should, therefore, be treated only as a general indicator of gassiness. Practical values are obtained from measurements made over a period of a few weeks of steady production. There are probably few, if any, large mines in Europe or the USA at which a specific emission value for working sections would not be widely known by mining and ventilation staff. For a given rate of coal production using different mining methods in similar geological conditions the following relativities in specific emission would be expected: longwall > shortwall \geq pillar extraction \geq room and pillar.
- 4.15 The observed relationship between specific emission and face advance or coal production rate derived using spot methane samples will exhibit some scatter for the following reasons:
- (i) timing of sampling for gas concentration and flow
 - (ii) coal production variations.

Gas samples taken near the beginning of a production shift would be lower if the previous shift had not produced coal than if they had been taken towards the end of the current shift because of the general decrease in background due to periods of non production. When a high coal production week follows a low production week, the emission in that week will be lower than for sustained high production. A low specific emission is therefore obtained. These effects are likely to be more conspicuous on longwall sections than in room and pillar sections due to the fewer gas sources involved.

4.16 Empirical models offer the following basic features:

- simple mathematical expressions of observable physical phenomena;
- require few input parameters;
- generally lack enough theoretical rigour for detailed predictions;
- usually site specific.

Longwall mining

4.17 Gas emission prediction methods for longwall workings have been developed in Belgium by the former INIEX (Institute National des Industries Extractives), France by the former CERCHAR (Centre d'Etudes et de Recherches des Charbonnages de France), in Germany by the former STBV and WBK (Steinkohlenbergbauverein and Westfälische Berggewerkschaftskasse), in Poland at Mine Barbara, in the UK at the former MRDE (Mining Research and Development Establishment) and in the former Soviet Union at the Skochinski Institute.

4.18 The longwall gas emission prediction methods examine some or all of the following gas emission sources:

- coal seams in a gas emission zone above and below the worked seam;
- rock strata in the gas emission zone;
- the worked seam itself;
- coal on conveyors.

Methodologies for estimating the emission from the worked seam and conveyed coal are, in principle, equally applicable to room and pillar mining.

- 4.19 The zone above and below the workings from which methane is released as a result of longwall mining may extend up to about 200m above and down to about 70m below the worked seam. Coal seams are the principal gas source but some methods also make an allowance for additional gas from the rock strata. In the German methane prediction method (Noack and Opahle, 1992), nominal seam gas contents are allocated to the strata and then attenuated by multiplying by 0.019 for mudstone, 0.058 for sandy shale or 0.096 for sandstone. Up to 50% of the methane flow into some UK mines is considered to be derived from conventional sandstone reservoirs which have been disturbed by longwall mining. Geophysical logging and cross-correlation techniques have been used to identify probable gas bearing rocks. A simple algorithm which calculates the gas release using the bed thickness, estimated porosity and estimated gas pressures has proved surprisingly accurate for estimating the extraneous gas flows.
- 4.20 The European methods are similar to each other in principle. The zone of gas emission around the workings is modelled, usually assuming a simple geometric form. A concept known as the "degree of emission" is used to represent the proportion of gas released from a specific stratigraphic horizon. It is usually expressed as a percentage of the virgin gas content. The degree of gas emission is estimated for each stratum and the rate of gas flow obtained by multiplying the expected emission per tonne of coal by the proposed coal extraction rate. The MRDE method is unique among the European methods in that it includes the dimension of time (Curl, 1978). The degree of emission is assumed to depend on the distance of a gas source from the worked seam and the age of the section. Curl (1978) reviewed European and US models some years ago and concluded that only the MRDE method was based on a coherent physical theory.
- 4.21 The method widely used in France was initially developed more than 30 years ago. It has been improved on various occasions since (Jeger, 1980; Tauziède and

Pokryszka, 1993). The limits of the emission zone are currently considered to be of the order of 170m in the roof and 60m in the floor of the mined seam. Within this zone, the desorbable gas content of a seam decreases from its initial gas content to a final residual gas content depending on its distance from the mined seam. The amount of gas released from rock strata is now calculated according to the porosity of the rocks, the initial in situ pressure and the residual pressure (INERIS, 1992). Application of the method is preceded by calibration on a reference face. Due to its substantial empirical content, the method is not readily transportable elsewhere.

4.22 Noack and Opahle (1992) have described progress achieved with gas emission prediction methods in Germany. Two methods for prediction of the proportion of gas content emitted from the seams disturbed by mining are mentioned:

- (i) degree of gas emission methods which assumes that gas release depends on geometric location of the source relative to the coalface and is independent of the initial gas content;
- (ii) the gas pressure method which considers initial gas pressures and spatial factors.

4.23 The degree of emission method uses empirical exponential equations for calculating emissions from the roof and floor. The practical limits are assumed to be 165m in the roof and 59m in the floor. The gas pressure method involves dividing the disturbed roof area into three zones; "caved", "cleaved" and "weakened" and the floor into two zones; "loosened" and "weakened". Each zone is characterised by a specific residual pressure gradient.

4.24 The following advantages are claimed (Noack and Opahle, 1992) for the German gas pressure method over their degree of emission method:

- no rigid limits to the extent of the gas release zone - these rather depend on the initial gas pressure and the type of strata;
- the effect of the height of coal extraction is considered;

- account is taken of both the adsorbed gas and the free gas;
- the total gas content is used rather than the desorbable gas content.

- 4.25 Both of the German methods determine the mean gas emission assuming a steady advance. The predictions are only applicable once the coalface has advanced sufficiently for the emission zone to have fully developed. Additionally, the face has to be longer than 180m to 190m at 600m working depth and longer than 220m to 240m at 1000m depth. Eicker (1993) has applied an empirical German emission prediction method to Middelbult Colliery in South Africa. He predicted methane flows from strata in the roof up to about 5m above the workings and down to about 7m in the floor. Of the predicted emission about 42% is ascribed to a coal seam and the remainder to pore space in the rock. It is presumed that the extent of degassing was deduced as a function of the total width of pillar extraction.
- 4.26 The above methods are effective in Germany where considerable site specific data has been obtained to develop the empirical relationships on which they depend. The tortuosity of some of the relationships would make application elsewhere difficult without undertaking detailed field trials to establish appropriate parameters for different sets of conditions.
- 4.27 Most of the limitations of the German methods have been overcome in the MRDE method, although recent findings have not yet been incorporated formally into the program.
- 4.28 The basic model underlying the MDRE method was developed by Airey (1971) in a mathematical theory of gas emission in coalmining operations. The theory envisages the seam ahead of the coalface, and seams in the roof and floor as disturbed to varying degrees by the stresses associated with the approaching coalface. The emission from the worked seam was calculated as the summation of the emission characteristics of a distribution of coal lump sizes created by the mining disturbance. Airey described the emission from adjacent seams in terms of an emission parameter which depended on the ratio of principal stresses σ_1/σ_3 . Thus, he was able to

compute a distribution of emission parameters (time constants) around the face and hence the degree of gas emission from seams in adjacent strata, as a function of distance from the face line.

4.29 The MRDE prediction method calculates the magnitude of the gas flow into a particular longwall mining district as a function of the gas contents, number and thickness of seams in the disturbed zone, the proximity of the seams to the worked seam, the age of the section and rate of advance or retreat.

4.30 A computer program (FPPROG) was written to implement the MRDE prediction method in a form useful to ventilation engineers. The program calculates the methane flow rate into a longwall section from the following input data:

- depth and thicknesses (less dirt) of all coal seams within 200m of the roof and 70m of the floor of the worked seam;
- proposed extraction parameters (face height, face length, ash content of the coal, advance/retreat rate and age of the section);
- methane content of the worked seam (a methane content/depth gradient being used to estimate gas contents of the roof and floor seams);
- positions of old workings above or below the proposed panel (to enable gas lost from previous working to be calculated).

Predicted and measured gas flows have generally been in good agreement, with accuracies better than 20% in most instances (Creedy, 1985). FPPROG is not available as a commercial package but it has been used by British Coal in overseas consultancy with some success eg., in Canada. The principal author of this report is currently developing a new version which may be made generally available on completion.

4.31 British Coal research into gas emissions when working single virgin coal seams revealed that where longwall faces are less than about 250m in length, the distressed zone in the roof may not extend as high as 200m (CEC, 1992). It was found that

progressively shorter faces tend to produce correspondingly smaller heights of emission zone in the roof leading to decreasing emissions per tonne of coal mined due to the smaller number of seams disturbed.

- 4.32 The extent of the gas emission zone around a longwall face seems to depend on the length of the coalface, the depth of working and effects of previous workings. Intuitively, coalface height and strata strength would also be expected to be relevant parameters. However, in a study of the Selby coalfield in the UK, Kershaw (1994) was unable to prove a relationship between the height of the degassing zone and strata strength. He maintains there are good reasons for accepting that face height will have an effect on the degree of disturbance and this is supported by the fact that the product of face height, depth and face length showed an improved correlation with height of emission over face length and depth alone. Based on the above findings a relationship was proposed for estimating the height of the emission zone:

$$H = k \cdot l \cdot d \cdot h$$

where H is the height of the emission zone (m), l the face length (m), d the depth (m), h the face height (m) and k a constant with a value of $4.15 \times 10^{-4} \text{ m}^{-2}$ based on the Selby data. Kershaw demonstrated that in some circumstances exceptionally strong strata probably exerted a bridging effect, allowing the detachment of strata below, thus reducing the "effective depth".

- 4.33 The above relationship only holds for single seam working of a virgin coal seam. Where previous mining has already taken place, the emission zone usually develops to its full height of up to 200m irrespective of face length.
- 4.34 The depth of working is not yet included as a variable in any of the European prediction methods and its use was discontinued in the MRDE (British Coal) method as no effect was apparent over the range of depths where it was usually applied. Provided that engineers are aware of the limitations of empirical prediction methods and have an understanding of those factors which might increase or reduce the level of emission beyond that calculated then additional complexity is not necessarily warranted.

- 4.35 Gas drainage and ventilation studies in Germany (Winter, 1958), the USA (Kravits et al, 1993) and France (Jeger, 1980), show that coal seams can sometimes be disturbed by mining and hence the gas-permeability of the coal increased without the gas necessarily entering the mine workings. This suggests that the flow of gas into longwall workings is determined not by the extent of coal fracturing but by the extent of the fracture zone in the surrounding rock mass which allows the gas to flow across the measures. This occurs because coal is inherently weaker than the surrounding strata and will therefore break before any migration paths are available. Confirmation of the hypothesis would facilitate an approach to gas flow modelling for longwall faces which involved calculating the extent of rock failure resulting from coal extraction. The model would then not be limited by such factors as face length and depth as they would be intrinsic to the calculation.
- 4.36 An important corollary is that some gas drainage systems may not necessarily be contributing to the control of methane in the underground environment and could be venting a greenhouse gas to the atmosphere that otherwise would not be released.
- 4.37 Prediction calculations made during this study, using a modified form of the MRDE method, indicate that such a situation may obtain above shortwall faces in South Africa. The predicted methane release from a minor seam situated about 56m above the worked seam was $0.4\text{m}^3/\text{t}$, a value close in magnitude to the long-term average methane flow vented from surface boreholes drilled into the goaf.
- 4.38 Available methane emission prediction models for longwall coal mines have been reviewed by Jensen et al (1992) in Australia. European and US models were examined. All were criticised for their lack of sophistication and use of too few variables to represent the complexities of the mining situation. They listed 36 variables which affect methane emission rate. The writers were probably correct in their scientific analysis but totally misunderstood the practical requirements of the user. They suggested that a "universal" gas emission prediction method ought to be developed. Whilst this would be academically satisfying it is doubtful whether the coal mining industry would recognise such a priority. It is only necessary that a

prediction method works satisfactorily within the realm of a particular mining company.

- 4.39 The possible pitfalls of applying European longwall models to Australian conditions has also been discussed by Williams, Maddocks and Gale (1992). They stated that *"probably the worst examples of the over-extended use of empirical models is the application of those based on European conditions to Australia..... . So many fundamental parameters are different, that if the correct emission is forecast, it would be more due to good fortune than good science"*.
- 4.40 This criticism is not wholly justified. The authors freely admitted in their paper that virtually no work had been done to define the height of the emission zone, degrees of gas emission and residual gas contents of seams disturbed by mining in Australia. The requirement identified, therefore, would seem to be the collection of underground data rather than the improvement of models in the first instance. Whilst empirical relationships should not be translated beyond the coalfields in which they were established, fundamental principles are universal and it is these which can be distilled from the methods and new empirical data fitted to them. Empirical approaches are inherently limited but due to the complexity of gas emission phenomena are unavoidable. The need for additional rock mechanics modelling as a way forward is recognised by various authors (Williams et al, 1992; Kershaw, 1994).
- 4.41 Williams et al (1992) considered the ideal model based on physical principles of rock and fluid mechanics which included stress, permeability, fluid and rock property conditions *"unlikely to be worth the effort"* from a commercial point of view.
- 4.42 An attempt to introduce rock mechanics aspects into longwall gas emission prediction for Australian coal mines has been described by Lunarzewski et al (1995). Commercial PC based computer programs "Floorgas" and "Roofgas" have been produced (see Appendix 3) which use empirical rock failure criteria to process geomechanical and geological input data and predict gas emission for selecting mining configurations. If the appropriate input data are available, gassiness predictions of

10% to 15% accuracy are claimed for Australian conditions. The model is primarily designed to identify the potential gas release regions around the workings by assessing the stress distribution patterns and does not provide a specific methane emission rate. The programs are understood to be applicable to shortwall, and, bord and pillar methods of extraction.

Empirical prediction of emissions from the worked seam and headings

- 4.43 Longwall prediction methods include an allowance for gas emission from the worked seam. As this component may represent only 10% to 15% of the total gas make in many longwall mines, a high precision is not essential. The principal gas contributors in this situation are the coalface itself, the cut coal at the machine and coal on the face conveyors. In a coal heading, consideration must also be given to the exposed sides of the roadway. Heading models are theoretically applicable to room and pillar mining.
- 4.44 Specific empirical prediction models have not been developed in the UK for headings because significant gas flows have seldom been encountered. Exceptions are at one colliery site in North Wales where advanced drainage of virgin ground was needed to allow headings to proceed and also occasionally where there are interactions between headings and longwall faces. Two virgin headings in the Selby coalfield were closely monitored (CEC, 1992) but it was not possible to trace the decaying emission along the driveage. The degree of emission was assessed as 60% of the initial gas content with 30% to 50% of the total emission occurring in or near the cutting zone. The measured methane flows of around 3 l/s in the headings were an order of magnitude below those reported in the Reumaux and Simon Collieries in France by d'Albrand (1988).
- 4.45 Pokryszka and Tauziede (1994) described ongoing work in French collieries to develop a prediction method for headings using Airey's empirical emission equation which involving summation of terms representing daily elemental advances.

4.46 A raft of empirical methane emission equations have been developed in Germany (Noack and Opahle, 1992) to describe:

- gas emission from the longwall coalface itself;
- adjustments to take account of the configuration of the coalface ends and access roads (an apparent extension or shortening of the face length);
- gas emission from the side walls of headings;
- gas emission from the heading face;
- gas emission from conveyed coal in the heading;
- gas emission from seams intersected by cross-measures drifts.

4.47 With sufficient underground experimental work, relationships similar to those established in German mining and geological situations could be developed for other countries. This process could, however, be costly and time consuming, Eicker (1993), has applied the above equations to South African conditions for estimation purposes but did not have the opportunity to validate the method.

Airway methane concentration peaks

4.48 In any attempt to use a prediction method to calculate the air quantity required in a roadway to dilute the methane concentration to acceptable levels, it is essential to take into account maximum rather than mean levels of emission. For this purpose German (Eicker, 1993) and UK (CEC, 1978) prediction methods have incorporated the CERCHAR concept of the coefficient of irregularity (Bruyet, 1968). The value of this coefficient is obtained by finding the maximum and mean methane concentrations for a (preferably large) number of days. The coefficient of irregularity is then defined as the daily maximum value which is exceeded on only 5% of the days considered, divided by the mean of all the daily mean values. Anomalous situations, such as stoppage of the ventilation or firedamp drainage, are excluded from the calculation. The 5% level may be calculated statistically if it is assumed that the maximum recorded daily values are normally distributed. Using this method reasonable estimates of the coefficient have been obtained from observations over as few as seven days (CEC, 1978). The 5% level exceeds the mean of the maximum

values by 't' times the standard deviation where Student's 't' takes a value appropriate to the number of values examined and is obtained from standard statistical tables (eg. Snedecor, 1946). A typical value of 1.5 is often assumed in longwall gas emission prediction methods. Actual measurement data would need to be examined to assess whether a similar value is applicable to room and pillar working.

Simulation Models

- 4.49 Simulators invoke general principles derived either solely from theoretical considerations or from such considerations in conjunction with empirical relationships which have an underlying physical basis. Methane flow simulators have been developed for both coal mining applications and for projecting coalbed methane production from unmined coal seams.
- 4.50 Mathematical models for calculating methane recovery from coal seams have been reviewed in detail by King and Ertekin (1989) and King (1994) who, in total, examined 53 models (see Appendix 4). Amongst these they included empirical models, such as that of Airey. The authors listed the features of each of the models to highlight their applicability to coalbed methane reservoir simulation, classifying them according to their treatment of methane desorption:
- equilibrium (instantaneous) desorption
 - non-equilibrium (time dependent) desorption.

The basic features of the above types of models are summarised in Table 13.

- 4.51 Equilibrium desorption models assume that gas emission is limited by the rate of laminar (Darcy) flow rather than diffusion processes. Nguyen's (1989) model which describes the flow of methane through a single porosity coal seam is of this type. Non-equilibrium models consider the kinetics of the desorption process. The closer the simulation approaches reality, the greater the degree of complexity. One advanced research model (Durucan et al 1993) considers dual-porosity, (representing coal matrix and microfracture), dual permeability (gas and water flow) and stress

dependence of macropore permeability. Saghafi (1989) and Saghafi et al (1987) developed a non-equilibrium desorption model specifically for coal mine emissions. The model solves two dimensional problems using the finite difference approach. Features of the model included consideration of the effects of mechanical stresses, pore pressure, coal shrinkage and dewatering on seam permeability.

4.52 A computer model described by Patton et al (1994) uses a coalbed methane reservoir simulator for prediction of gas emissions in pre-drainage boreholes and on longwall coalfaces. A ventilation network modelling facility is also incorporated.

Table 13
Basic features of gas flow models

<p>Equilibrium Sorption Models</p> <ul style="list-style-type: none"> ● theoretically derived ● single, partial differential equation models ● single-porosity models ● instantaneous gas desorption ● generally predict optimistic results ● both single and two phase models have been developed
<p>Non-Equilibrium Sorption Models</p> <ul style="list-style-type: none"> ● dual porosity ● isothermal flow ● gas transport through the secondary porosity (fracture or microfracture) obeys Darcy's law, Ficks First Law or a combined form of these laws ● gas in the secondary porosity is free gas ● gas in the primary porosity is adsorbed gas ● gas transport through the primary porosity is by diffusion
<p>Pseudo-Steady State Non-Equilibrium Models</p> <ul style="list-style-type: none"> ● dual porosity ● use Ficks First Law to describe gas transport in primary porosity ● modest computational requirements ● good for long-term predictions
<p>Comparison of Pseudo-Steady State and Unsteady State Models</p> <ul style="list-style-type: none"> ● both yield similar results for long term predictions ● agreement is better and occurs earlier for high diffusion coefficients and small cleat spacing ● should use pseudo-steady state model for long term predictions ● should use unsteady state model for pressure transient applications

4.53 The references can be consulted for mathematical details of the various models. The important point to be made here is that most of the numerical models are research codes. These are the subject of intellectual property rights and would not normally

be made available to third parties. This may be indicative of the limited market for commercial gas emission simulation software which in turn means a limited choice of commercial software.

4.54 There are substantial differences between models designed to simulate coalbed methane reservoirs compared with those used for predicting gas emission in coal mines as shown in Table 14. All draw from the same basic set of theories regarding the storage and flow of fluids in coal but the application of many coalbed methane simulators to coal mines is limited by their inability to account for the removal of coal as the mine workings progress through time.

Table 14

Use of Available Commercial Methane Emission Software to Collieries

Advantages	Disadvantages
<ul style="list-style-type: none"> ● Savings on research and development costs. ● No specialised computer skills required. ● Able to concentrate on problem solving rather than development of tools. ● May be available on free trial basis for a limited period. 	<ul style="list-style-type: none"> ● Not necessarily tailored to users specific needs. ● Computer code not accessible to allow adaptation to local requirements. ● Costly to license for widespread application by different collieries. ● Limited choice of software packages. ● Validation tests required. ● Not appropriate for unusual methane emissions.

4.55 However, COALGAS, a simulator developed by S A Holditch and Associates (SAH) Inc, has features which allow both coalbed methane and mining applications (see Appendix 5). COALGAS is commercially available at about 68,000 Rand for a single PC user license. The model divides coal seams into discrete blocks. Each grid block is assigned reservoir properties such as permeability, porosity, adsorbed gas content and water saturation, using available geologic and engineering data. Grid blocks that represent parts of the coal seam which will be removed by mining can be removed from the simulation at the appropriate times, without re-starting the simulation run. As the calculation proceeds, each movement of the roadway is simulated by removing part of the grid and the model estimates the gas flow from the

roadway face. In addition, the volume of gas in the removed coal blocks is recorded. This provides an estimate of the potential gas volume that may be liberated, in addition to gas flow across the roadway face, due to the breaking of the mined coal. These simulations provide an estimate of the amount of methane that must be handled by a mine's ventilation system and also assist in the planning of a suitable pre-drainage programme. The volume of gas inflow which will occur during roadway development can also be estimated. The program should, in principle therefore, be also applicable to room and pillar mining. Arrangements can be made with SAH to receive the software on a free-trial basis.

The advantages and disadvantages of using commercial software for colliery methane predictions are summarised in Table 15.

Table 15

**Comparison between coalbed methane production
and mine gas emission prediction simulators**

Coalbed Methane Production		Mine Gas Emission Prediction
1.	Fixed location of production well in gas reservoir.	Dynamic situation due to moving coalface.
2.	Well bore resistance important limiting factor.	Dynamic stress-permeability effects strongly influence emission rates.
3.	Generally involves two-phase (water and gas) flow.	Single phase flow usually adequate.
4.	Usually only considers coal seams as reservoirs.	Coal seams and adjacent strata are considered.
5.	Permeability parameters often determined by history matching model with gas production data.	Permeability related parameters either measured or determined empirically.
6.	Mining factors not usually relevant.	Account taken both of current mining and any previous mining disturbance.
7.	Purpose of model is to determine an optimum gas flow rate and facilitate the design of a multiple well gas production system.	Purpose of model is to aid design of underground methane control methods to ensure adequate dilution of gas and hence minimisation of risks of explosion or asphyxiation.

Use of CFD for methane prediction

- 4.56 CFD is a valuable simulation tool for evaluating the localised effects of ventilation changes on methane concentrations and distributions around machines in headings and on longwall faces and also for studying the gas emission behaviour of goafs. Detailed work has been done, or is in progress, in most of these areas. Whilst providing a rapid, low cost means of evaluating new technology the technique must be used with care and calibrated against field or full-scale test results. However, CFD cannot provide technical solutions to methane emission hazards, only assist in the evaluation of new ideas. As CFD software is becoming increasingly user friendly it is also becoming potentially more dangerous as novices can obtain solutions to inappropriately defined models. Users should, therefore, be conversant with the physical processes they are modelling and have a sound understanding of fluid mechanics. The benefits and limitations of CFD are ably described in detail elsewhere (Meyer, 1995).

Expert Systems

- 4.57 Increase in methane emissions as a result of increases in coal production or smooth changes in other variables can usually be predicted by conventional mathematical modelling. However, methane problems often arise as a result of abnormal conditions such as interruptions to ventilation, intermittent caving of the goaf, loss of bleeder roads, the effect of rapid barometric pressure falls on sealed-off areas and emissions of gas from dyke intersections. Most of these events are predictable in their occurrence but not in terms of their timing and precise effects. Knowledge and practical experience provides an indication of the likely outcome of a particular event and generally also a means of minimising its impact. The heuristic approach adopted by a human specialist can be incorporated into a computer program known as an Expert System. Expert Systems manipulate knowledge rather than data and are particularly suited for assessing processes which are too complex or ill-defined to permit mathematical analysis.
- 4.58 Expert systems have been introduced into the mining industry in various countries (see Table 16). They have been shown to offer tangible benefits especially when used

Table 16
Examples of Mining Expert Systems

System name	Country of origin	Developed by	Approximate date	Application
PROSPECTOR	USA	Stanford University (Gaschnig, 1982)	1970's	Probabilistic interpretation of soil and geological deposit data
METHPRO	USA	USBM (Kissel et al, 1987)	1986/7	Diagnosis of methane control problems in US coal mines
DIMES	USA	USBM (Mitchell, 1991)	1991	Hydraulic maintenance of a continuous miner using information from on-board sensors
UKMVM	USA	University of Kentucky (Wala et al, 1989)	1989	Ventilation management using analyses of continuously monitored underground environmental data
SHEARER	UK	British Coal (Perkin & Price, 1986)	1986	Fault diagnosis system for the Anderson Strathclyde AM500 range of coal cutting machines
UFEL	UK	British Coal (CEC, 1988)	1986	Assessment and minimisation of unusual gas emission risks in UK coal mines
HELPDRAIN	UK	British Coal (CEC, 1990)	1990	Identifying and resolving methane control problems (incomplete)
GPS	UK	British Coal (Perkin & Price, 1986)	1986	Gate road planning system for aiding selection of the best support arrangement for underground coal mine roadways in the UK
ESSH	UK	University of Nottingham (Denby and Ren, 1992)	1992	Control of spontaneous combustion risk
BURST	China	(Yansheng D et al, 1990)	1990	Predict the risk of coal and gas outburst and advise on control methods
HZES	China	(Li et al, 1990)	1990	Selection and design of roadway support patterns
ZES	China	-	1990	Advice on fire control and rescue
ASTUR LABOR-hulla	Spain	(Cortina. M, 1988)	1988	Selection of an appropriate mining method for a new coalfield area
XPS	Germany	(Wilke and Seewald, 1988)	1988	Planning face layout and operations
ECAS	Australia	(Nemes-Nemeth et al, 1991)	1991	Safety training and optimisation of hazard control options in an emergency.

to aid fault-finding (Perkin, 1986; Perkin and Price, 1986; Price and Lewis, 1989; Barker-Read and Shuxing, 1992b). The writing of Expert System programs is aided by the availability of commercial "shells" within which the knowledge can be logically structured. Programs are generally written by a specialist familiar with knowledge based computer systems assisted by a technical expert who provides a detailed interpretation of available information, seeking additional input as required.

4.59 A program, known as UFEL, was developed by British Coal (CEC, 1988) to complement its methane prediction program. UFEL was designed to assist ventilation engineers predict the likelihood of unusual methane emissions occurring in a particular mine or section. The program indicates measures for reducing the potential risks. By combining geological, mining and ventilation knowledge, UFEL broadened the understanding of causal factors underlying occurrences which previously were treated as problematical by environmental engineers. A similar approach was adopted by the USBM who developed METHPRO to assist US mine operators resolve methane control problems. An expert system for the evaluation and reduction of methane explosion risk has been developed in Spain (Alarcon and Silva, 1990). The program is understood to use probabilistic methods to assess risks rather than provide guidance on engineering solutions.

4.60 It should be stressed that practical Expert Systems do not replace the human element. The success of even simple applications comes from ensuring that all the relevant questions are asked for a particular problem thus minimising oversights. There is a danger of spending disproportionate periods of time designing elegant programs to cover a wide variety of problem areas. In some instances, the requirements of a mine may be better served by written technical guidance or specialist training. Expert Systems are not a panacea.

Summary of methane emission prediction

4.61 Most of the existing mine gas emission prediction models are primarily aimed at longwall workings. Some are also applicable to bord and pillar methods of mining but not necessarily proven outside their country of origin. Coalbed methane

simulators are potentially applicable to both caving and non-caving type mining operations but are likely to need considerable modification to suit specific mining applications. International interest in gas prediction for longwalls over room and pillar methods of mining is explained by the substantially higher gas emissions experienced with the former method compared with the latter. Significant gas emissions only tend to arise in headings or room and pillar workings where seams are relatively permeable. In such instances the method of gas control often involves pre-drainage. A methane flow simulator may then be of assistance for optimising drainage flows. There is currently no evidence for such a requirement in South African coal mines.

- 4.62 Methane prediction methods have been developed for gassy coal mines which usually are those employing longwall methods of working. The methods are largely empirical, few having a theoretical basis but all apparently successful in their countries of origin. Of the European methods, only the MRDE method is based on a coherent physical theory. With some tuning it has the potential to be applied to South African longwalls. Knowledge based computer programs have been developed to guide the treatment of methane emission problems which are not easily represented by mathematical models.
- 4.63 A fundamental approach to methane emission prediction requires a combination of rock mechanics and modelling of fluid flow in permeable media. Such theoretical models are likely to be too cumbersome for everyday, practical ventilation planning but they have a role for providing a greater insight into the underlying processes controlling gas emission in coal mines.
- 4.64 Commercial methane flow simulation software is principally aimed at the design of methane drainage programmes. No commercially available software has been identified which could be immediately applied to South African coal mines to satisfy the practical needs of environmental engineers.

5 CURRENT METHANE PREDICTION RESEARCH OUTSIDE SOUTH AFRICA

5.1 Information on the status of methane prediction research around the world has been obtained from publications, questionnaires sent to key organisations, Internet searches and E-mail enquiries. The survey is extensive but not necessarily exhaustive.

Research in the US

5.2 Since the 1970's, the US Department of Energy (US DOE) has promoted research and development for the recovery and use of methane found in both workable and unworkable coal seams (Byrer and Guthrie, 1994). Recently, the US DOE have been jointly participating with the US Environmental Protection Agency (EPA) in President Clinton's Climate Change Action Plan which aims to reduce greenhouse gas emissions to their 1990 levels by the year 2000. The US DOE is involved in natural gas research at its Morgantown Energy Technology Centre but mine gas research and development is focused on gas exploitation not specifically on the problems of controlling gas in underground workings.

5.3 Until recently, much relevant research was published by the US Department of the Interior Bureau of Mines (USBM). Since the demise of this organisation at the end of 1995 it is unclear whether the previous level of methane emission research will be maintained. The former US Bureau of Mines Health and Safety Research Program has been transferred to the Department of Energy. The US President's 1997 budget proposes that this work is assigned to the National Institute for Occupational Safety and Health (NIOSH). The Pittsburgh and Spokane Research Centres are continuing health and safety research previously performed by the US Bureau of Mines.

5.4 The Gas Research Institute (GRI) supports US research on gas flow modelling in coal seams amongst other projects. Research interests include the production of methane from coal seams. The publication "Gas TIPS" provides news on recent developments some of which may be of relevance to the study of gas emissions from coal seams. GRI is also accessible through its web site on the Internet <http://www.gri.org/>. For additional information the Product Manager R McBane can be contacted by E-mail at: [rmcbane @ gri.org](mailto:rmcbane@gri.org).

- 5.5 The University of Arizona in Tucson (S Harpalani) is conducting laboratory investigations into the mechanics of gas flow in coal in order to develop techniques for measuring the two most important parameters controlling gas flow in coal - diffusion coefficient and permeability. A transient approach is being used.

European Research

- 5.6 Considerable research on methane measurement and emission prediction has been undertaken in Europe (Belgium, France, Germany, Spain and the United Kingdom) principally by state agencies with financial support from the European Coal and Steel Commission (ECSC). The research organisations involved have included CERCHAR (now integrated into INERIS) in France, INIEX in Belgium, DMT in Germany, AITEMIN in Spain and TSRE (formerly MRDE) in the UK. Private companies and universities have also taken part in ECSC funded methane research. Most of the development work on methane emission prediction for coal mining was completed during the 1970's and 1980's. Roughly 90% of the methane prediction effort was directed at longwall mining with the remainder on gas emissions in headings. The major mining research centres in Europe are now scaling down their coal research programmes. The research budget of the ECSC is being progressively reduced as hard coal mining declines within the member countries. Coal research will shortly lose its special status as it becomes integrated within the overall energy programme of the European Union. The coal research interests of the European Union are now more concerned with the historical legacy of a declining coal industry than coal production related problems. Nevertheless, some projects relevant to methane control and prediction are continuing.
- 5.7 The Department of Mineral Resources Engineering at Nottingham University in the UK (Dr J S Edwards and Dr T X Ren) are currently developing a longwall methane flow model incorporating Computational Fluid Dynamics (CFD) techniques to assist in representing stress-permeability relationships in the goaf and surrounding strata. Novel apparatus has been produced for the determination of in situ methane contents of coal seams and the stress-permeability behaviour of Coal Measure rocks has been

studied along with the influence of mining induced stress on post-failure rock mass permeability.

- 5.8 The Earth resources Engineering Department of Imperial College in London, UK (Dr J Q Shi, Dr S Durucan and Dr T S Daltaban) is involved with gas flow modelling and research into the stress sensitivity of the permeability of coal matrix and fracture systems. A non-linear finite element model is being developed to study the dynamic changes in the state of stresses and the post-failure behaviour of coal seams and surrounding strata during longwall mining. Failure zones are defined at each extraction time step and used in characterising the mining induced stress-dependent permeabilities of the coal seams and surrounding strata. A coalbed methane simulation program has also been developed to model the physics of methane storage and flow within a reservoir. Given details of reservoir characteristics and specified well configurations, the expected yield from the boreholes can be obtained, together with the corresponding pressure profiles.
- 5.9 The Institute of Occupational Medicine (IOM) in the UK (Dr A D Jones) in conjunction with the Institute de l'Environnement Industriel et des Risques (INERIS) in France (Mr C Tauziede) and Charbonnage de France have constructed aerodynamic scale models for predicting methane concentrations around retreat longwall coalfaces complemented by CFD simulations and underground studies in operational coal mines. Whilst the current scale models represent longwall configurations, the principles that have been established could be used to investigate the ventilation of room and pillar mining systems.
- 5.10 International Mining Consultants Ltd (IMCL) are undertaking two methane research projects for licensed British Coal, one is concerned with improving the drainage of gas from longwall faces and the other with investigating methane emissions from rapidly - advancing drivages. Both projects are scheduled for completion in September 1996.

- 5.11 Wardell Armstrong in the UK is currently preparing a worldwide review of practices and recent developments in gas control for coal mines on behalf of International Energy Agency Coal Research. Consideration is being given to longwall and room and pillar methods of mining amongst others. The project team includes contributors from the USA (Gates Wardell), Australia (CSIRO), China (China Coal Information Institute and Fushun Coal Research Institute). Assistance is also being provided by the Department of Mineral Resources Engineering at the University of Nottingham.
- 5.12 The Department of Mining Exploitation and Prospecting at the University of Oviedo in Spain (C G Nicieza) are evaluating a model designed to predict methane emissions in vertical coal seams mined using a sublevel stoping method.

Canadian Research

- 5.13 The Cape Breton Coal Research Laboratory is investigating ways of improving the health and safety of underground miners through research aimed at reducing the risk of explosion and fire, improving mine ventilation and reducing exposure to respirable dust. Current research is understood to include improvement of methane control, monitoring methane emissions in longwall sections and quantifying the methane content of coal through various testing procedures.
- 5.14 A study on sorption rate is reported to be taking place in the Department of Geology at the University of British Columbia.

Australian Research

- 5.15 The Commonwealth Scientific and Industrial Research Organisation (CSIRO) are involved with various gas emission related projects for coal mining. A global review of methane emissions to the atmosphere from coal mines sources has recently been completed for the International Energy Agency. The CSIRO Division of Petroleum Resources, Exploration and Mining are developing methods for measuring gas emission parameters, gas flow modelling and the production of practical prediction programmes. Further details have been requested but not yet received.

- 5.16 The Department of Civil and Mining Engineering of the University of Wollongong (Associate Professor N I Aziz, Dr E Y Baafi and Professor R N Singh) includes research into mine gases within its broad engineering interests.
- 5.17 The Department of Mining and Metallurgical Engineering at the University of Queensland (Dr Stewart Gillies, E-mail : S.Gillies @ minmet.uq.oz.au) reports ongoing research on mine dust, gas explosibility and ventilation of deep, hot underground workings, an interdisciplinary study of the occurrence and flow of methane in coal seams and adjacent strata and a programme to improve drilling methods for gas drainage. The latter involves the Co-operative Research Centre for Mining Technology and Equipment (CMTE).

Research in New Zealand

- 5.18 The Department of Geology at the University of Auckland (Basil Beamish, E-mail: bbl, beamish @ auckland, ac.nz) is involved in several methane related projects:
- (i) Sorption of gas by coal and associated phenomena in underground mining: This project was started in 1988. It basically encompasses combining laboratory results obtained during 1991-1992 at the Coalseam Gas Research Institute, James Cook University, Townsville, Australia, with mine site experience. The research looks at sorption capacity, sorption rates and pore nature of coals from the Bowen Basin, Australia and Huntly Coalfield, New Zealand. and how these relate to gas emission and outburst phenomena in underground coal mines. The research is due for completion in June 1996.
 - (ii) Controls on methane flow in coal: The sorption capacity of New Zealand coals has been studied using high pressure microbalances at the Coalseam Gas Research Institute. The testing has been completed with the results being compiled in a publication for submission to the New Zealand Journal of Geology and Geophysics.

- (iii) Effects of coal type on methane sorption in New Zealand coals: The sorption capacity and sorption rate behaviour of selected coal lithotypes obtained from the Greymouth Coalfield are being examined.
- (iv) Emission value index for outburst-proneness of coal: This project is aimed at improving the ability to predict outburst-prone conditions at the face and the understanding of emission variations that occur. It is due to commence in 1997, and is also the subject of a larger application to the Australian Research Council through the Coalseam Gas Research Institute where parallel work is in progress.

Research in China

- 5.19 The Department of Mining Engineering at the China University of Technology (Professor Yu Qixin) is active in conducting research in gas flow prediction, control and drainage in coal mines.
- 5.20 The Fushun Coal Research Institute of the Ministry of Coal in China (Mr Wen Yongyan) is undertaking fundamental research on methane content determination and prediction in coal mines. In addition, robust methane monitoring and control systems are being developed for underground coal mines.

Summary of current international research direction

- 5.21 Research and academic institutions in various coal mining countries throughout the world are actively engaged in work relating to the prediction of methane emissions in coal mines. Electronic communications now enable researchers in different parts of the globe to maintain contact and exchange ideas. This may help to reduce any unnecessary duplication of effort.
- 5.22 Most of the current research on methane flow modelling for coal mines is aimed at improving the accuracy of simulations and enhancing the understanding of strata behaviour, gas flow and gas emission processes. The studies although often targetted

at longwall mining, are relevant to all methods of coal extraction and should provide a basis from which future practical methane prediction software could be developed.

- 5.23 Future methane prediction models are likely to be more general and less empirical than existing models but of a complexity which makes them unwieldy for day to day colliery ventilation planning purposes. However, they could have an important role through centralised planning and problem solving services provided within major mining houses or by external consultants.
- 5.24 A high proportion of the ongoing visible research effort is academically orientated. However, there is probably additional unreported activity taking place within various mining and equipment manufacturing companies, where the emphasis is on developing practical and pragmatic solutions to specific technical problems. Trade journals and the publications of the professional mining institutions need to be regularly reviewed to find the results of such work.

6 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

Discussion

- 6.1 Research relating to the prediction of methane emissions in South African coal mines has been pursued for some 11 years by both post graduate students and contract researchers but lacking a clarity of direction and focus. Many of the research studies have been made at atypical colliery sites where, had the causes of gas emissions been investigated in greater detail, the results could have furthered the understanding of gas emission processes in general. Rather than pursue such investigations, efforts tended to be concentrated on conducting laboratory or underground tests to measure specific gas-related coal properties or coal seam characteristics. An almost obsessive interest in barometric pressure effects on gas emission may be symptomatic of a lack of appreciation of fundamental physical principles by some researchers and coal mining engineers. Nevertheless, useful work has been done on the characterisation of the reservoir properties of South African coals, an advanced gas flow simulator has been developed and a range of underground investigation tools have been designed, tested and applied. The standard of current research is variable but generally comparable with that elsewhere in the world. However, there are gaps in methane prediction research which if filled could increase the overall effectiveness of the safety research programme. Effectiveness, in this instance, means a reduction in the incidence of ignition and explosion incidents in South African coal mines which currently are unacceptably high.
- 6.2 The currently available manpower resource for methane prediction research in South Africa is substantially lower than that formerly applied by European coal mining countries to the same problem. For example, approximately 10 researchers were engaged on developing methane measurement and prediction methods by British Coal (Mining Research and Development Establishment) in the late 1970's and throughout the 1980's. During the same period an additional 10 to 15 staff were working on ventilation and dust research. Active recruitment ensured an influx of research trainees and new ideas. High profile projects and a reputation for quality work drew both experienced research professionals and high calibre graduates into coal research which had been previously viewed as unattractive. With the decline of the coal

industry in recent years, reduced funding, cessation of graduate recruitment and loss of key professionals has led in some instances, to a stagnation of ideas and a deterioration in the quality of output.

- 6.3 CSIR Miningtek has a small core of methane researchers whose developing knowledge and expertise are essential to continuing research in the field, but the team is not of a sufficiently critical mass to provide the necessary balance of theoretical and practical scientific and engineering skills to make the rapid advances needed by the industry. There are also individuals within academia and the coal industry with invaluable experience of methane emission and measurement problems. Excellent laboratory and workshop resources are available at the University of Witwatersrand, Department of Mining Engineering, along with laboratory and full-scale testing facilities at CSIR Kloppersbos but they are not being exploited to their full capacity.
- 6.4 An insularity is evident in some areas of methane research where, if external contact had been extended, more rapid advances may have been achieved. This situation is not unique. Many coal research programmes throughout the world, when examined in retrospect, have duplicated work previously done elsewhere. Sometimes the previous work may not have been well-publicised or contemporaries have failed to recognise parallel interests. Other reasons may include commercial secrecy, national pride, language differences, obduracy, limited travel opportunities and sustainment of employment. Mallett (1993) remarked on unnecessary duplication of effort which had occurred in Australia due to a lack of national co-ordination of research.
- 6.5 There also has been much duplication of effort in methane-related research within the coal mining countries of the European Union and it is probably only in the last few years that truly collaborative projects have been developed. This situation has been precipitated by a declining coal industry no longer able to support large research programmes.
- 6.6 The continued decline of the coal industry in Europe, together with uncertainties as to the funding of future mining research by the Federal Government of the United

States, may well mean that emerging coal mining nations will need to take on a greater responsibility for safety related research. South Africa and Australia are well placed, geographically and geologically to undertake collaborative research. If this is undertaken in the near future, continuity with the research already undertaken in the Northern Hemisphere can be maintained and use made of the expertise currently available in those countries with declining coal mining industries.

Application of the Research

- 6.7 Control of methane emission risks in South African coal mines can be improved by technological developments but this alone is not sufficient for effective application of research. Technical responses to health and safety problems are only likely to lead to sustained improvements if implemented in a receptive environment.
- 6.8 Research programmes must involve the potential user to ensure that the practicalities of proposed solutions are recognised. This does not mean, however, that the researcher should be required to assume a subjugate role, the contributions of all parties being relevant for their specific skills.
- 6.9 Transfer of research to the field requires a commitment from the recipient as well as the research organisation. The user should be prepared to provide relevant training for personnel and subsequent refresher training with the research organisation supplying technical, expert support.
- 6.10 The SIMRAC organisation provides the framework within which appropriate consultation on the development and execution of research programmes can take place. It is also a forum from which the more difficult task can be tackled of:
- interpreting research findings to provide practical advice to collieries;
 - encouraging the implementation by mine operators of new tools and technologies arising from the research.

Methane prediction needs for South African collieries

- 6.11 Practical methane prediction methods have been developed in countries where, as a result of improved mechanisation, gas emission rates have increased commensurate with the increases achieved in coal production rates. In many instances, ventilation techniques alone are not able to dilute the gas to safe, statutorily acceptable concentrations, necessitating the use of methane drainage methods to enable coal production targets to be met. The specific methane emission (ie. amount of gas released per unit mass of coal extracted) at which gas becomes an important constraint on coal production and safety depends on the geology and the mining method but generalisations can be made.
- 6.12 In the USA, methane drainage tends to be required at a specific emission of around $11\text{m}^3/\text{t}$. Advance planning of ventilation and methane drainage is accomplished with the assistance of gas emission prediction software. Where the permeabilities of coal seams are relatively high, gas flow simulators are sometimes used to determine the design parameters for draining the gas in advance of mining.
- 6.13 Preliminary calculations indicate that ventilation limits could be reached on South African longwalls at a specific emission of around $2.5\text{m}^3/\text{t}$ due to the exceptional coal production levels that are achieved. This would assume a simple ventilation system with a total of about $35\text{m}^3/\text{s}$ of air available in the return airway. Alternative ventilation configurations would allow higher specific emissions to be achieved without recourse to methane drainage.
- 6.14 Substantial quantities of air are generally available in the return airways of bord and pillar sections. Initial estimates indicate that gas dilution problems are not likely to arise below specific emissions of $14.5\text{m}^3/\text{t}$. Specific emissions of such magnitude are likely to be rare in South African bord and pillar mines due to the generally low seam gas contents. By way of contrast, in the actual headings where ventilation quantities are relatively low, methane emission problems are omnipresent. Virtually pure methane is released at the cutting head of a continuous miner from the cut coal and passes through the explosive range as it mixes with ventilation air. This is a high risk

process due to the juxtaposition of flammable gas and an incendive source in the form of cutter picks. The ventilation of headings and continuous miners is already receiving considerable research attention and deservedly so, although it is difficult to envisage a robust solution to the critical ventilation problem without wider use of ducted auxiliary ventilation systems or "narrow-side" brattice systems as practised in Australia.

6.15 The above discussion indicates that methane prediction methods could be of benefit:

- to predict gas flow into the cutting zone of continuous miners to assist in the design of systems to reduce methane ignition risks

- for predicting gas emission on longwalls as these are more likely to be constrained by gas release than room and pillar workings due to the greater volume of gas bearing strata disturbed by coal extraction. The prediction methodology could also be applicable to pillar recovery although extraction rates of coal are not likely to be comparable to longwall mining and hence not limited by methane emission rates.

6.16 Exceptional gas emissions sometimes occur in South African coal mines in the vicinity of igneous dykes, sills and other geological features. A greater understanding is needed of these factors. If such emission events proved to be of widespread significance then there would be a strong argument for investigating knowledge based approaches to emission prediction to assist the identification of appropriate gas control measures. The necessary information can be obtained from analysis of gas emission data from individual production sections making use of remote monitoring systems, where available, and the CSIR Miningtek portable gas measurement equipment. Details of the geology, mining methods and coal production should be recorded and the in situ methane content of the worked seam measured. There is, therefore, a prerequisite for a reliable method of underground sampling and gas content determination. The "statistical" method described in Chapter 3 may be appropriate.

- 6.17 The content and priority of further methane flow modelling research is difficult to determine without an indication of the range of methane emissions being experienced in the present mines. A first step in guiding the future research strategy could, therefore, be an overall assessment of the magnitude of gas emissions in South African collieries. Measurement of total airflow and methane concentrations from upcast shafts would be needed together with average monthly coal production data and a note of the mining method being employed. Where different mining methods are being practised in the same mine, data could be collated on a section by section basis. Due to the usually low concentrations of methane in shafts and airways, samples may need to be taken for analysis by gas chromatography using a flame ionisation detector. A representative database could be obtained with a sampling programme which involved taking a gas concentration sample from upcast shafts during a working shift towards the end of each working week, along with a measurement of air quantity. To ensure comparability of data, the measurement procedure would need to be rigorously defined, results adjusted to standard conditions of temperature and pressure and a pro forma prepared to ensure all relevant information is recorded.
- 6.18 The results of the above study could be evaluated against specific emission criteria depending on the mining method. Suggested criteria follow although these could be refined as part of the survey:
- a significant proportion of longwalls with specific emissions greater than $2\text{m}^3/\text{t}$ would justify refining an existing empirical prediction model (eg the MRDE model) to suit South African conditions;
 - if specific emissions from mines working predominantly longwall methods do not exceed $2\text{m}^3/\text{t}$ a very basic empirical prediction approach would probably suffice as an aid to ventilation planning;
 - a significant proportion of bord and pillar workings with specific emissions exceeding, say $11\text{m}^3/\text{t}$ would be justification for developing the CSIR Miningtek prediction model into a streamlined, practical form for use by collieries;

- should specific emissions in bord and pillar mines not attain the above criterion, a simple empirical approach to flow prediction would probably meet most practical requirements. In the event that this was the outcome, the CSIR Miningtek model should be retained for use on an ad hoc consultancy basis for problem solving and research support purposes.

6.19 Irrespective of the outcome, there are three areas of work which should either be initiated or incorporated into current research programmes. These would involve development of methods for the:

- (i) prediction of gas flow into the cutting zone of continuous miners using existing elements of the CSIR Miningtek model where appropriate and aimed at providing a practical means of designing site specific heading and machine ventilation requirements to minimise frictional ignition risks. A development programme for a machine gas emission prediction model would need to be supported by underground testing. Full-scale measurement work in a test-gallery would be helpful as an interim step;
- (ii) reliable measurement of seam gas content from surface or underground samples to provide input to (i) in addition to any general gas emission prediction methods;
- (iii) assessment of unusual gas emissions associated with geological features such as intrusions along with other factors together with appropriate gas control measures such as pre-drainage of gas and ventilation precautions.

6.20 The degree of sophistication required of an emission prediction method will depend on the general magnitude of emissions.

Experience elsewhere, the results of this project and observations in South Africa would indicate that in developing a practical methane prediction program, irrespective of its complexity, consideration should be given to the following:

- For ventilation planning, "worst case" emission quantities are generally needed rather than details of the shift to shift variations. A steady state model should, therefore, suffice for most purposes.
- Methane control and ventilation planning is a colliery function, therefore, a gas prediction model should run on a modestly sized personal computer, use inputs which are readily available to colliery environmental staff, and produce output relevant to usual South African mining practices.
- A robust and practical program should be based on sound physical principles, using sensible mathematical representation of emission processes or empirical relationships established either experimentally in the field or from simulation exercises with a validated, detailed mathematical model. The existing CSIR Miningtek model could, after testing, be used for the latter.
- The input and output requirements of a methane prediction program should be decided in consultation with colliery mining and environmental staff.
- Program inputs in the form of geological, mining and coal production data are likely to be familiar to colliery staff but permeability, gas pressure or gas content data will not be readily available. The magnitude of predicted flows will depend strongly on the accuracy of such values. The options are to provide the mine with its own gas content measurement equipment or, alternatively, provide an independent gas content measurement service. The latter choice is preferable due to its convenience to the mine and because standards would be better controlled and any improvements to gas content measurement technique introduced more rapidly. An additional benefit would be the accumulation of a national gas content database which eventually may facilitate the modelling of seam gas content trends and hence the need for continuing measurements may reduce. In any event, analysis of the data would contribute to a greater understanding of seam gas content distributions and the controlling influence of various geological factors.

- The methane prediction model should be tested at a range of colliery sites over a sufficiently long period to obtain gas emission measurements representative of the normal cycle of mining events.

- Site specific data could be gathered from underground field trials in parallel with the development of the prediction program. This would speed program development and validation in addition to enabling the researchers to maintain regular contact with the "end user". Information obtained from each test site should include a geological section of the worked seam and surrounding strata, seam gas contents (measured on coal cores from surface or underground boreholes using a direct method or alternatively the statistical sampling method subject to a demonstration of its applicability), a section layout plan with face dimensions, daily run-of-mine coal production and advance rates. The quantity of methane leaving the section should be monitored using existing colliery remote airflow and methane monitors where available, complemented by additional monitoring of coal production activities with the CSIR Miningtek multi channel methane logger. Production-related activities should be manually logged over a day or so and additional investigations carried out to identify the cause of any fluctuations in airflow or methane concentrations that are recorded.

- Any issue of methane prediction software to collieries or mining houses should be accompanied by training both in the use of the computer program and the practical application of the output ensuring any limitations are fully understood. Any improvements in methane management at the mine are likely to occur as much from the reinforcement of ideas and understanding as from the methane prediction capability of the software.

Conclusions

- (i) Substantial methane content and emission data have been obtained from investigations on South African coal seams but only at a limited number of sites. Much of the research has concentrated on unusually gassy locations

which are not necessarily representative of the majority of operating coal mines in South Africa.

- (ii) The overall magnitude of gas emissions in South African collieries does not appear to have been quantified. A national survey is needed to properly assess the scale of the problem.
- (iii) No reliable method has been established in South Africa for measuring the methane content of coal seams. As a consequence, an understanding of the variations in seam gas content from place to place and possible natural causes of such variations has not been obtained. Knowledge of in-situ methane contents and access to a reliable measurement method would assist quantification of the methane hazard facing a development from an existing mine into a virgin area of coal or a new underground mine.
- (iv) Underground, multi-point methane concentration and air pressure measurement tools have been developed in South Africa. These will be valuable for use in underground investigations of unusual emissions, of specific gas control problems and also for testing prediction models.
- (v) Seam gas transport properties have been characterised, an understanding of methane emission processes from coal seams gained, and the principles embodied in a sophisticated 3-dimensional gas flow simulator. The model has yet to be tested and validated using underground field data. The performance of the model is likely to match existing models from elsewhere in the world. Considerable empirical simplification would be required to produce a practical version for colliery use.
- (vi) Research in South Africa, and elsewhere, has established that coal seam permeabilities measured in the laboratory are not comparable to those obtained from in situ measurements. Whilst various methods have been devised for determining the in-situ permeability of coal seams, the values are only of

limited use in models due to the complexity of variations around workings caused by mining induced stresses. Practical gas emission models usually rely on "history matching" to provide appropriate permeability data for future predictions where similar geological and mining configurations prevail.

- (vii) The aim of methane prediction is to provide estimates of methane flows that are likely to arise during underground coal mining operations taking account of both geological and mining related parameters. Thus, methane control and monitoring requirements can be planned in advance of working to prevent constraints on coal production due to statutory methane concentrations being exceeded and, in particular, to minimise explosion risks. A computerised methane prediction method will not solve methane problems in its own right; it is a tool which should assist in the design of engineering measures to reduce methane risks.
- (viii) The basic concepts inherent in most European longwall gas prediction models are equally applicable in South Africa. The MRDE method is probably the most appropriate model to apply due to its sound physical basis. With empirical adjustment, assisted by comparative studies of strata mechanics processes accompanying goaf caving, this model should be capable of providing reasonable steady state estimates of gas releases on longwall faces and during pillar recovery operations in bord and pillar mines. Development of a more sophisticated numerical simulator would be difficult to justify given the paucity of longwall operations in South Africa.
- (ix) A large number of the prediction models used at collieries in other coal mining countries are largely empirical. More sophisticated numerical and analytical models have been developed by research organisations and universities but few appear to have been applied in practice. However, as the simpler methods appear to work surprisingly well in their countries of origin there has been little demand for enhanced versions. The main features of successfully implemented programs appear to be:

- relative simplicity of use;
 - based on physical principles understood by the user;
 - attuned to local conditions and needs.
- (x) Limitations of empirical models are openly recognised by the users who, in general, are able to make appropriate allowances when unusual conditions obtain on the basis of experience or guidance arising from research findings. Empirical methods which seek to avoid the modelling of complex situations are inevitably limited to their prediction capability. However, as there is only a limited range of control measures available at the mine, predictions need only be sufficiently accurate to assist selection of the most appropriate response.
- (xi) Considerable progress has been made by research institutions in various countries in developing advanced gas emission prediction software. In many instances they have had to rely on a theoretical approach due to the difficulties of obtaining access to mines and to reduce the frustrations of underground scientific investigation. Whilst not used directly by practising engineers these simulation-type models are used for consultancy purposes and can be helpful to a mining company when faced with particular strategic methane problems. The CSIR Miningtek model could be considered to fit such a category.
- (xii) Emission processes in South African mining situations appear to be reasonably well understood from previous research although there is a need for more detailed information on seam gas contents and gas emissions in the vicinity of igneous intrusions. There is also a need for the recording and scientific investigation of any unusual methane emission occurrences to assist in the formulation of additional technical guidance on methane monitoring and control which is not easily incorporated into a mathematically based prediction model. The knowledge could eventually be incorporated into an "Expert" system but would be equally useful if presented as a guidance document.

- (xiii) While methane prediction techniques can be of great assistance in determining the proper ventilation requirement, they cannot in themselves prevent incidents of ignitions or explosions, when local or temporary failures of ventilation occur. However, the monitoring techniques described in this report would provide values for "norms" against which alarm triggers could be set and, if permanently installed, such systems could alert management to the occurrence of unusual circumstances.

Recommendations

- (i) A survey should be conducted of methane flows and coal production rates from South African coal mines to establish the scale of the gas emission problem to guide future gas prediction modelling research and development.
- (ii) There is an urgent need to reduce gas ignition risks in continuous miner headings. A method for estimating the gas flow into the cutting zone should therefore be developed to facilitate the design of satisfactory gas control measures.
- (iii) A reliable, direct method of seam gas content measurement should be developed, capable of using surface or underground samples. The method should be designed to meet the logistical requirements of a sampling campaign which will prove the method, obtain the maximum advantage from any ongoing surface drilling programmes and provide input for any methane prediction algorithms. The South African institution involved with the development should be capable of providing a gas content measurement service to the collieries. In order to minimise error, sampling and measurement should be undertaken by trained personnel with emphasis on the quality of data rather than quantity. (Total gas content should be measured, not desorbable gas content).
- (iv) Seam gas content and underground gas emission data should be collected from a wide range of locations to obtain an improved understanding of the

influences of geological factors including coal rank, the proximity of seams in adjacent strata and the effects of igneous intrusions and geological faults. The feasibility should be studied of integrating the findings into a knowledge based program which will assist collieries to forecast potentially hazardous, or unusual methane emissions and plan suitable gas control measures.

- (v) Greater use should be made of remote monitoring systems at collieries for recording variations in specific emission, examining effects of varying coal production and for analysing methane problems. Continuously monitored methane concentrations combined with airflow data to yield pure methane flow can be correlated with coal production data to provide specific emissions and also to assist in identification of unusual emission events.
- (vi) Due to the greater extent of strata disturbed, longwalls are likely to release more gas than bord and pillar workings in similar geological situations. A method for predicting gas emission on longwalls may, therefore, be of benefit. It is recommended that the requirements of the relatively few longwalls for a methane prediction capability are met by introducing an existing European empirical prediction method of the MRDE type whose basic principles are, in general, universally applicable. The method should be applied at two or three longwall sites and also at a similar number of pillar recovery sites and the results evaluated in the context of the specific colliery requirements.
- (vii) In undertaking further research, expertise on colliery methane emissions already available within mining research organisations and academic institutions in South Africa should be supplemented by expertise from overseas. A balance between contract and postgraduate research would allow for the training of new research professionals and ensure diversity of ideas provided that individuals of appropriately high calibre can be attracted. Regular collaborative input from overseas would:
 - (a) stimulate South African research through continuing peer review
 - (b) inject new ideas gained from practical experience elsewhere

- (c) accelerate development and implementation of research products
 - (d) facilitate identification, adaptation and exploitation of existing overseas solutions relevant to South African gas problems.
- (viii) A more focused, practical and pragmatic approach to addressing perceived methane emission problems in South Africa should be adopted than has been the case in the past.

ACKNOWLEDGEMENTS

This project was undertaken by Wardell Armstrong with assistance from the Department of Mineral Resources Engineering at the University of Nottingham and the Department of Mining Engineering at the University of the Witwatersrand.

The principal author was David Creedy of Wardell Armstrong with assistance from Kevin Garner. Additional contributions were made by Dr T X Ren of the University of Nottingham. The draft report was reviewed by Mr A J Smith (Managing Partner) for Wardell Armstrong, Professor H R Phillips, Department of Mining Engineering, University of the Witwatersrand and Dr J S Edwards, Department of Mineral Resources Engineering, University of Nottingham.

Grateful thanks are expressed to Professor Phillips for his kind assistance during the field work and report preparation and also to fellow researchers, mining engineers and others who contributed to the various discussions in South Africa.

The permission of the Gas Research Institute, Chicago, Illinois, to reproduce figures from *A Guide to Determining Coalbed Gas Content* is gratefully acknowledged.

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APPENDICES

APPENDIX 1

**Review of South African methane prediction research
and research needs : visit programme.**

APPENDIX 1

Review of South African Methane Prediction Research and Research Needs : Visit Programme

27 February 1996	Prof. H R Phillips	The SIMRAC organisation Visits programme Background information
28 February 1996	Dr J Oberholzer P Linzer, K van Zyl	CSIR Miningtek Discussions with CSIR methane research team
29 February 1996	Mr H C van Zyl Mr J Viljoen	SIMCOL project presentations Clarification of project objectives
1 March 1996	Mr M Lawson Mr N Roman Mr A Birtles Mr D Hardman (Wits)	New Denmark Colliery - high production retreat longwall, methane drainage surface from boreholes into goaf
4 March 1996	Mr J Diedericks Mr E Kaber	Brandspruit Colliery, Secunda, continuous miner section, methane monitoring
5 March 1996	Mr A Cook	Discussion of previous research, SASOL research interests.
	Mr D Rowe	Department of Mineral and Energy Affairs Mine Environmental Control - standards, needs, legislative approach
6 March 1996	Prof H R Phillips	University of the Witwatersrand - literature search, review of research theses
7 March 1996	G Smith J du Plessis	CSIR - Kloppersbos facility, SAIMM technical visit, gas sorption apparatus, library.
8 March 1996	Prof H R Phillips	University of the Witwatersrand - literature review, methane research facilities

APPENDIX 2

Classified Bibliography

APPENDIX 2

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APPENDIX 3

Commercial Floorgas/Roofgas Simulation Programs



Lunagas PTY. LTD Underground Gas Control Specialists

115 Darby Street, Newcastle, Australia Telephone: (049) 296646 Facsimile: (049) 296606
 Address all mail to: P.O. Box 222, The Junction, N.S.W., 2291

Mr David Creedy
 Principal Engineer
 Wardell Armstrong Mining Consultants
 Lancaster Building High Street
 Newcastle-Under-Lyme STAFFORDSHIRE ST1PQ
 GREAT BRITAIN

2 May 1995

Dear *David,*

Lunagas Pty Limited is pleased to announce that the Floorgas/Roofgas Simulation Programs© have been successfully transferred to a commercialised PC-based, MS Windows™ format, including a 40 page User's Manual for each program, and are ready for use by specialised institutions, underground coal mines and/or individual specialists, who are responsible for the planning and control of coalbed gas (CH₄ and/or CO₂) problems in underground coal mines.

We highly recommend the software as a new, unique tool for the design of underground cross-measure holes and surface wells, gas make predictions and active gas resources evaluation.

Floorgas and Roofgas Software Purchase Costs		
	US\$	AU\$
1. Software Purchase:		
Floorgas (FG)	7,000	10,000
Roofgas (RG)	5,000	7,000
Package of both (PK)	11,000	15,500

Floorgas and Roofgas Software Running Costs		
1. Once only use of software (run by Lunagas):		
Floorgas (FG)	1,800	2,500
Roofgas (RG)	1,500	2,000
2. Multiple uses of software (run by Lunagas):		
Floorgas	1,100	1,500
Roofgas	800	1,000

Purchase includes: Master floppy discs containing the program(s), a User's Manual(s) and software support by mail, fax or Internet.

Use of software on a clients behalf includes: Collection and analysis of mining, lithological and geomechanical data: prepared and delivered by clients, data input and generation of three (3) colour outputs for Roofgas and/or Floorgas, delivery of results in the form of a colour report and/or bitmap images on floppy disk.

I have included two (2) Floorgas-Roofgas brochures and one (1) Lunagas company brochure for your attention.

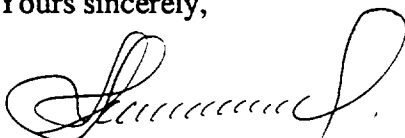
For further information on the software or to arrange a demonstration please contact Lunagas Pty Limited or fill in the form below and send to Lunagas by facsimile on 61-49-29 6606.

Name and position:			
Company:			
Address:			
Telephone:	Fax:		
Please mark (X) the appropriate boxes:			
Yes, I would like more information on the software:	<input type="checkbox"/>		
Yes, I would like to arrange a demonstration of the software:	<input type="checkbox"/>		
Yes, I would like to purchase the software:	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

Note: A full presentation of the software and its application will be carried out by Lunagas Pty Limited and Raven Ridge Resources (representatives in the USA), during the 7th US Mine Ventilation Symposium to be held in Lexington, Kentucky USA, between June 5 and 7 1995.

Please do not hesitate to contact us should you require any further information.

Yours sincerely,



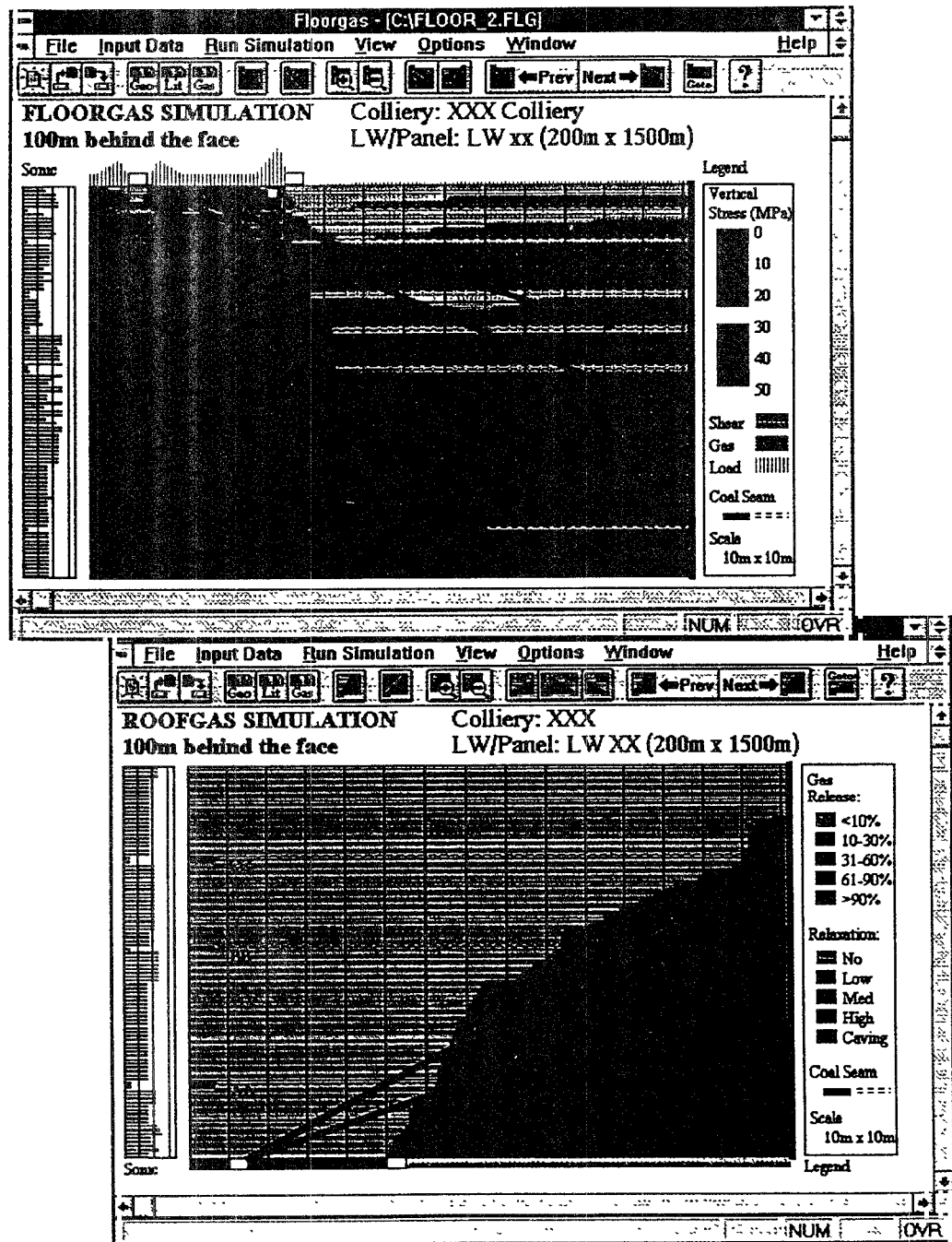
Leszek (Les) Lunarzewski
Managing Director
encl:

PC based,
MSWindows™
software
for
geologists,
gas drainage
and
ventilation
engineers

Floorgas and Roofgas simulation programs are professional engineering design tools for precise, graphical analysis of strata relaxation and gas release phenomena associated with mining activities in underground gassy coal mines.

Floorgas and Roofgas

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Floorgas and Roofgas outputs allows you to take a professional approach to:

- roof and floor strata relaxation zones identification
- underground roadways gas make prediction
- cross-measure drainage holes design
- surface gas wells design

Main Data Entry

Depth (m)		Thickness (m)		Sonic Vel (m/s)	Lithology to Sonic Conversion
From	To	Int	Cum		
509	510	1	1	3500	2400 Coal bright
510	511	1	2	3600	2500 Coal banded
511	513	2	4	4350	2600 Coal dull
513	515	2	6	4500	2800 Shaly coal (>70% coal)
515	516	1	7	2550	3100 Coaly shale (<30% coal)
516	517	1	8	3500	3700 Shale (or Claystone)
517	521	4	12	4000	4000 Mudstone
521	522	1	13	4300	4100 Siltstone
522	523	1	14	4000	4200 Conglomerate
523	524	1	15	2500	4500 Sandstone

Use Conventions
 Edit Conventions

Geomechanical Data | **Lithological Data** | Mining and Gas Data

- Specification of gas make prediction coefficients for local conditions.
- Definition of active gas sources and strata relaxation zones and their boundaries.
- Floorgas and Roofgas are used routinely by Lunagas Pty Limited and specialised mining and geological companies in Australia, USA and Europe.

Input Data

- Mining and gas data
 - longwall or bord and pillar geometry
 - in situ gas contents and gas source properties
- Lithological data
 - strata geology - lithology, geo or sonic log
 - gas sources thickness and position
- Geomechanical data
 - vertical and horizontal stress characteristics
 - rock types and geomechanical properties

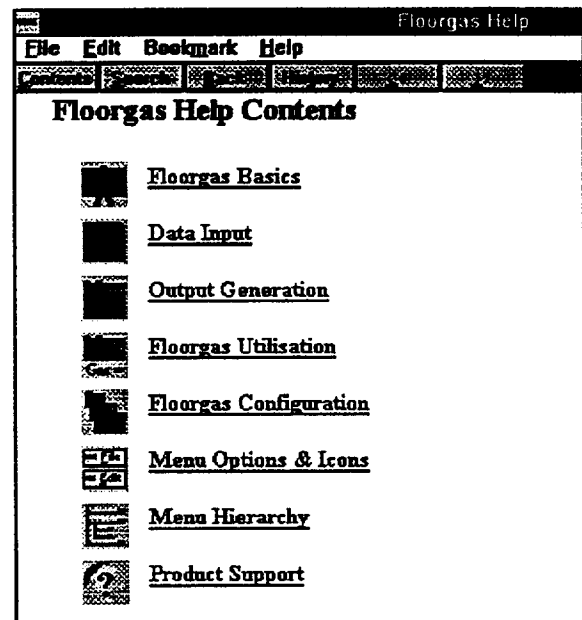
Output

- Both simulation programs produce a vertical cross-section of half of the longwall strata in graphical form, at specified distances ahead of and behind the longwall face.
- Floorgas generates a cross-section as a colour map of vertical stresses in the strata down to 100 meters below the working seam. The cross-section can be viewed from either maingate or tailgate.
- Roofgas generates a cross-section as a colour map of strata relaxation zones up to 200 meters above the working seam. The cross-section can be viewed from maingate, tailgate or both sides simultaneously.

Potential Applications

- Design of optimum parameters for cross-measure drainage holes and surface gas wells.

Online Help

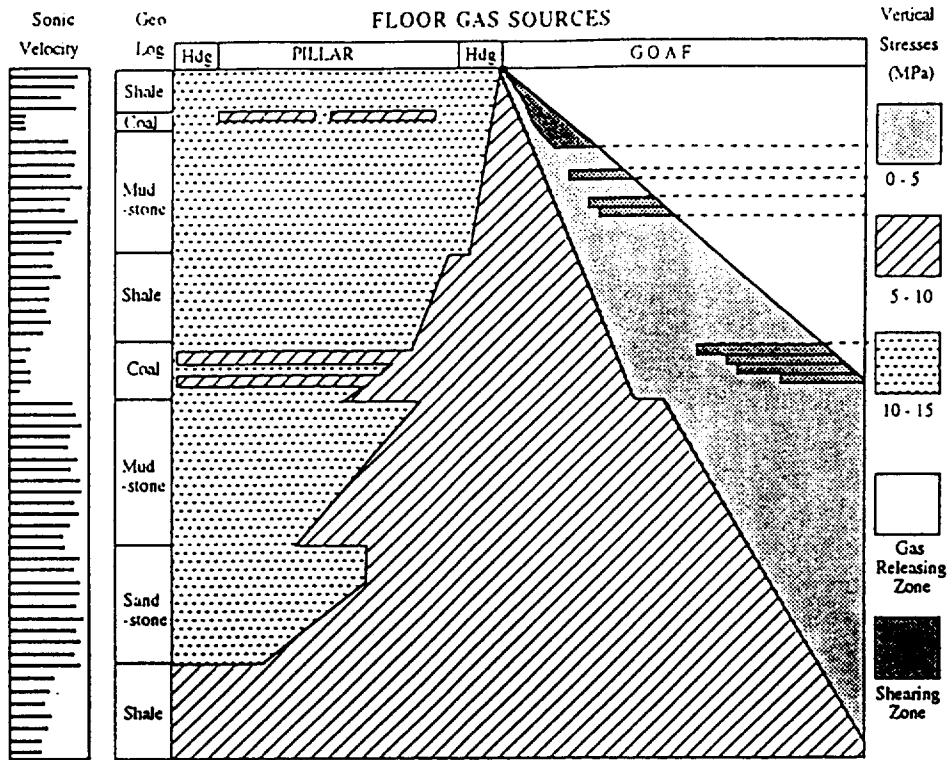


Hardware & Software

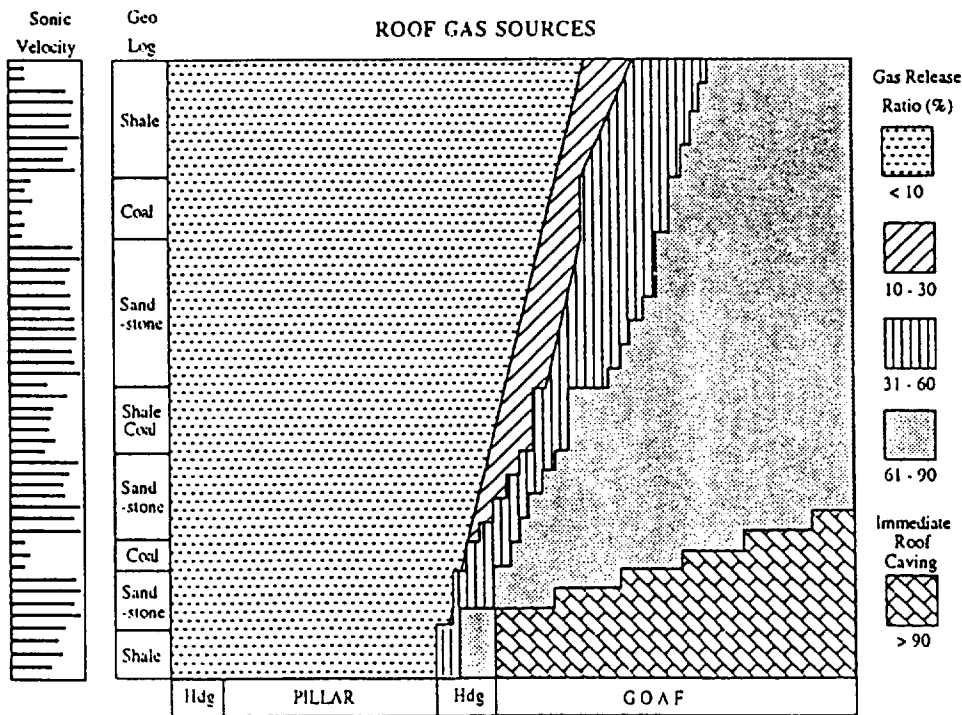
- '386 based PC with coprocessor or higher
- VGA or SVGA colour display
- 4MB of RAM (8MB recommended)
- A hard disk with 2MB of free space
- MS-DOS® and MS Windows™ version 3.1 or later

Technical Support

Lunagas Pty Limited
 PO Box 222, The Junction
 NSW 2291, Australia
 Ph: 61-49-296646 AH: 61-49-632069
 Fax: 61-49-296606



Simulated Strata Relaxation Zones in the Floor (Simplified Floorgas Output)



Gas Release Zones and Their Ratios in the Roof (Simplified Roofgas output)

APPENDIX 4

Comparisons of gas flow simulators (after King and Ertekin)

Model	Scale		Miscellaneous		Geology		Primary Pressure (Metastable System)		Secondary Pressure (Metastable System)		Gas Storage		Gas Transport		Gas Storage		Gas Transport				
	Lab	Senge	Field	Unsteady	Phases	Dual	Multi-Phase	Coal	Shale	Gas	Adsorption	Desorption	Gas	Adsorption	Desorption	Gas	Adsorption	Desorption	Gas	Adsorption	Desorption
Coome et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Jerry-1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Jerry-2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
INTERCOMP-1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Gorbachev et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Owens-Egr	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Wernippen et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Kovalev et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Kissel	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Vorobiov et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Fedorov et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Yatungum-1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
INTERCOMP 2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Chase	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Traditional Decline Curves	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Yatungum-2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Kuchuck et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Serra et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
BOM (MARRS 1-D)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
BOM (MARRS 2-D)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Smith et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
SUGAR	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
SUGAR WAT	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Collings	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Penn State-1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MARRS (1-D)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MARRS (2-D)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Penn State-2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Penn State-3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Jacks et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Bryles et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Burn et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Penn State-4	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Chen	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
COMET	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Acfel et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Burn	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Sorocet et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
COAL GAS	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Hygen	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Erskin and Sung	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Singhal and Singhal et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Carlson and Mercer	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Kamal et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Modified Black Oil	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Webber and Erskin	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Modified p/z	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Modified Material Balance	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Ed et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Sells	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Type-Curves	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Durkin et al	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Key: Y Yes
 N No
 NA Not Applicable
 NR Not Reported
 LI Langmuir Isotherm
 H.L. Henry's Law Isotherm
 EM Empirical Formulation
 EQ Equilibrium Formulation
 PSS Pseudo Steady-State Formulation
 USS Unsteady State Formulation
 IGL Ideal Gas Law
 RGL Real Gas Law

Table 1 Comparison of Physical Properties Considered by the Surveyed Models

Model	Vertical Wells				Slanted Wells	Horizontal Wells		Mine Activity		
	Unstimulated	Hydraulically Fractured				Horizontal Fractures	From Surface	From Shaft Bottom	Stationary Workings	Advancing Workings
		Vertical Fractures								
		Infinite Conductivity	Finite Conductivity							
Lindine et al	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	N	N	
Airey-1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Airey-2	N	N	N	N	N	N	N	N	N	
INTERCOMP-1	Y, M	N/R	N/R	N/R	N/R	N/R	N/R	N	N	
Gorbachev et al.	N	N	N	N	N	N	Y, S	Y	N	
Owli-Eger	N	N	N	N	N	N	N	Y	N	
Karagodin et al	Y, S	N	N	N	N	N	N	N	N	
Kovalev et al.	N	N	N	N	N	N	N	Y	Y	
Kussell	N	N	N	N	N	N	N	Y	N	
Vorazhtsov	Y, S	N	N	N	N	N	N	N	N	
Fedorov et al.	Y	N	N	N	N	N	N	Y	N	
Nottingham-1	Y, S	N/R	N/R	N/R	N/R	N/R	N/R	Y	N	
INTERCOMP-2	Y, M	Y, M	Y, M	Y	N	Y	N/R	N	N	
Chase	Y, S	N	N	N	N	N	N	N	N	
Traditional Decline Curves	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	N	N	
Nottingham-2	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	N	
Kuchuck et al	Y, S	N	N	N	N	N	N	N	N	
Serra et al	Y, S	N	N	N	N	N	N	N	N	
BOM (MINES 1-0)	Y, S	N	N	N	N	Y	N	Y	Y	
BOM (MINES 2-0)	Y, M	Y, M	N	N	N	Y	N	Y	Y	
Smith et al	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	
SUGAR	Y, S	N	N	N	N	N	N	N	N	
SUGAR MO	Y, M	N	N	N	N	N	N	N	N	
SUGARWAT	Y, M	N	N	N	N	N	N	N	N	
Collings	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Penn State-1	Y, S	Y, M	Y, M	Y	N	Y, S	Y, M	N	N	
ARRAYS (1-0)	Y, S	Y, S	N	N	N	N	N	N	N	
ARRAYS (2-0)	Y, M	Y, M	N	N	N	N	N	N	N	
Penn State-2	Y, M	N	N	N	N	N	N	N	N	
Penn State-3	Y, S	N	N	N	N	N	N	N	N	
McKee et al	Y, S	N	N	N	N	N	N	N	N	
Bayles et al	Y, S	N	N	N	N	N	N	N	N	
Bumb et al	Y, S	N	N	N	N	N	N	N	N	
Penn State-4	Y, M	Y, M	Y, M	Y, M	N	Y, M	N	Y	Y	
Chen	Y, M	N	N	N	N	N	N	Y	N	
COMET	Y, M	N/R	N/R	N/R	N/R	N/R	N/R	N	N	
McFall et al	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N	N	
Bumb	Y, S	N	N	N	N	N	N	N	N	
Spencer et al	Y	N/R	N/R	N/R	Y	Y	N/R	Y	N/R	
COALGAS	Y, M	N/R	Y, S	N/R	N/R	N/R	N/R	N	N	
Nguyen	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	
Ertekin and Sung	Y, S	N	N	N	N	N	N	N	N	
Saghafi and Saghafi et al	Y, M	N	N	N	N	N	N	Y	Y	
Carlson and Mercer	Y, S	N	N	N	N	N	N	N	N	
Kamal et al	Y, S	Y, S	Y, S	N	N	Y, S	N	N	N	
Modified Black Oil	Y, M	Y, M	Y, M	N/R	N/R	Y, M	N	Y	N	
Anarbari and Ertekin	Y, S	Y, S	Y, S	N	N	N	N	N	N	
Modified p/Z	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y, M	Y	N	
Modified Matenal Balance	Y, M	Y, M	N	N	Y, M	N	N	N	N	
Ediz et al	Y, S	Y, S	N	N	N	N/R	N/R	N	N	
Seidle	Y, S	Y, S	N	N	Y, M	N	N	N	N	
Type-Curves	Y, S	N	N	N	N	N	N	N	N	
Orucan et al	Y, M	N/R	N/R	N/R	N/R	N/R	N/R	N	N	

Key: Y Yes
N No
N/A Not Applicable
N/R Not Reported

M Multiple-Wing
S Single-Wing

Table 2 Comparison of Exploitation Methods Considered by the Surveyed Models

Model	Scalability		Machine		Coordinate System			Description Formulation			Solution Method			Validation Method		
	Lab	Single-Model	Full-Model	Euler	Rectangular	Cylindrical	Spherical	Elliptical	Empirical	Equilibrium	Non-Equilibrium		Analytical		Finite-Difference	Numerical-Element
											Pseudo Steady State	Unsteady State				
Indre et al	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	Y	N	N	N/R	
Arey-1	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	SV	N	N	CD	
Arey-2	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	SV	N	N	N/R	
INTERCOMP-1	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	SV	N	N	FD	
Opbach et al	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	N	N	N	N/R	
Oxt-Eger	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	N	N	N	AM	
Karagodin et al	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	N	N	N	FD	
Kovalev et al	N	Y	Y	Y	SI/R/1-D	SI/R/1-D	SI/R/1-D	SI/R/1-D	Y	N	N	LT	N	N	N/R	
Qsset	N	Y	Y	Y	SI/R/1-D	SI/R/1-D	SI/R/1-D	SI/R/1-D	Y	N	N	SV	N	N	N/R	
Vorotnikov et al	N	Y	Y	Y	N	N	N	N	Y	N	N	Y	N	N	N	
Fedorov et al	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	Y	N	N	O	
Noningham-1	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	Y	N	N	N/R	
Noningham-2	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	Y	N	N	FD	
Chesse	N	Y	Y	Y	F/R/2-D	F/R/2-D	F/R/2-D	F/R/2-D	Y	N	N	Y	N	N	N/R	
Noningham-2	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N/A	N/A	N/A	FD	
Kuchuck et al	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	N/R	
Serra et al	N	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	AM/NM	
BOM (MINES 1-D)	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	LT	N	N	N/R	
BOM (MINES 2-D)	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	LT	N	N	FD/AM/NM	
Smith et al	N	Y	Y	Y	F/1/1-D	F/1/1-D	F/1/1-D	F/1/1-D	Y	N	N	N	N	N	FD/AM/NM	
SUGAR	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	CD	
SUGAR MD	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	N	N	N	FD/AM/NM	
SUGARWAT	N	Y	Y	Y	F/1/2-D	F/1/2-D	F/1/2-D	F/1/2-D	Y	N	N	N	N	N	FD/AM/NM	
Colings	N	Y	Y	Y	F/R/2-D	F/R/2-D	F/R/2-D	F/R/2-D	Y	N	N	N	N	N	N/R	
Penn State-1	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	N	N	N	FD/AM/NM	
ARRAYS (1-D)	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	N	N	N	FD/AM/NM	
ARRAYS (2-D)	N	Y	Y	Y	F/R/3-D	F/R/3-D	F/R/3-D	F/R/3-D	Y	N	N	N	N	N	FD/AM/NM	
Penn State-2	N	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	FD/AM/NM	
Penn State-3	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	FD/AM/NM	
McKee et al	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	BT	N	N	FD/AM/NM	
Byles et al	N	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	AM	
Turnb et al	N	Y	Y	Y	F/R/1-D	F/R/1-D	F/R/1-D	F/R/1-D	Y	N	N	BT	N	N	AM	
Penn State-4	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD/AM/NM	
Chen	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	O	
COMET	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD	
McEal et al	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD	
Burr	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	N/R	
Spencer et al	N	Y	Y	Y	PC	PC	PC	PC	Y	N	N	N	N	N	FD/NM	
COALGAS	N	Y	Y	Y	MF/WS/PC	MF/WS/PC	MF/WS/PC	MF/WS/PC	Y	N	N	N	N	N	FD/NM	
Nguyen	N	Y	Y	Y	F/1/1-D	F/1/1-D	F/1/1-D	F/1/1-D	Y	N	N	N	N	N	FD	
Erfeld and Sung	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD	
Saghi and Seghal et al	N	Y	Y	Y	F/1/2-D	F/1/2-D	F/1/2-D	F/1/2-D	Y	N	N	N	N	N	FD	
Carlson and Mercer	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD/NM	
Kamal et al	N	Y	Y	Y	N/A	N/A	N/A	N/A	Y	N	N	N	N	N	FD/NM	
Modified Black Oil	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	NM	
Arbaci and Erfeld	N	Y	Y	Y	O-D	O-D	O-D	O-D	Y	N	N	N	N	N	AM/NM	
Modified Material Balance	N	Y	Y	Y	O-D	O-D	O-D	O-D	Y	N	N	N	N	N	NM	
Edz et al	N	Y	Y	Y	F/1/3-D	F/1/3-D	F/1/3-D	F/1/3-D	Y	N	N	N	N	N	NM	
Selde	N	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	N/R	
Type-Curves	N	Y	Y	Y	N	N	N	N	Y	N	N	N	N	N	FD/AM/NM	
Gurucan	N	Y	Y	Y	N/R	N/R	N/R	N/R	Y	N	N	N	N	N	NM	
	N	Y	Y	Y	N/R	N/R	N/R	N/R	Y	N	N	N	N	N	N/R	

Key: Y: Yes; N: No; N/A: Not Applicable; NR: Not Reported; MF: Main Frame; WS: Work Station; PC: Personal Computer; F: Finite; SI: Semi-Infinite; R: Regular; I: Irregular; SV: Separation of Variables; LT: Laplace Transform; BT: Boltzman Transform; BD: Backward Difference; MOL: Method of Lines; CN: Crank-Nicholson; IMPES: IMPES Method; NR: Newton-Raphson; SS: Simultaneous Solution; CD: Core Data; FD: Field Data; AM: Analytical Models; NM: Numerical Model

Table 3 Comparison of Mathematical Techniques Considered by the Surveyed Models

APPENDIX 5

**The commercial COALGAS coalbed methane
methane reservoir simulator**



S. A. Holditch & Associates, Inc.
PETROLEUM ENGINEERING CONSULTANTS

777 North Eldridge, Suite 710
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FAX TRANSMISSION TO: 44-(1159)-678494 (page 1 of 6)

April 2, 1996

Dr. T.X. Ren
University of Nottingham
Department of Mineral Resources Engineering
Methane Research Unit
Nottingham NG7 2RD, UK

Dear Dr. Ren:

Here is the information you requested about our coalbed methane reservoir simulator COALGAS™ and Simulation Manager™, the pre- and post-processor that makes it easy to use. To receive the software for a 30-day trial period please sign and return the accompanying "trial software license agreement" and "trial software request form".

As the accompanying price list indicates, the list price for the software outside the U.S. is currently \$18,000. With the upcoming release of the Windows version, we have announced an introductory special price of \$11,995, which will apply for the remainder of 1996. However, as a university, and with the stipulation that the software would be used only for educational purposes and specifically not for commercial work, we can arrange for the university to receive an educational license for only the cost of annual maintenance fees, which are 20% of the list price, or \$3,600 per year. If after reviewing the software you are interested in obtaining an educational license on those terms, please let me know, and I will make the arrangements.

We very much appreciate your interest in HOLDITCH engineering software. If there are any questions, please feel free to contact me at any time.

Sincerely,

A handwritten signature in black ink, appearing to read 'W. E. Powell', is written over a horizontal line.

W. E. "Bill" Powell
Corporate Marketing Manager

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- Regional migration calculations using either material balance or directional flow calculations
- Multiple relative permeability regions

SABRE, COALGAS and SHALEGAS Ver. 4.2.7 also include these features:

- an automated installation procedure that takes only minutes,
- low-cost, minimum hardware requirements, such as an IBM PC-compatible 386 or 486 computer with 4 MB of total RAM, running DOS, DOS/WINDOWS 3.x or OS/2 2.x,
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- *SIMULATION MANAGER* is included free with a license of any one of three S. A. Holditch and Associates, Inc. reservoir simulators, *SABRE*, *COALGAS* and *SHALEGAS*

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For more information about *SABRE*, *COALGAS* and *SHALEGAS*, including how to get a working trial copy of the software, contact Bill Powell at 777 N. Eldridge, Ste 710, Houston, TX 77079 USA, (713) 558-9120, FAX (713) 558-7945, info@holditch.com on the Internet.