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## SEAM GAS AND DRAINAGE

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### INTRODUCTION

The subjects of seam gas and to a lesser extent of seam gas drainage, are so involved with other aspects of coal mining practice that they are difficult to exclude from discussions of those other aspects.

Seam gas may be evident in surface exploration and there have been some occasions when outbursts appear to have occurred in holes during exploration drilling. In regard to the geological setting, the deeper, flatter deposits of higher ranks of coal are those likely to have the highest seam gas quantities and with that, the greatest need for gas dilution by ventilation, and the greatest need for seam gas drainage. Historically, pollution of mine ventilation by seam gas is a limiting feature of high productivity development, particularly at greater depths, and it is only at such depths that other gas problems including outbursts of coal and gas occur. As mining methods and practices improve, productivity increases, and the exposure of freshly cut ribs is much faster, roof and floor strata relaxation is more extensive than was the case only ten years ago. Now a single longwall face is capable of producing up to 30,000 tonnes per day, and average productions of 10,000 tonnes per day are being achieved consistently by many underground mines in the United States, Australia, and Europe. The total quantity of gas released when extracting 10,000 tonnes of coal per day could conceivably reach 250 m<sup>3</sup> of gas per minute per single longwall block and 450 m<sup>3</sup> for the total mine.

In the breaking of coal and rock, high gas content reduces the strength of coal and rock and the irregular geometry of mining openings in development or extraction of virgin coal provides higher than average stress environments which may affect permeability and may cause preferential failure. Thus, whilst more uniform geometry leads to better rock mechanics conditions and therefore better mining conditions, the same uniformity tends toward better stability from the point of view of gas evolution.

Development workings tend to induce more gas production than other workings; this includes development of bord and pillar and of longwall and shortwall retreating faces. Where seams occur close together, working seams in sequence from the top seam down will tap gas from lower seams, if close enough, and from any upper, unworked, seams. Where pillars exist in previously worked seams, these may cause stress concentrations restricting natural escape of seam gas from areas of the working seam, creating abnormally high gas conditions and proneness to gas and stress problems.

A comprehensive treatment of seam gas emissions and outbursts was given by Lama and Bodziony (1996).

### ORIGINS OF GASES IN COAL SEAMS

#### Normal metamorphic

Concurrent with the metamorphism of coal is the generation of migratory products and a definite sequence of the generation of these fluids has been postulated (Hargraves, 1962). In addition to the physical squeezing out of water in the free spaces, water (H<sub>2</sub>O) is also produced chemically during the metamorphism through lower ranks. With diminution of chemical water production, mostly carbon dioxide (CO<sub>2</sub>) is produced chemically, and in the later stages of metamorphism in bituminous and high rank bituminous and anthracitic coals, methane (CH<sub>4</sub>) is the predominant fluid produced. These stages overlap and are exemplified in Figs. 1 and 2 (Hargraves, 1962). The amount of migratory products produced during the total metamorphism is vast compared with the comparatively small proportion of such products remaining in any coal seam. Thus, although in the production of one tonne of high rank bituminous coal 0.62 tonne of H<sub>2</sub>O, 0.85 tonne equivalent to 470 m<sup>3</sup> at NTP, of CO<sub>2</sub>, and 0.17 tonne, equivalent to 260 m<sup>3</sup> at NTP, of CH<sub>4</sub> have been produced, the proportions of these found in such coal in the course of mining at depth are quite small. Moisture may be only 1% by mass of coal, compared with the total H<sub>2</sub>O produced during coalification of 62% of the mass of dry coal, CO<sub>2</sub> only 16 m<sup>3</sup>/tonne equivalent to 4 % of the CO<sub>2</sub> produced and CH<sub>4</sub>, only 10 m<sup>3</sup>/t of coal equivalent to 4 % of the total CH<sub>4</sub> produced to that time (Fig. 2). Although CH<sub>4</sub> is the usual gas encountered in black coal mining it is not the only product. The other major products H<sub>2</sub>O and CO<sub>2</sub> are usually produced earlier in the metamorphism and have been largely flushed away by the subsequent production of CH<sub>4</sub>. Had the

metamorphism proceeded further, to the stage of anthracite, the total production of migratory products would be even greater, especially of  $\text{CH}_4$ , as shown in Fig. 1.

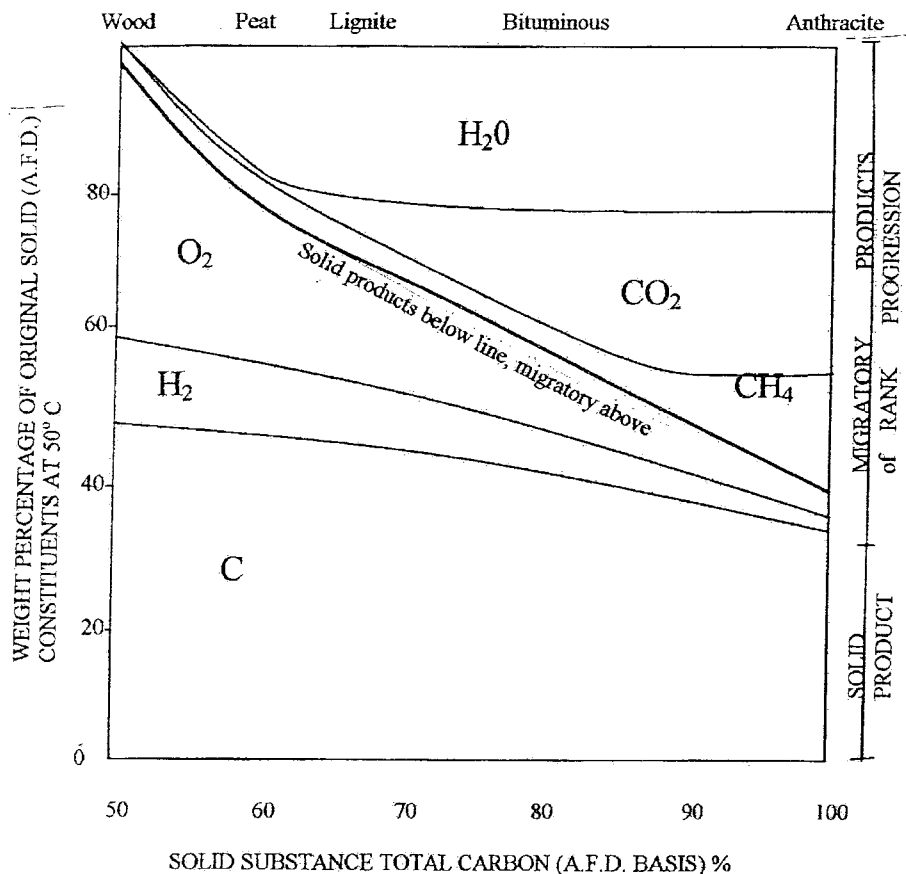


Figure 1. Production of migratory products by process of coalification

In the above dynamochemical metamorphism of coal,  $\text{CH}_4$  may not be the sole hydrocarbon produced. But in the Australasian context, higher hydrocarbons in seam gas are not often reported, are only in small proportions, and are usually only ethane ( $\text{C}_2\text{H}_6$ ). In some overseas coals significant proportions of higher hydrocarbons are found in seam gases (Rice, 1917). Perhaps the most notable example of  $\text{C}_2\text{H}_6$  in Australasian coal mining is in the gases of the Bulgo Sandstones overlying the coal measures of the Illawarra area. The Bulgo gases sometimes invade extraction workings in the Bulli Seam.

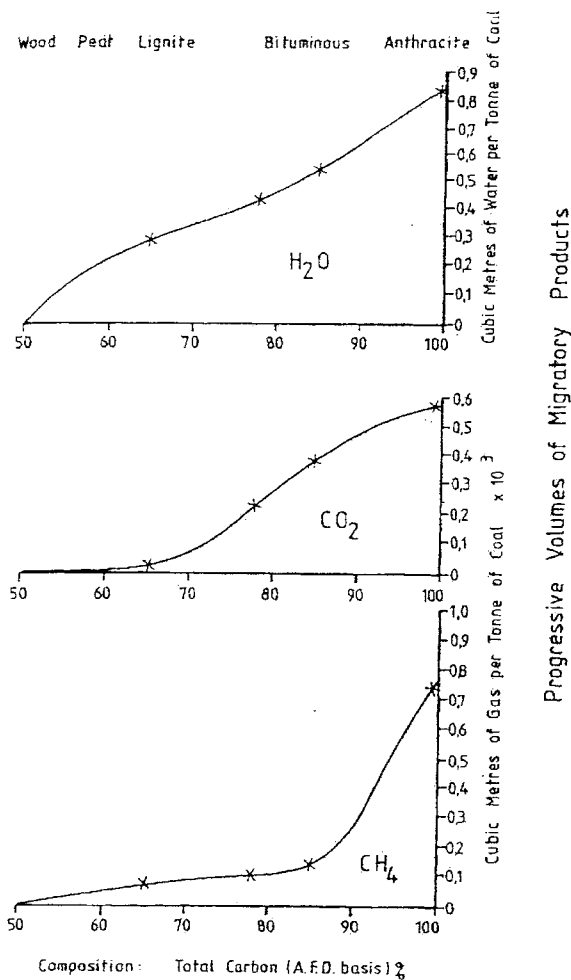


Figure 2. Migratory products production per tonne of coal at various ranks during coalification

Hargraves (1962), in Fig. 1, presumed that the ash constituents of the original vegetable matter have no significant effect on seam gas composition and that any protein constituents disappear early in the eventual metamorphism to anthracite. The presumption in regard to protein may not be completely valid as some proportion of nitrogen (N<sub>2</sub>) is always present in seam gas. Filipowski (2002) showed that nitrogen content of the seam gas increases proportionally to drainage of methane and carbon dioxide. Sometimes other constituents Argon (Ar), Hydrogen (H<sub>2</sub>), Helium (He), and Hydrogen sulphide (H<sub>2</sub>S) are also present. Oxygen (O<sub>2</sub>) is not a constituent of seam gas. The metamorphic fluids which have disappeared have been driven out of the coal usually towards the land surface by their continuing generation in the metamorphic process as part of an equilibrium condition between the escape of the fluids in the permeation paths to lower pressures through paths such as joints, bedding planes and faults.

Gas is stored in the coal seam primarily by sorption into the coal (Gray, 2003). This typically accounts for 98% of the gas within a coal seam. Gas is stored in the pores or cleat space either in free form or in solution.

#### Other sources of seam gas

In the course of igneous intrusion other gases may be introduced into strata including any coal seams either at the site of intrusion of the seams by contact metamorphism or from more remote locations. Thus in addition to the normal (dynamochemical) metamorphism of coals with depth of burial and time and the concurrent production of the migratory products shown in Fig. 1, the effect of contact metamorphism by intrusion into the coal or adjoining strata is to introduce pneumatolytic gases into the seam gas, perhaps almost completely overwhelming or displacing the original CH<sub>4</sub>, (Hargraves, 1962). The prime example of such introduction of gas from outside the seam, is CO<sub>2</sub> which because of its greater affinity for coal than is the case for CH<sub>4</sub>, it displaces the normal metamorphic CH<sub>4</sub>, until such time as CH<sub>4</sub> derived from later normal metamorphism can drive the CO<sub>2</sub> out again. Smith and Gould (1980) have shown that the isotopic composition of the carbon (C) in

the CO<sub>2</sub> differs from that of the C in the CH<sub>4</sub> and the coal. It more closely resembles that of C in the CO<sub>2</sub> of pneumatolytic gas. Some H<sub>2</sub>S may be of similar pneumatolytic source. Seam gas comprised mainly of CO<sub>2</sub> is termed blackdamp and is heavier than air. Hargraves, (1993) postulates that the higher proportions of N<sub>2</sub> sometimes found in seam gases could also be of pneumatolytic origin. If occurring with minimal CO<sub>2</sub> in the seam gas, the preferential removal of the more chemically reactive CO<sub>2</sub> component between pneumatolytic source and the coal seam is also postulated.

Another source of seam gas is the oxidation of coal and carbonaceous material by air dissolved in rain and surface waters permeating down through strata towards the water table. In shallow levels, generally above the water table, a light extinctive seam gas, rich in N<sub>2</sub> and with some CO<sub>2</sub> and lesser CH<sub>4</sub> may occur. This is generally in small amounts in the coal and derives from oxidation with production of CO<sub>2</sub> with remnant N<sub>2</sub> (Hargraves, 1962) and is also termed blackdamp. This light blackdamp forms a shallow level extinctive seam gas with only limited flammable gas content.

### Other gases

As above, air may contribute to shallow level seam gas, and not only does emitting seam gas mix with air, but it is difficult to sample and analyse seam gas to the absolute exclusion of air. It is therefore pertinent while dealing with seam gases to mention air and some other important contaminants of air. Some other gases found in coal mines are listed by the Joint Coal Board (1981).

Air is drawn, rarely forced, into mines as a source of ventilation. Safeguards are taken to ensure that uncontaminated surface air is used. The composition of dry air, by volume, is essentially

O <sub>2</sub>	20.95%
N <sub>2</sub>	78.08%
Ar	0.93%
CO <sub>2</sub>	0.03%

Other inerts such as Neon (Ne), Helium (He), Krypton (Kr), and gases such as CH<sub>4</sub>, Hydrogen (H<sub>2</sub>) and Nitrous Oxide (N<sub>2</sub>O), make up the remainder. Additionally, depending on history of exposure to water or moist materials and on temperature, mine air may contain up to 3 % H<sub>2</sub>O as water vapour.

O<sub>2</sub> present in air oxidises the coal to produce CO<sub>2</sub>. Also O<sub>2</sub> is generated with H<sub>2</sub> in the process of battery charging.

Ozone (O<sub>3</sub>) may be found in the vicinity of electrical equipment.

N<sub>2</sub> is a normal, usually minor constituent of deep seam gas and a major constituent of some shallow level seam gases.

Sulphur Dioxide (SO<sub>2</sub>) is not a seam gas but occurs where Sulphur is a significant component of coal, and other combustibles in mines, subject to spontaneous and normal combustion.

Carbon Monoxide (CO) is not regarded as a seam gas. It occurs during spontaneous and other combustion, such as diesel engine exhaust, through incomplete oxidation of carbonaceous materials.

CO<sub>2</sub>, as well as being an important seam gas in Australia, derives from combustion of carbonaceous materials, spontaneous combustion of coal, diesel engine exhaust and combustion generally, from attack of carbonates by acid waters, and from exhalations of animals.

Aldehydes are not seam gases but are produced in diesel engine exhausts.

H<sub>2</sub>S occurs as a seam gas usually in small quantities and usually at shallow levels especially in high sulphur coals. It may possibly be of igneous metamorphic origin. It may be formed by the action of acid waters on pyrite in coal and strata.

Oxides of Nitrogen are not seam gases but are formed particularly in diesel engine exhausts and in fumes from use of explosives.

Water vapour is a normal constituent of air and is also a normal product of combustion of hydrocarbons such as in diesel exhaust and in spontaneous combustion of coal. Seam gas will have a content of water vapour depending on the moisture of coal, temperature and pressure.

Apart from being a minor inert constituent of normal air He is also found in small proportions in some seam gases such as in the Illawarra area of N.S.W.

Of this list of other coal mine gases, only CO<sub>2</sub>, N<sub>2</sub>, H<sub>2</sub>S and perhaps He are considered important as seam gases.

### PROPERTIES OF COAL MINE GASES

All of the properties of gases are important in coal mining. Although the flammability of CH<sub>4</sub> is given great attention, the density of gases relative to air which determines their tendency to collect at roof or floor and consequently their resistance to mixing with air is also of great importance. Mixed gases will not segregate due to density differences, so unmixing is not a possibility. Rather, mixed gases mix with each other in the same proportions as their mixtures although at "interfaces" between gases a gradation of composition exists from one to the other of dimensions dependent upon relative velocity and turbulence. The viscosity of gases increases with temperature. As a first approximation, the properties of mixed gases can be taken as the proportionate properties of the components. Some gases may be detectable by smell. Whilst H<sub>2</sub>S for instance, is detectable in low concentrations by smell, higher concentrations may deaden the sense of smell. Specific heat of component gases is important not so much because of sensations produced on the skin as its influence on whether mixtures including flammable gas of a particular calorific value lie within the explosive range. Some gases are poisons, others may only be air diluents causing reduction of oxygen content. Temperature and humidity of atmospheres are important as monitors of comfort and higher temperatures broaden explosive limits of flammable gases.

Notwithstanding these many differences in properties, all gases and gas mixtures in mine openings follow reasonably closely the gas laws of Boyle and Charles.

Table 1 gives important properties of coal mine gases. Unless gases have physiological effects their maximum concentrations allowable in air are at the point where oxygen deficiency reaches the statutory limit. In cases of CH<sub>4</sub> and C<sub>2</sub>H<sub>6</sub> the minimum threshold of explosibility occurs at lower concentrations, before the statutory maximum limit for O<sub>2</sub> deficiency is reached. Further, the factor of safety from explosion incorporated in the statutory maximum limits of CH<sub>4</sub> and other flammable gases, well below lower limits of explosibility, reduces even further any risk of O<sub>2</sub> deficiency. For further gas properties reference is made to the publication of the Joint Coal Board, (1981).

Table 1  
*Gas properties significant in coal mine samples*

Gas	Mol. Wt	Mol. Dia. A	Viscosity micro-poise at 0°C	Density rel. to air	Condensation point C°	Solubility in water g/100ml	Any physiological effect	Toxicity	Odour	Approx. max. conc. in air for prolonged exposures %	Lower explosive limit in air %
Air	28.30	3.62	94 at 30	1	-	29.18 at 0°C	No	Nil	No	-	
O <sub>2</sub>	32.00	2.92	198 at 0	1.11	-183.0	4.89 at 0°C	Yes	Nil?	No?	25?	Non-Combustible
CO <sub>2</sub>	44.00	3.23	137 at 0	1.52	-78.5	171.3	Yes	Yes	Yes	0.5	n.c.
CH <sub>4</sub>	15.03	2.30	108.9/ 20	0.55	-161.5	9 at 20°C	No	No?	No	9**	5.4
C <sub>2</sub> H <sub>6</sub>	30.07	4.42	90.9/ 20	1.045	-88.3	4.7 at 20°C	No?	No?	Yes?	9*?*	3.2
CO	28.00	3.12	166 / 0	0.975	-190	3.5 at 20°C	Yes	V.High	No	0.01	16.3
H <sub>2</sub> S	34.09	2.69	116 / 0	1.19	-61.80	437 at 0°C	Yes	V.High	Yes	0.002	4
N <sub>2</sub>	28.02	3.16	170.7/ 10.9	0.974	-195.8	2.33 at 0°C	No	No	No	9*	n.c.
NO <sub>2</sub>	46.01	2.38	-	1.60	21.15	Soluble and decomposes	Yes	V.High	yes	0.005	n.c.
H <sub>2</sub>	2.016	2.34	83.5 / 0	0.07	-252.8	2.14 at 0°C	No?	No?	No	9*	6.1
SO <sub>2</sub>	64.07	2.86	1.2 / 10	2.23	-10.0	22.8	Yes	V.High	Yes	0.0005	n.c.
H <sub>2</sub> O	18.0	1.92	1.798 / 0	0.63	100	-	Yes	No	No	3.2+	n.c.

\* Approximate concentration equivalent to 19%O<sub>2</sub>

+Equivalent to 28° saturated air

### AREAL DISTRIBUTION

For reasons concerned with the different origins of component seam gases in any one coal seam or in any one series of coal measures the composition of the seam gas may not be constant throughout. Changes in composition of seam gas may occur over short distances.

Changes in seam gas composition are in the main, related to

1. depth below surface, especially relative to the watertable,
2. the occurrence of faults or other fractures which are channels of transfer of gas from place to place and horizon to horizon,
3. the incidence of igneous intrusion into the seam and/or strata responsible for the introduction of pneumatolytic gases, particularly CO<sub>2</sub> into the seam, and
4. the time which has elapsed since any particular igneous event and to the degree of metamorphism which has taken place in the seam since that event.

Thus in the two major coal basins in Australia, the Sydney and Bowen Basins, both of which have experienced significant amounts of igneous activity, the extent of introduction of CO<sub>2</sub> is quite great and significant on a world basis.

Regarding New Zealand coals, in general the mining depths appear to be too shallow at a maximum depth of around 270 m, and the ranks too low for the coals to be as highly gassy as experienced in some eastern Australian mines. However, gas contents of 9 to 10 m<sup>3</sup>/tonne were reported at Mount Davy Colliery which experienced 21 outbursts (Packham et al, 2003). Whilst there is extensive information on New Zealand's coal resources, there has been no comprehensive published assessment of New Zealand's coal seam gas resources. The majority of New Zealand's coal resources in which coal seam gas could be found are in the Waikato, Westland, Taranaki, Otago and Southland coal fields. In an attempt to predict where and when outbursts may occur, Beamish et al (1996, 1998) studied the methane adsorption mechanisms and capacities of coal seams in the Greymouth Coalfield. It was found that the methane sorption capacity decreased as rank increased, with a minimum occurring in medium volatile bituminous coals. Sorption capacity was found to decrease with increasing moisture content, as water and methane compete for sorption sites on the internal surfaces of coal pores. Coals with discrete vitrain bands had higher sorption capacities than non-banded coals. New Zealand coals were found to have lower sorption capacities than similarly ranked Australian coals, due to higher amounts of volatile compounds in New Zealand coals and a resultant lower microporosity. Graham (1953) indicated much higher permeability of the low rank sub-bituminous coals than the higher rank Greymouth coals as might be expected. The CH<sub>4</sub> content of seams gases of some New Zealand coals is indicated by the gas explosions which have occurred in the past in the Otago, Greymouth, Collingwood and Waikato (Huntly) coalfields. The possibility of CO<sub>2</sub> of contact metamorphic origin is reduced, but accepted in some instances, such as in the Blackball and Benhar mines where CO<sub>2</sub> has been identified bubbling out of strata, (Graham, 1953). Only nominal N<sub>2</sub> occurs in the typical heavy blackdamps. But clearly the usual seam gas is CH<sub>4</sub> and even deeper mines, such as at Huntly at 270 m deep, after face advance it can be heard hissing from freshly exposed coal, a commonplace occurrence in deep mines in Eastern Australia.

## SEAM GAS

### Sampling

Sampling may have a number of purposes but most are for analysis, either analysis on the spot or analysis in some remote laboratory, explained as follows.

1. For analysis on the spot, samples are immediately tested in apparatus with a local analytical facility, such as a portable apparatus with colorimetric tubes.
2. For remote analysis samples are either pumped continuously or transported in discrete batches in containers to a laboratory usually situated on the surface.

Most gases are relatively inert for short periods of storage in appropriate containers and can be transported satisfactorily. However other gases may chemically attack or sorb in the material of the sampling vessel. Thus, any container which has oxidizable materials will tend to absorb some of the O<sub>2</sub> of any air in the sample. CO<sub>2</sub> in a sample may preferentially dissolve in moisture within the sampling container or may attack metal of the sampling container. CH<sub>4</sub> may dissolve in the grease (if used) in the cock of the sample container. H<sub>2</sub>S may attack metals of the container. Any rubber components in the container may be impermeable to some gases and yet permeable to others, so that some gases will be preferentially diffused through the rubber and lost. Other gases may migrate into the sample from the atmosphere. Hence the choice of sampling container is most important.

For air sampling, the sampling point must take account of any tendency of gases of different specific gravity, before mixing, to accumulate gravitationally. For an air stream in which regular sampling is done, some sort of hurdle may be advisable immediately before the sampling point, to ensure if layering is taking place that the turbulence caused by the hurdle is sufficient to completely mix any separate gases and ensure the sample taken is representative of the whole airstream. Seam gases may be sampled almost to the exclusion of air by sampling directly from the coal such as by drilling a hole in a coal seam and withdrawing the gas through a small seal. In such an instance, if moisture is present in the seam then a water trap may be desirable to prevent water entering with the sample. As gas samples and some air samples may be saturated with moisture, reduction in temperature in storage may lead to condensation of moisture within the sample container.

There are various sample containers

1. self-aspirated types such as a bottle of water, inverted to discharge the water and draw in the atmosphere and scaled evacuated flasks which draw in the atmosphere when the seal is broken until resealed. Water bottle types are outdated because of the differential solubility of various gases,
2. aspirated types such as a double cock Pyrex tube, flushed by many times its volume to effectively replace its volume by true sample,
3. inflated, such as rubber bladders or currently gas barrier plastic "wine bags" which consist of aluminium foil, coated on both sides by polythene plastic and which are evacuated before use and filled at atmospheric pressure, or not much above, by a simple pump,
4. pumped, such as Schraeder-valved non corrosive metal cylinders hand pumped, usually in the atmosphere to be sampled but sometimes pumped from sources below atmospheric pressure for storage at or above atmospheric, such as suction pipelines, and positively flushed or filled double cock tubes or evacuated rubber or gas barrier plastic bags from sources of gas at over atmospheric pressure such as sealed drillholes into virgin coal and gas pipelines.

### **Analysis**

There are two methods of analysis of air and gases, chemical, presently not much used, and by some type of transducer arrangement. In the chemical analysis, gas components are successively taken up in particular liquids and contractions are measured by atmospheric pressure. The sequence of removal of gases from air is firstly moisture, then CO<sub>2</sub> followed by O<sub>2</sub>. After adding a known quantity of O<sub>2</sub> the ignition of any flammables is conducted. The contraction due to condensation of the resultant moisture and then the absorption of the resultant CO<sub>2</sub> are measured. In the case of air with minimal amounts of flammable gas the ignition may take place prior to the removal of the remaining oxygen.

All other types of analysis are done by some sort of cell employing a principle which provides a separate response from different component gases, such as thermal conductivity, infra-red

absorption and ionisation. It is normal in such apparatus to employ not a continuous sample but a small amount of sample in a carrier gas of known composition and of known reactivity passing at a known rate through a partitioning (chromatographic) column. By dividing the sample into separate discrete slugs of individual gases before passing them in sequence through the detector cell, identification is made by time and sequence and quantification. The analysis of gases and airs from collieries is covered in detail by Barnes, 1983.

## **PREDICTIONS OF GASSINESS**

### **Gas Occurrences**

#### *Seam Gas Emission*

The measured values of methane content in coal beds are up to 25 m<sup>3</sup> per tonne of coal. A methane content of > 9m<sup>3</sup> per tonne or higher is considered as being "very gassy" in the context of underground mining. During the mining process, methane is released from coal seams and the surrounding gas-bearing strata, mixing with the mine ventilation air. Inadequate air quantities in the ventilation system may cause dangerous gas accumulations in the mines and may lead to gas explosions under certain circumstances and conditions. It is generally found that the quantity of gas released from all coal seams and gas bearing strata, per tonne of coal produced, is about six to nine times the measured gas content per tonne of in situ gas in the worked coal seam. This discrepancy is attributed to the emission of gas from the active adjacent strata, goaf areas, and previously formed faces and ribs; it is also relative over time. The wide range of gas emission in the underground workings can be linked to the different stages in the life of a coal mine, and depends on the type of operational and extraction activities and methods.

#### *Specific Gas Emission (SGE)*

SGE is the quantity of gas which is expected to be released to the underground workings from all gas sources (working seam, roof and floor) as a result of mining activities and related to the extraction of one tonne of mined coal. Various coefficients are characteristic of different local conditions and include the degree of gas emissions from the floor and roof gas sources, the contribution of working seam gassiness and the influence of gas drainage systems on total gassiness.

#### *Absolute Gassiness*

Absolute gassiness is the predicted or measured quantity of gas expressed in cubic metres or litres and emitted to the underground workings, and captured by recovery systems, during a defined period of time (seconds through years). Absolute gassiness is a true reflection of underground gassiness conditions in terms of total quantity of gas released from the strata during a specific period of time. Total measured gassiness is a combination of gas emission rate into the underground workings and underground/surface gas drainage system. Absolute gassiness is the only condition, which can be utilised as an expression of a colliery's gassiness, in determining the appropriate ventilation requirements necessary to dilute gas emitted into the ventilation system to the statutory limits. Absolute gassiness can also be related to periods of longwall extraction/development drivage in terms of face location or time.

#### *Relative Gassiness*

Relative gassiness is the predicted and/or measured quantity of gas expressed in cubic metres (or litres), and related to the associated coal production levels achieved during various periods of time. Relative gassiness reflects the relationship of absolute gassiness with coal production levels over a specific period of time. Relative gassiness must always be qualified when expressed with its associated period of time and in terms of mining activities and areas of influence (for example, longwall or pillar extraction, development drivage, colliery district or



whole mine). Relative gassiness can only be utilised as an expression of underground gassiness if consistent mining conditions and coal production levels are maintained over significant time periods. The period of time for longwall extraction with caving has been found to be a minimum of ten days to two weeks. The range of relative gassiness variation diminishes as time periods are extended. If coal production levels are consistent for two weeks or more, then relative gassiness is similar to the SGE calculated for these conditions. The high range of variations suggests that development-relevant gassiness should not be expressed relative to time but to advance rate.

### Gas emission in relation to coal production, longwall geometry and gas conditions

The highest gas emission can be expected when coal is extracted and, consequently, floor and roof strata are relaxed. The degree to which degassing takes place depends on the particular relaxation behaviour of the strata, the physical properties of the system "floor-seam-roof", the geometry of the longwall panel, the volume and proximity to gas sources, and configuration of the relaxed zone. Practical experience has shown that gas emission and associated tonnages of extracted coal are specifically related to daily and weekly coal production levels and to the time factor. This relationship has been expressed by the empirical formula:

$$Q = a * \sqrt{CP} + b$$

where: Q - total methane emission rate expressed in litres CH<sub>4</sub> per second  
 CP - daily coal production rate expressed in tonnes  
 a and b - empirical coefficients related to weekly coal production levels and number of working days per week (time) as determined for high productivity longwall mining systems.

There are substantial differences in gassiness associated with coal production level, longwall geometry and gassy conditions. Variations in absolute gassiness exist for different in situ gas contents and/or SGE as well as coal production levels, as shown in Figure 3.

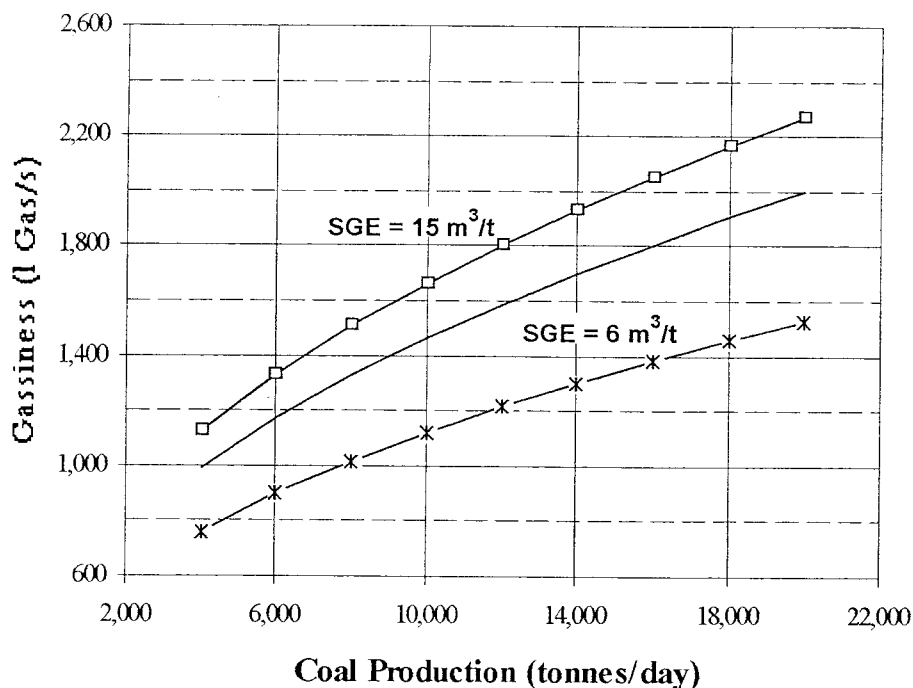


Figure 3. Gas make trends (litres gas per second) for various daily coal production levels and SGE

## Active and inactive gas resources

### General

Gas emissions into underground workings and gas capture by underground and/or surface drainage methods depend upon two basic factors: strata gas resource capacities, and the type of mining activities associated with strata relaxation and gas release ratios (Lunarzewski,1994). The gas resources for specific mine leases and purposes are, in most cases, calculated as geological virgin or total insitu gas sources. The sorbed and free gases from these sources are never wholly emitted and/or captured during mining activities or even during the life span of the colliery. The gas release and capture ratios versus coal production levels and periods of time, depend on coal-gas properties, the method of mining, and the characteristics of strata relaxation zones. A typical mine lease usually comprises various underground workings and mining activities such as first workings, coal extraction workings, pre-drainage headings and/or holes, old goaf areas and unworked areas. These are associated with various strata relaxation zones in the roof and the floor of the working coal seam and with differing gas release ratios. For planning purposes, the magnitude of gas emission, capture and utilisation can be assessed using appropriate gassiness prediction methods which calculate the quantity of gas to be released to the underground workings and/or captured by various gas recovery methods.

### Definition of gas resources in relation to mining activities

Gas sources within the strata contain the entire insitu quantities of adsorbed and “free” gas, however, only part of the gas can be released either to the underground workings or to existing gas capture systems. Appropriate strata permeability (relaxation) and gas migration networks must be in place to release and transport the gas toward the capture system and/or to the underground workings. The gas release rate and efficiency, as well as permeability, depend on the type of mining activities, the boundaries and extent of strata relaxation zones, lead time for effective drainage and differential pressure between insitu gas pressure, and ventilation and/or gas capture pressure (suction) conditions.

### In situ gas resources

Calculation of in situ gas resources for mining safety and gas utilisation purposes is based on the dimensions of the coal seams and gas bearing rocks, insitu gas content, insitu gas pressure, rock porosity, and local geology. The accuracy of calculations varies within a wide range and depends substantially on the number and credibility of input data. From a technical and mine planning point of view, there are three basic categories for insitu gas resources calculations: entire insitu gas resources, resources capable of gas release under mine and gas recovery pressure conditions, and remaining (residual) gas resources. Figure 4 outlines the logical steps of gas emission and gas capture from active resources and their application for coal mine methane capture and utilisation.

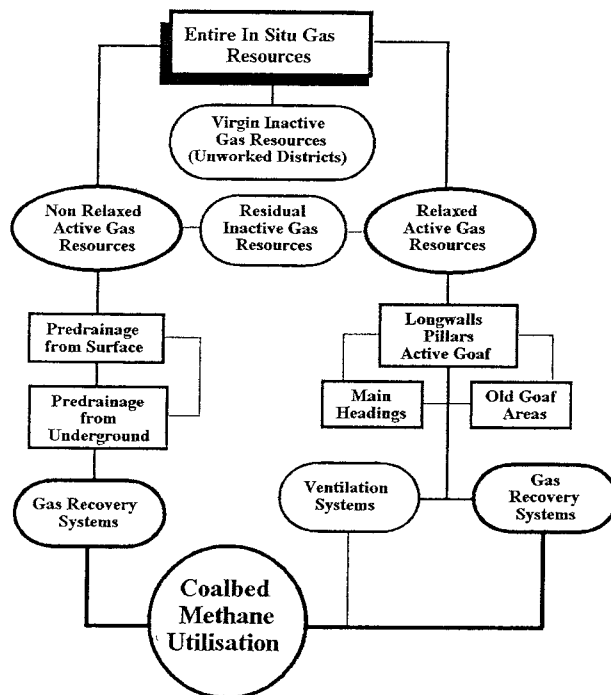


Figure 4. Logical steps of gas emission and gas capture from active resources

### Active gas resources

The quantity of gas, which can be released from the working seam and adjacent gas sources in the roof and floor, depends on local gas, geological and mining conditions. Strata gas can be released and captured from existing gas sources when mining activities take place and/or when a drilling program has been introduced, either from the surface or from the underground workings. Strata gas can be captured and/or released from two existing active gas resources:

- (a) non-relaxed active gas resources: gas recovery from sources with sufficient permeability and an ability to be pre-drained under virgin conditions, and
- (b) relaxed active gas resources: gas release and/or recovery from the strata relaxed by mining activities and/or artificial stimulation such as hydraulic fracturing.

Gas capture efficiencies from non-relaxed active gas resources depend on the nature of the gas sources, geology and system of gas recovery. In most cases this requires an expensive investment over a long period of time. The most important factors are coal seam and/or strata permeability as well as lead times. Gas capture efficiencies from relaxed active gas resources depend on the type of mining activities and the shapes and boundaries of strata relaxation/gas discharge zones. The most important factors are local geological and mining conditions and the system of gas recovery. The following classifications are used: first workings such as main headings, coal extraction workings such as longwall, room and pillar, active goaf, pre-drainage headings, in-seam pre-drainage holes, old goaf areas, and unworked districts. For each mining activity, empirical coefficients have been developed and used for active gas resources calculation. Gas emissions to the first workings are characterised by a radius of strata relaxation around the roadways. Gas release to the coal extraction workings, such as longwalls, is calculated using local strata relaxation coefficients in relation to gas source characteristics and distances from the working seam. Goaf gassiness, however, depends on lead time, remaining insitu pressure conditions, and the nature of the surrounding gas sources. The contribution of active gas resources varies widely and depends on the type of mining activities.

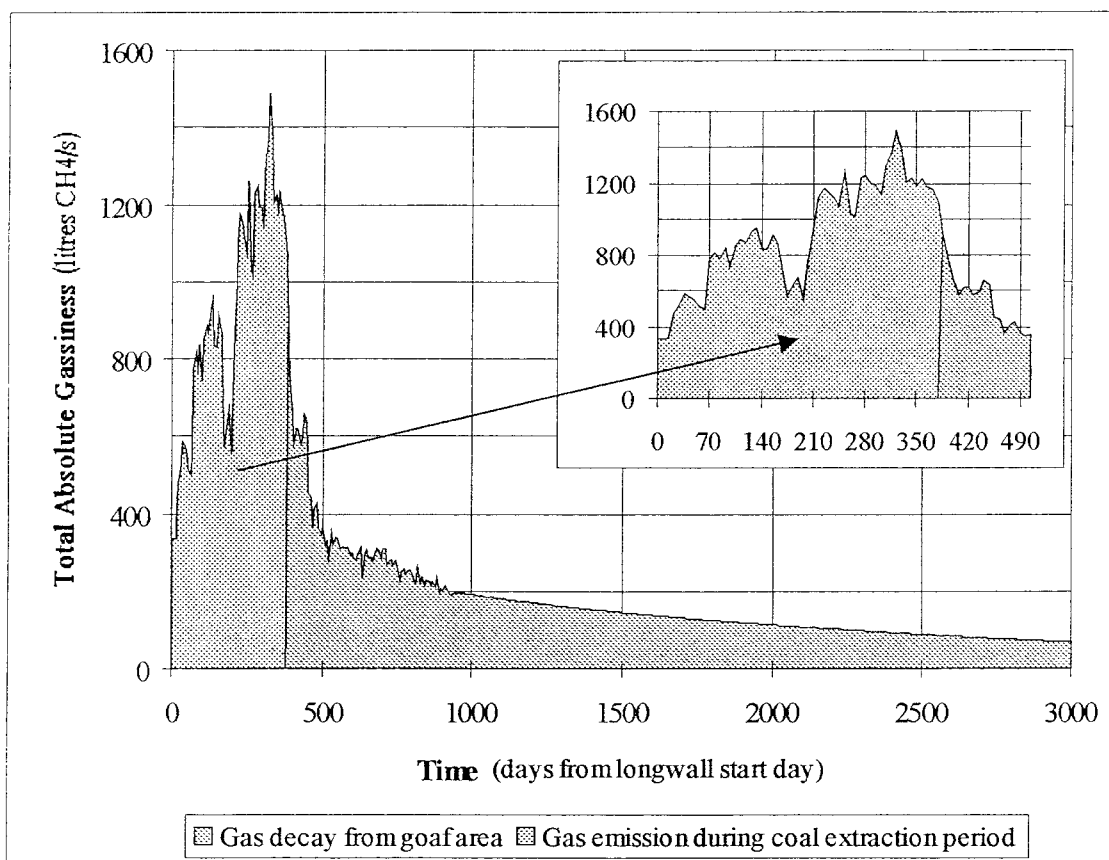


Figure 5. Example of gas production (absolute gassiness) from a typical longwall

#### *Quantities and contributions of gas emitted and/or captured following coal extraction*

Lead time for gas release and/or capture from abandoned or sealed areas is a function of the magnitude of gas emission during coal production periods and gas make decay in goaf areas after coal production has ceased. Both the contribution of the gas quantities and the shape of the decay curve represent an empirical mathematical relationship which depends on gas, mining, and geological conditions as well as on a time factor. Figure 5 shows an example of absolute gassiness (gas make) changes during both coal production and goaf area gas make decay periods for a 200m longwall width, an average coal production level of 8,000 tonnes per day, working seam in situ gas content of 5 to 7 m<sup>3</sup> CH<sub>4</sub> per tonne, and an SGE of 20 m<sup>3</sup> CH<sub>4</sub> per tonne of mined coal.

#### *Active and inactive gas resource calculations*

Inactive gas resource magnitudes, both virgin and residual, can be calculated using various empirical and/or hypothetical methods and selected technical assumptions for the mine site construction, development drivage and coal production periods, respectively. Active and inactive residual gas resources, above and below the working seam, can be calculated using an appropriate method of gassiness prediction which identifies strata relaxation and gas release zones and their boundaries in both vertical and horizontal planes. For some colliery leases, only 10 to 20% of the original gas resources become active due to mining activities.

### **Longwall gassiness prediction**

#### *Definitions of gassiness prediction*

The primary objective for the prediction of the level of gassiness is to determine the maximum gassiness which will be attained during longwall extraction. Most of the prediction methods adopt the same basic parameters, however, the accuracy of the final results depends substantially on specific factors and coefficients established for local geological and mining conditions (Lunarzewski et al., 1983). The results of comparative tests, using various methods, have shown that large errors are possible in all methods tested within a range of -64% to +105% (Dunmore, 1979), however, for a high coal production level these errors have been found, in some stages of longwall extraction to be up to 200%. Underground mining activities, mainly longwall extraction, disturb the adjacent strata and consequently upset the equilibrium of the gas sorbed and affect some coal/rock properties such as permeability and "connectivity". Relaxation and the resultant fracturing of the strata open flow paths for the gas to migrate into the underground workings. Only desorbed and free gas can migrate into the mine workings. However, in non-coaly material the contribution of free gas depends substantially on gas bearing rock properties (mainly porosity and "connectivity"), degree of strata relaxation, and existing differential pressure between in situ gas pressure and mine ventilation system pressure. Relaxation of the roof and floor rocks and generated "connectivity" allow gas to flow from all gas sources to the underground workings including goaf areas. Intensity of gas flow depends on the degree of strata relaxation and substantially on the type and strength of rocks in the adjacent strata. For this reason accurate borehole logs of coal seams and rocks and a good stratigraphic model are essential to the application of any gassiness prediction method, or model of gas emission to the underground workings. A reasonably accurate prediction of gassiness can be made, using internationally recognised methods, when mining in situations of reasonably homogeneous stratigraphy, provided sufficient geological and gassiness data are available. However, non-predicted and unexpected changes in the level of gassiness can occur when mining in areas of significant changes in geological conditions. Mathematical modeling of the roof and floor deformation on mining (Lunarzewski et al., 1995) is used to predict the strata behaviour and unexpected high gas emissions from strata gas sources in relation to local lithology and coal/rock properties.

Figure 6 shows a flow chart for longwall extraction using a modern gassiness prediction model, and coefficients developed for various geological and mining conditions. The empirical relationships used in the prediction models are: gas release ratio coefficients (degree of gas emission) - "Floorgas" and "Roofgas" simulation program outputs, face emission coefficient, and coal output emission coefficients (empirical relationship between SGE, time, and daily and weekly coal production levels). The coefficients have been empirically developed for highly productive individual longwall systems and are unique for longwall face widths of 100 to 300m.

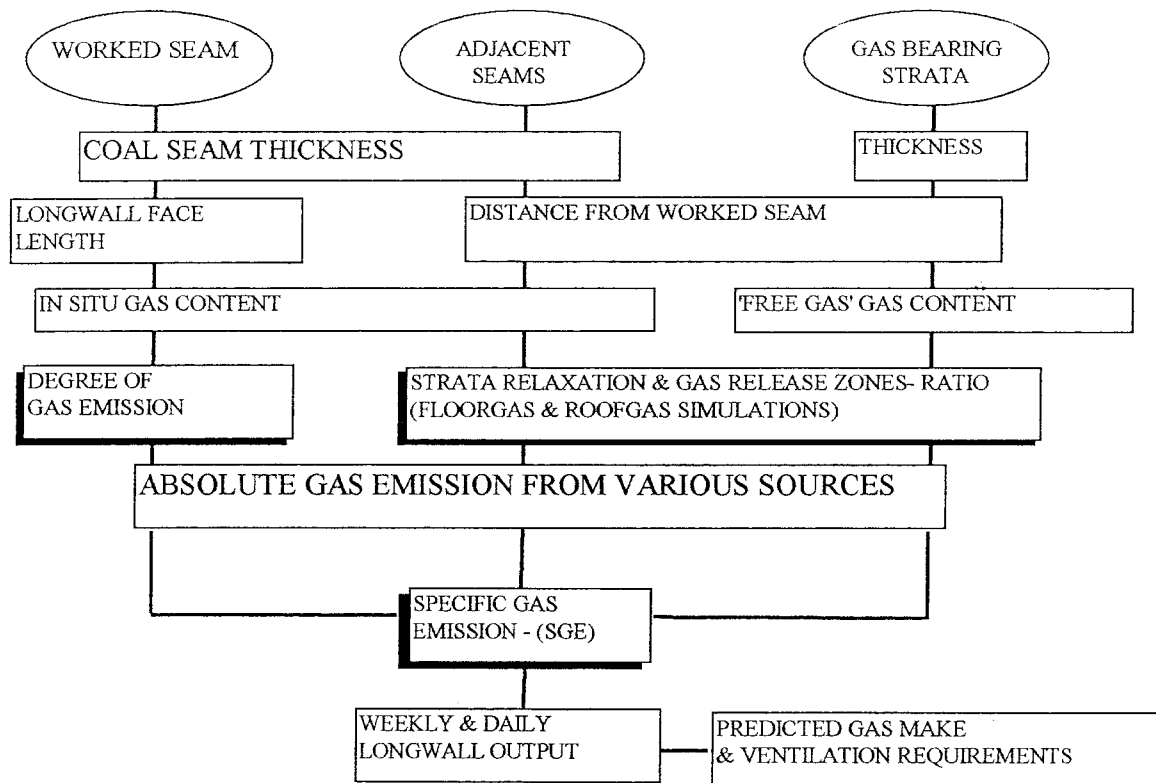


Figure 6. Flow chart for longwall extraction gassiness prediction

#### *In situ gas content*

The accurate determination of the gas content of the sources of gas emission plays a major role in the eventual precision of the gas emission predictions. A number of methods of gas content determination are available, but they are normally classified as direct or indirect methods. The direct method involves the development of a gas desorption-time curve from fresh exploration and in-seam bores, coal cores, coal lump samples or cuttings collected from the working face. The volume of gas "lost" prior to sealing the sample in the desorption vessel is calculated by extrapolation of the initial linear section of the desorption-time curve. Desorbed and remaining gas in the coal, after initial desorption are determined by direct measurements of the quantity of gas desorbed in the field and laboratory and by crushing coal samples using various crushing techniques. Indirect methods make use of "sorption isotherms", which are laboratory determined gas content/pressure curves, and the gas pressure in the coal seam, which is measured insitu, using a pressure gauge or manometric desorbometer. The difficulty with this method is that the gas pressure measurement requires a perfect seal (leakage free) around the borehole. In addition, the effect of strata water has a marked influence on the insitu moisture content of the coal which, in turn, affects the methane sorption capacity. However, from a scientific viewpoint, the indirect method is more accurate in terms of lost gas determination and the simultaneous measurement or calculation of insitu gas pressure. An accurate value of insitu gas content of worked and adjacent coal seams is of prime importance for any gas prediction technique. For unassessed areas, the combination of indirect and direct methods is recommended to establish insitu gas content and pressure, and sorption isotherms of the coal. In some instances the direct method is sufficient.

#### *The mined coal seam*

Although the quantity of gas released from the mined coal seam is assessed by different authors as a varying percentage of virgin insitu gas quantity, it is physically possible to determine this quantity using statistical data or practical measurements of the percentage of gas released in relation to the longwall face geometry and advance rate.

Gas emission into underground workings is described as a combination of the quantity of gas released from both the mined coal seam and adjacent strata (Lunarzewski et al., 1983). This relationship is expressed as:

$$SGE = QM + (\sum f.GC*f.DC*f.TA*TM^{-1} + \sum r.GC*r.DC*r.TA*TM^{-1})$$

- where: SGE - quantity of gas emission into underground workings per tonne of mined coal  
 QM - gas quantity released from the mined coal seam  
 GC - gas content of the gas reservoir in the floor (f.) and/or roof (r.)  
 DC - degassing coefficient or strata relaxation factor in the floor(f)and/or roof (r)  
 TA - thickness of the gas source in the floor (f.) and/or roof (r.)  
 TM - thickness of the mined coal seam

The major differences between the various methods of methane emission prediction rests with the actual curves used to establish the contribution of gas emissions from sources above and below the workings. Curves showing the percentage of strata relaxation gas emission contributions from roof and floor gas sources are a function of distance from the worked coal seam according to selected world authorities (Boxho et al., 1980). The variations in these graphs are a direct result of the physical models, and different mining and geological conditions. The Stuffken, Koppe, and Cerchar curves are based on residual gas content and quantity measurements. The Lidin, Gunther, and Winter curves consider gas emission from rectangular blocks of strata above and below the workings, extending up in the roof and down in the floor to a level where the emission contribution is zero. The Airey theory considers the solid coal seam as an assemblage of lumps of broken coal; the dimension of these lumps varying in accordance with their distance from the working coal face. As coal extraction proceeds, the increased load on the strata induces fractures which produce the coal lumps. As the maximum stress in the front abutment zone is approached, an increase in induced fracturing results thereby reducing the coal-lump size. The importance of Airey's theory is that the gas emission rate is dependent on the dimension of the coal lumps expressed as a function of the longwall advance rate and time. Prediction of the rate of methane flow into workings is complex due to the large number of variables.

The following variables of geological origin must be considered: lithology and stratigraphy, coal and rock properties of the floor and roof strata, effects of non-homogeneous coal seams, effects of water content, proximity and nature of faults, temperature and temperature gradients, indigenous permeabilities, variations in gas content within each seam, dip angle, contributions from floor and roof coal seams, contributions from gas bearing rocks, coal rank, and volatile content of coal. Variables arising from the mining process include: face length, history of face advance rates, effect of advance rate, volume of the gas emission space, distribution of coal particle size in each region around the excavation, fracture systems which occur near the excavation, rates of change of permeability and "connectivity", depth of mined seam, water drainage rate, other water-induced effects, methane drainage rate, bulk factor of goaf, conveyor clearance rate, virgin and residual gas content, virgin and residual gas pressure versus dip and distance of strata from the worked seam, thickness of extracted and adjacent seams, distance between extracted and adjacent seams, distance from abutment zone, coal particle size inversely proportional to the distance from the abutment zone, coal shrinkage rates, strength of surrounding strata, and time-dependent rates of change on many of the above variables.

Figure 7 shows an underground workings gassiness prediction flow chart and outlines the logical steps of inputting and utilising various factors affecting the final output.

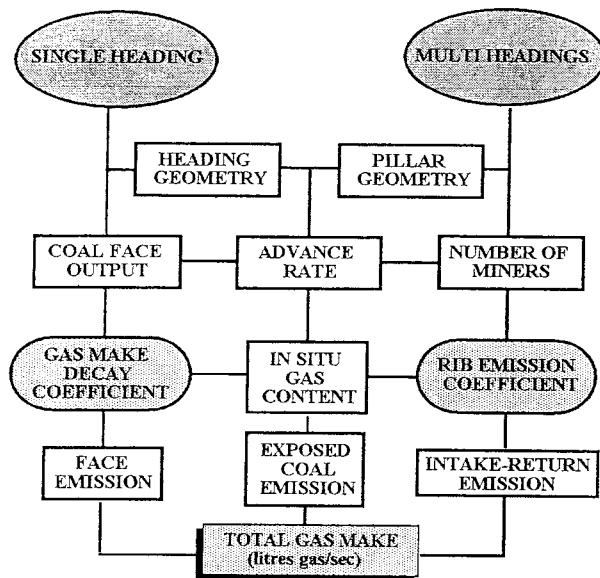


Figure 7. Gassiness prediction flow chart

Figure 8 shows a graphical illustration of gassiness prediction values for a panel length of 250 to 1,250 m for a continuous miner advance rate of 12 m per shift, various insitu gas contents, and intensities of gas release - "E" coefficients. Precise gassiness values are dependent on local factors.

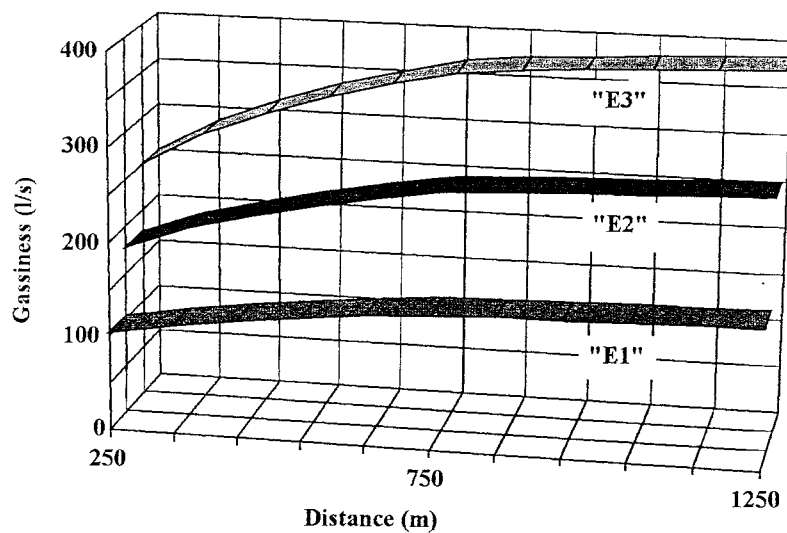


Figure 8. Predicted gassiness for various "E" coefficients.

#### Seam gas recovery

The classification of gas drainage methods is based on the phase during which degasification is performed in relation to the coal extraction. The six basic methods used are:

1. Pre-drainage by vertical or directional boreholes drilled from the surface,
2. Pre-drainage by horizontal long holes drilled from development headings,
3. Post-drainage by in-seam 'gas collection headings',
4. Post-drainage of relaxed strata using inclined (cross-measure) holes drilled into the overlying and/or underlying gas sources,
5. Post-drainage by vertical wells drilled from the surface to the goaf areas, and

6. Post-drainage of sealed goaves or abandoned coal mines from underground roadways or from the surface.

*Pre-drainage*

The term pre-drainage refers to gas drainage from sources, prior to coal extraction. The ability of the drainage system to capture gas in the pre-drainage phase depends substantially on the permeability of the coal seams and adjacent strata, their gas migration properties, conductivity, and the provision of sufficient lead-time.

*Post-drainage*

The term post-drainage refers to gas drainage from the relaxed strata during and after coal extraction. In post-drainage methods, advantage is taken of the phenomenon of increased strata permeability and connectivity (mainly coal) due to stress relaxation of the floor and roof rocks, which occurs as a consequence of coal extraction.

*Goaf drainage*

The term goaf drainage refers to capturing a high percentage of gas from sealed goaf areas. In order to operate an efficient goaf drainage system, the goaf area must be effectively sealed and an equilibrium be maintained between gas desorption rate and the quantity of gas captured. Figure 9 shows the logical and necessary steps required to design gas drainage systems for underground coal mine safety and gas utilisation purposes, taking into account the mine's predicted gassiness.

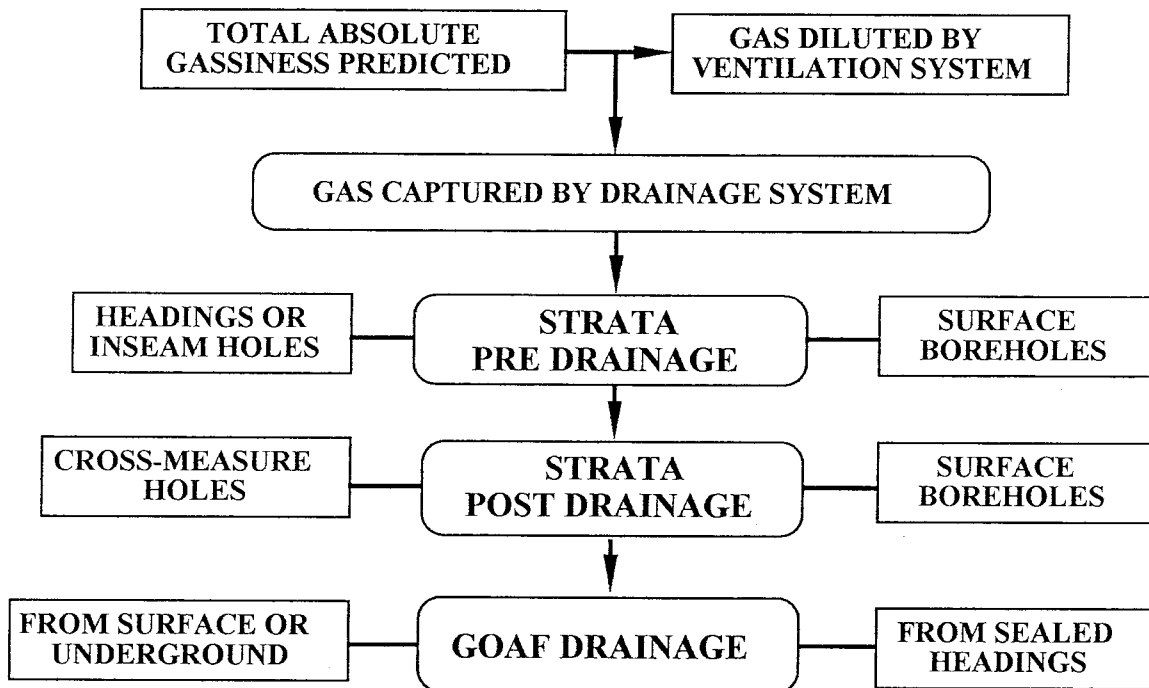


Figure 9. Steps required for design of gas drainage systems.

### SEAM GAS AND GAS DYNAMIC PHENOMENA

**General**

Normally the emission of gas into mine atmospheres from exposed seams is continuous, varying from place to place due to overall mine geometry. Other, less frequent aspects of gas release can cause special problems and, if not preventable, they at least merit special precautions. These are primarily outbursts of coal and gas and blowers from the coal seam and gas-outs or blowers from the floor or roof. These are sometimes met unexpectedly in the course of mining, and the formation of layers of seam gas, separated by density differences before mixing in ventilation air can occur. In the transition between air and CH<sub>4</sub> seam gas, some explosive compositions are inevitable.



### **Outbursts and blowers**

Sudden and large volumes of seam gas being liberated into mine openings cause dangers of asphyxiation due to oxygen deficiency, of poisoning by noxious gases, of explosion by inadvertent ignition of the resultant explosive mixtures, and of injury due to violence, and perhaps of exposure to dense blinding choking dust. There are three distinct phenomena in this category: outbursts, blowers from in the seam and blowers from the roof or floor.

Outbursts of coal and gas, which have been described by Hargraves (1983), and covered in comprehensive detail by Lama and Bodziony (1996) are the disintegration of coal from a solid standing face, (however strong or weak the coal may have been), together with the release of its contained gas during the disintegration, and the projection of the broken to pulverulent coal aided more or less by the energy of the gas so released. It is a process occurring in seconds.

Gray (2003) stated "the occurrence of an outburst is preceded by failure of the coal. In an outburst, the failed material is ejected with energy and with gas. The difference between a rockburst and an outburst is the gas that is emitted. The gas contributes in a major way to the expulsion of the coal and is generally thought to be the main contributor to total energy release in the majority of cases. Failure of solid coal containing gas occurs with a combination of effective stresses that exceed the strength of the coal. Effective stress is the stresses due to total load minus fluid pressure. The fluid may be either liquid or gas. The existence of fluid pressures mean that tensile stresses may exist in the coal. Coal does not resist tensile stress well and in the presence of compressive and tensile stresses many shear planes may develop.

The way in which the coal breaks up is governed by the structure of the coal. In numerical terms it is governed by the toughness of the material. Toughness is not usually a concept applied to coal rock mechanics, however it is extremely important. Tough materials require energy to propagate a failure whilst brittle materials require little energy. As the coal breaks up and expands outwards the rock stresses become less important and internal fluid pressure is the dominant stress that leads to the further fragmentation of the coal. This gas-driven splitting has parallels with explosive-driven splitting. The degree to which fragmentation occurs is vital to the outburst process. The broken material is carried from the outburst cavity by energy. This energy may be to some degree supplied by the closure of the cavity as a rock mechanics effect but more importantly in outbursting it is carried out by gas. The gas is derived from the broken material. The transport of the material outward from the outburst cavity is at first the effect of gas expanding behind the coal, as a piston. Then as the fragments separate, the process becomes more one of fluidized transport. Here the particles are carried by the gas in turbulent flow. The combined effects may represent a large release of energy. The solid coal outburst usually ceases to occur as the cavity from which the coal is ejected reduces in size with depth. The cessation of the outburst is a function of confinement. As the outburst proceeds back into the coal the unconfined face reduces in size. In addition the outburst may choke itself off from the front if there is not enough gas to expel the particles".

Spent gas outbursts are characterised by the usual gas escape channel over the top of the blown coal, with signs of wind erosion on the surface of deposited coal.

Coupled fluid flow and geomechanical modelling of mine development has contributed greatly to the understanding of outburst mechanisms (Wold and Choi, 1999). The model findings strongly support the importance of gas content and geological structures in determining gas threshold values for outburst risk, but show that outburst proneness is dependent on many factors (Fig. 10). However, in a mechanistic sense, pore fluid pressure and its gradient rather than gas content is a key determinant of outburst initiation risk. The pressure gradient field is in turn a function of the reservoir pressure, desorption pressure, permeability components, relative permeability and desorption isotherm. The possibility of anisotropic regional stress conditions should also be considered. The field data required for modelling are sparse.

## Interactive factors in outburst mechanisms

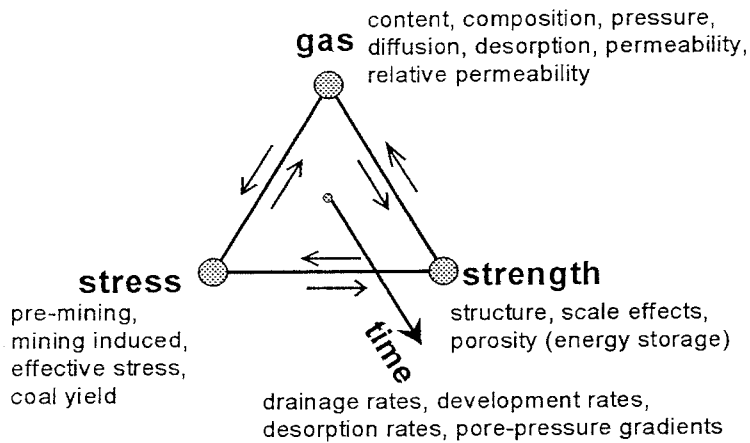


Figure 10 - Interactive factors in outburst mechanisms (after Wold and Choi, 1999)

Gas outbursts are primarily phenomena of development work - cross measure intersections of a seam and drivage in a seam. In extraction, generally, only longwall advancing and work in the freshest and largest of pillars is liable to outbursts. However, two outbursts occurred at West Cliff Colliery from the face of a retreating longwall in undrained coal (Walsh, 1999). Generally only the higher ranks of coal are prone. Locations are usually, but not invariably associated with faults, dykes, seam variations and dislocations. In some mines, such as Leichhardt Colliery in Queensland (Hanes, 1995) outbursts have occurred without any abnormal geological structure (Figure 11) or with structures which elsewhere in the same mine have been quite benign (Figure 12). Aspects of the prediction, prevention, control and researching of instantaneous outbursts are comprehensively documented by Lama and Bodziony (1996).

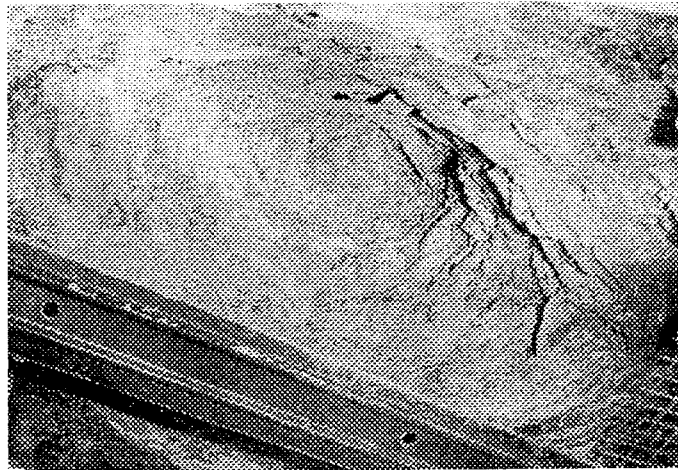


Figure 11 – Outburst cavity in coal roof, Leichhardt Colliery



Figure 12 – Outburst cavity from partly sheared coal, Leichhardt Colliery

Harvey (2001, 2002) summarised the history of outbursts in Australia. There have been 9 fatalities caused by outbursts in Queensland, 12 in New South Wales and 3 in New Zealand.

Blowers, sometimes unfortunately termed “outbursts”, are the tapping of reservoirs of fluids under pressure by mining openings resulting in the projection of fluids from the reservoirs into the mine openings. The fluids may be gas with or without water and sometimes with particulate solids in suspension. These blowers are characterised by the channel in the rock from which the fluids escape and the usual duration of the process is much longer than for outbursts.

If the fluid is largely gas the phenomenon is usually termed a blower and as the blower proceeds it may be supplemented by desorbed gas from the strata from which it is derived or through which it passes with any disintegration of those strata arising from attrition. The nature of blowers usually confines them to strata with suitable breaks to form a gas storage reservoir, such as faults and well developed joints or sheared coal. They are usually confined to development work and often confined to the first intersection of a persistent structure.

Blowers and in-hole outbursts have been experienced during drilling, sometimes with violence sufficient to damage equipment and threaten personnel. The drilling of holes of more than a few metres in length in gassy strata should be by mounted machines and with equipment at the collars of holes to contain any surges of gas and gas-propelled flushing medium or debris. A gas drainage borehole which was inadvertently pressurised blew out at Appin Colliery when the mine face passed within close proximity to it.

Where stress adjustments surrounding extraction areas tap gases from adjoining seams through induced or natural breaks, blowers of gas may result from floor, and perhaps roof, especially where floor strata are massive and break intermittently instead of progressively as is more usual. Such gas, desorbing rapidly from adjoining seams without the coal disintegrating, and blowing especially from the floor at discrete breaks instead of widespread filtering, constitutes a floor blower. The duration of such blowers is often prolonged, lasting until one break is superseded by new breaks as the extraction face advances.

In conventional pillar extraction where the dimensions of pillars are progressively reduced, small pillars (“stooks”) may be fully extracted or may be left as a roof support medium around the working edge of the goaf. Sometimes such stooks fail and burst violently. This is in fact a rockburst of coal, with highly loaded coal fracturing suddenly and violently, projecting solid coal fragments, Taiman and Schroder (1958). Pillar coal is most often virtually winded, desorbed, of gas, and such bursts, bumps, mountain bumps, are purely stress phenomena. But the sudden removal of support between roof and floor may induce sudden progression of roof and floor fractures around the goaf edge, allowing gas from adjoining seams to escape suddenly in the vicinity of the pillar burst. Thick, massive, relatively unjointed adjoining strata are more prone to such sudden intermittent breakages during extraction. Such pillar failure and high gassiness are concurrent yet separate phenomena.

Notwithstanding the different mechanisms underlying the three types of violent gas emission phenomena, in the one mine it is possible that all three gas phenomena may exist. One such mine is Appin Colliery, NSW, which has experienced outbursts, blowers from the seam in development, and also gas emitting, from under the face conveyor of a longwall face and from floor fissures induced in the goaf, of such intensity as to exceed the statutory limit of CH<sub>4</sub> content in the face air.

Some mines in both the Sydney and Bowen Basins are prone to outbursts. Whilst the mechanism of outbursts is generally understood, its operation is inherent in the process of mining virgin coal, and more prone environments are not necessarily identifiable prior to manifestations. The particular mining practices in use in Australia and the rapid development work necessary to sustain high productivity retreating longwalls highlight the influence of rate of advance on face gassiness and proneness to outbursts. As the outburst of coal and gas phenomenon is one of high gas and high stress within the coal face, the simplistic solutions to the threat of these phenomena lie in either degasification or destressing (or enough of both) ahead of mining in present geometries. Then there must be proof that the required degasification and/or destressing has been achieved. Currently proof is acquired by testing gas content of bore cores ahead of development faces to assure that the gas content is below adopted threshold values. Williams (2002) emphasised the importance of location and frequency of gas content test cores and the validation of gas content analyses. Such extra activities involve expense and delays, perhaps equivalent to slowing down development advance rates, itself potentially a partial preventative.

At Mount Davy Colliery in New Zealand's Greymouth Coalfield, mine development commenced in mid 1995 with the construction of two 1,200 m long stone drives to access pit bottom. Approximately 500 m of development drives produced about 13,000 t of coal. 21 significant coal outbursts were initiated during this development ranging in size from 40 tonnes to 2000 tonnes (Hughes, 2000) (Packham et al, 2003) which could not be controlled or mitigated. Three lives were lost. The desorbable gas content was 9 to 10 m<sup>3</sup>/tonne CH<sub>4</sub>.

The problem of outbursts of coal and gas will continue, even increase with deeper mining, more CO<sub>2</sub> experience, and faster development rates.

#### **Accumulations and layers**

Where gas emission rates are high and ventilation is slow to sluggish, there is ability for emitted gases lighter than air to move under gravity to the roof or gases heavier than air to move to the floor. They form accumulations at those places if the geometry is favourable. Such accumulations of CH<sub>4</sub>, for instance, can occur in rising places where ventilation at the face is not good, in irregularities in the roofline, or in goaves. Accumulations of CO<sub>2</sub> can occur in dipping places or in hollows in the floor. Seam gases never occur in absolutely pure compositions, thus a nominally CH<sub>4</sub> seam gas may have 1% N<sub>2</sub> and may have 1 to 5% CO<sub>2</sub> and a nominally CO<sub>2</sub> seam gas may have a few percent of CH<sub>4</sub>. There is a complete range of seam gas compositions existing in some mines, ranging from virtually pure CH<sub>4</sub> to virtually pure CO<sub>2</sub> (Hargraves, 1963a). An intermediate mixture with approximately 50% of each has a density equal to that of air and therefore has no tendency to move under gravity and has a ready ability to disperse into the air moving around the face. Whilst gases may mix readily with air, there is no possibility for practical purposes of unmixing of these mixed gases. It is erroneous to consider the gravity separation of CH<sub>4</sub> from a mixture to accumulate at the roof or of CO<sub>2</sub> to accumulate at the floor. Any such accumulations are from purer sources which have not yet had the opportunity of mixing with air. Such accumulations and layers, particularly of CH<sub>4</sub> may move against the air current, especially when gravity can assist them to move along a rising roof against an air stream. Because of its relatively high density compared with air, the accumulations of CO<sub>2</sub> which occur are more difficult to move than of CH<sub>4</sub> and there are instances of plugs of seam gas rich in CO<sub>2</sub> being most difficult to remove from the bottom of a mine. In fact, the high density of CO<sub>2</sub>, when in large quantities, makes it rather difficult for a fan with a low water gauge to remove such an accumulation unless it can be removed progressively.

### **SEAM GAS EMISSIONS**

#### **Before mining commences**

The situation of seam gas in a virgin seam remote from any mining is an equilibrium between

1. the seam gas generation related to the particular rank of coal and its time rate of generation.
2. the back pressure against escape of seam gas to zones of lower pressure and ultimately to the surface, and
3. the passage of gases from other sources, usually other coal, through and to some extent residing in the coal in question whilst on its way to the surface.

This equilibrium gas in a coal is of a particular composition, in a particular concentration in the coal, and at a particular gas pressure, with a particular gas pressure gradient pattern to the surface at any time.

#### **After mining commences**

The effect of exposing a seam below surface is to induce a new gas pressure gradient into the strata. The gradient is from virgin gas pressure at some distance into the strata to zero gauge or atmospheric pressure at

the exposure. The gradient will depend on the virgin gas pressure at that horizon, the permeability of the coal, the sorptive capacity of the coal, the composition of the gas, the mining geometry, the history of face advance to the exposure and other factors.

Gas emits through the exposure into the mine workings via processes of diffusion from the coal matrix to cleats or other fractures then by Darcy flow in the cleats. The atmospheric pressure will depend on depth below surface and daily variations which are proportionately small, but especially small in relation to virgin seam gas pressure.

Normally, immediately after exposure of virgin faces, or virgin ribs, emissions are high and then settle to a steady state. In the case of virgin pillars, which have a finite amount of enclosed gas, the rate of gas emission falls as the amount of gas remaining in the pillar reduces, until eventually gas emission becomes virtually nil.

Gas emits from all virgin exposures, but coal seams are not all homogeneous or completely isotropic. There are changing properties, directional properties, planes of weakness including bedding planes, cleat planes, and faults, induced fractures due to the mining process, and changes of a chemical and physical nature, including permeability, such as where the seam is affected by nearby igneous intrusions. All of these can effect desorption rates

Regarding coal seam permeability, Gray (2003) states

“Matrix permeability exists in the cleats where two phase (gas and water) Darcy flow takes place down a potential (principally pressure) gradient. During the drainage cycle the permeability changes due to changes in water saturation and due to effective stress variations in the coal. Effective stress is the difference between the total stress, which varies with direction, and the fluid pressure. Permeability reduces with effective stress in coals. The softer and more cleated the coal, the more dramatic this reduction is. Thus as a coal seam gives up fluid the effective stress might be expected to increase due to reduced pore pressure. This is often not the case. The reason for this is that the effective stress is not solely related to the fluid pressure but also to the gas content of the coal. It has been shown repeatedly that the change in linear dimension of a piece of coal is dependent on changes in gas content. With reference to seam drainage this dimensional change is one of shrinkage.”

“Most coal seams are bounded by significantly stiffer roof and floor rocks and therefore the lateral dimension of the seam is more or less constant but the vertical dimension is free to move. In this environment the total vertical stress in the seam can be expected to remain constant but the effective vertical stress will increase with fluid removal. In the absence of shrinkage, lateral effective stress could be expected to increase due to a reduction in seam fluid pressure. The lateral effective stress increase would be less than the vertical stress increase because the seams are laterally extensive and usually bounded by much stiffer roof and floor rocks. Shrinkage tends however to reduce the coal dimension and with it the effective stress.”

“The two effects on effective stress are opposing and without adequate testing it is not possible to determine whether matrix permeability will increase or decrease. From field experience both cases are known to exist. The matrix permeability can in some reservoirs change by orders of magnitude with gas production. This change may increase or decrease permeability. Knowing which is vital. Because cleats are directional and stress is directional the matrix permeability is also directional, though fracture permeability may mask this feature in many instances. Frequently major joint sets also exist within the coal seam and lead to a second level of greater permeability. Major faults may also transect the coal seam acting as barriers, fluid sources or sinks. Some coal seam reservoirs behave as though they contain quite different domains with significantly differing properties. These domains are known in some instances to be bounded by faults and are thus structurally different.”

Gurba (2002) showed that in samples of coal from areas that had proven difficult to drain gas, the micro-cleats were filled with calcite or other mineralisation. In easily drained areas, the micro-cleats were essentially open and free of mineralisation. Titheridge (2003) described how the microscopic structural picture could be extrapolated to the macro scale when he described calcite in coal at Tahmoor Colliery and its association with low permeability. He interpreted that the macro-mineralisation pattern in the coal is partly controlled by geological structure and by palaeo-stress. Hanes (2004) identified the understanding of geological structures and the causative palaeo-stresses as critical for understanding of poor drainage and outburst risk.

Thus gas emission into mine workings is not uniform per unit area of coal exposed but is very dependent on planes of weakness and especially the geometry of those planes of weakness. As cleats are usually more developed in one direction than in the complementary direction, emission from the major cleat is generally more ready than emission from the subsidiary cleat. For this reason development work advancing parallel to the major cleat would have more ready emission into the face than work advancing perpendicular to the major cleat. In the latter instance the seam gas pressure gradient could be expected to be higher ahead of the face thus increasing outburst risk, but gas emission into the ribs outbye the face would be relatively high. Gas issues into the mine workings from the exposed coal substance but only in small amount compared with the amount emitted through the planes of weakness which are exposed. The density of CH<sub>4</sub> seam gas relative to air is 0.55 and the density of CO<sub>2</sub> seam gas relative to air is 1.53 and so normally there is a difference in density between emitting gas and ventilation air. However if ventilation around exposed faces and ribs is brisk then the emitting gas is readily dispersed into the ventilation circuit without significant gravitational movement in the airstream.

### Gas capture in relation to gas desorption and emission stages throughout the colliery life cycle

#### General

The wide range of gas desorption, emission, and drainage (capture) from coal seams in underground coal mines is associated with different stages of the mine life and operational activities. In addition, mobility of coal seam gases under insitu conditions depends substantially on particular mining activities, strata properties and the lead time involved.

#### Natural or pre-mining activity stage

Strata gas can slowly penetrate through the overburden to the surface via the permeable strata and/or direct connections via faults, cracks, and geological disturbances. This stage is the natural undisturbed state of existing strata with entrapped gas being capable under some conditions to slowly permeate to the surface. If the stratum is not permeable, then the entrapped gas will remain insitu or relocated within the strata.

#### Surface exploration gas well stage

This stage creates a very small relaxation zone around a vertical borehole as it penetrates vertically through the strata (including coal seams) in a specific area. A significant change in the gas pressure gradient occurs from the insitu zone through the permeable strata (relaxed zone) and into the borehole, thus, allowing gas flow to occur provided the water can be initially drained or removed successfully from the hole. This stage also permits pre-drainage systems to be introduced either under free flow conditions or using suction. Hydraulic fracturing is one of the options which may substantially improve the efficiency of gas drainage prior to mining.

Johnston (2002) described a successful trial of surface to in-seam medium radius drilling at Oaky Creek in Queensland and Poole (2003) described a similar trial at West Cliff Colliery in NSW. In both cases, holes were drilled from the surface, curving through a broad radius to intersect the coal seam at an acute angle and continuing for 800m to 1450m in the coal seam, intersecting vertical sump holes drilled from the surface for draining water from the coal seam. The drilling of the in-seam holes was conducted under a water head thus facilitating drilling and maintaining hole stability while drilling. This technology holds promise for pre-draining coal seams well prior to mining and for seam structure exploration, especially when geophysical logging of the holes becomes practical. Figure 13 shows the concept.

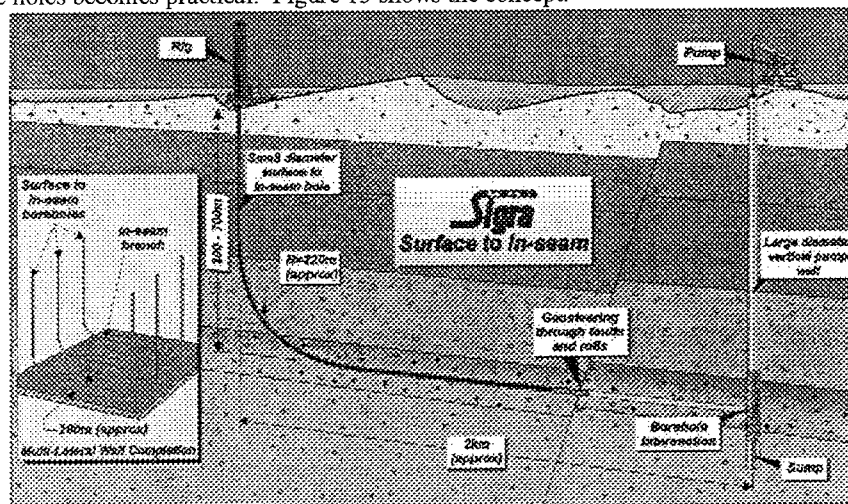


Figure 13 – Surface to in-seam drilling concept (courtesy of Sigma)

Tight radius drilling using a water jet attached to flexible tubing for in-seam drilling from a vertical access hole has the potential for relatively inexpensive gas pre-drainage from the surface.

*Shaft sinking stage*

Significant ventilation is provided during shaft sinking by the use of large exhausting fans. The provision of ventilation increases the gas pressure gradient resulting in increased flow of gas through the shaft into the open atmosphere. Some horizontal holes can also be drilled from the shaft, for pre-drainage purposes.

*Seam development stage – in-seam drilling*

Mining allows gas to emit from the mined coal and freshly cut face, as well as from relaxation zones in the floor and roof strata. Entrapped gas in the coal desorbs and consequently releases free gas into the mine workings during strata relaxation. The distance of the relaxed zone is up to three times the “radius” of the driven heading. Assisted mine ventilation increases the gas flow rate due to the significant pressure gradient change.

In-seam drilling is conducted to drain gas prior to mining. The majority of the 450 km of in-seam drilling conducted in Australia annually is lateral or across-panel drilling. Some advance drilling is conducted to assure potential geological structures which are sub-parallel to the lateral holes are not missed.

Lateral holes extend generally in a fan pattern from the rib sides of former developments towards or across the paths of imminent new developments, where hole spacing averaging around 20 m, depending on seam virgin permeability, is achieved. Holes are typically 350 m long, ie across the block and into the next block a sufficient distance to allow for the reduction in drainage around the ends of holes. Figure 14 shows typical patterns used at a NSW mine.

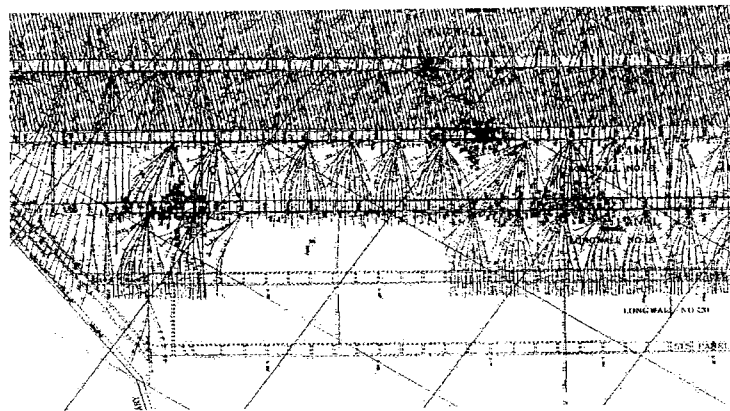


Figure 14 – Fan Pattern In-seam Drilling

The drilling technology for these holes is well developed with the effectiveness and uniformity of predrainage depending on the regular geometry of the patterns of holes. Uniformity is dependent on accuracy of drilling which has accompanied the adoption of down-hole-motor drilling with a survey tool behind the bit (Figure 15).

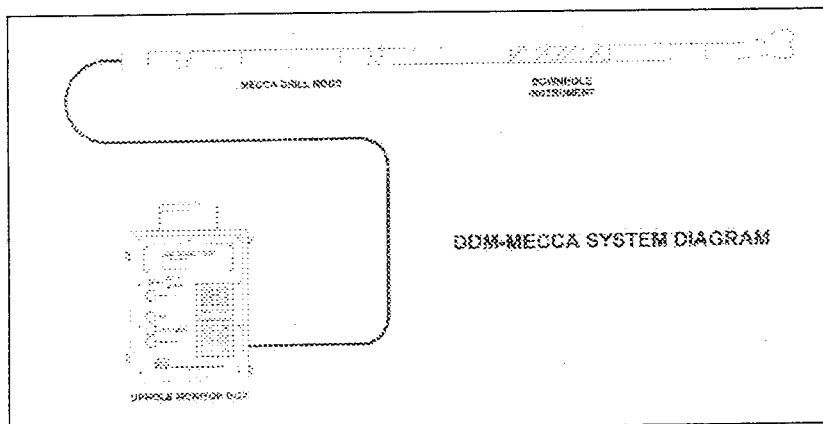


Figure 15 – Arrangement of survey tool and monitor (courtesy Advanced Mining Technologies)

During the 1990's, most drilling for gas drainage was rotary drilling. The trajectories of these holes were assumed and very few were surveyed. They typically curved, generally to the right as determined by the clockwise rotation of the rods, however cleats in the coal also affected the trajectory. A fatal outburst occurred at West Cliff Colliery in 1994 in a drive which was "protected" by three rotary holes which had been drilled along the alignment of the drive, one in the middle of the drive and one inside each rib-line. Subsequent to the outburst which occurred from the right hand rib/face intersection, it was found that all three holes had diverted to the left hand rib. Consequently, the industry immediately adopted the more accurate down-hole motor drilling with surveying of each hole. With down-hole motor drilling, the drill rig is generally only used to push the rods into the hole and to retrieve them. The drill bit is rotated by the down-hole motor located just behind the bit. The down-hole motor is activated by water flow through the rods. A survey tool is located behind the down-hole motor. Survey tool accuracy is now accepted, as long as preparatory precautions for calibrating the tool are taken and allowances are made for contributing factors such as depth of hole and hole curvature. Typically there is a 1.25° bent sub located behind the drill bit. The bent sub facilitates changing of drilling direction. Typically, 6 metres of hole are drilled with the sub pointing to the left of centre and then it is flipped to the right, thus allowing the hole to advance in a series of "flip-flops". Hole surveys are conducted at regular intervals. One colliery and one contract driller advance the hole by slowly rotating the entire down-hole assembly. They claim they produce straighter and more accurately located holes using this method while reducing hole friction, thus enabling the drilling of longer holes. The longer the hole or the more curved the hole, the wider the envelope of accuracy (Hungerford, 1995).

Figure 16 shows a typical drill rig used for in-seam drilling. Figure 17 shows details of the threads used on Boart Longyear NRQHP drill rods compared with the older NQ rods.

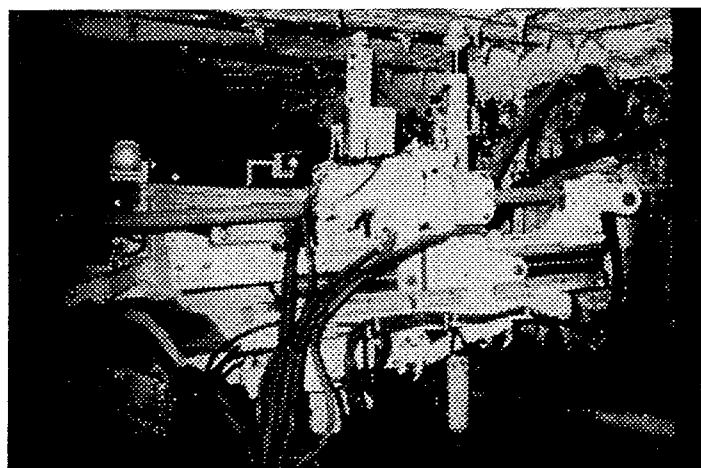


Figure 16 - LMC55 drill rig (photo courtesy Boart Longyear Australia)

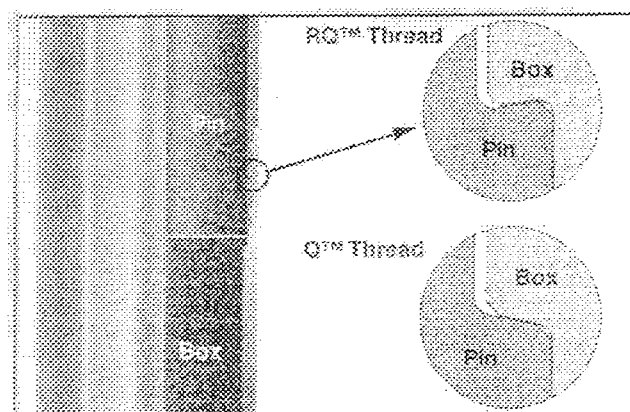


Figure 17 – Thread details of NRQHP drill rods (upper detail) compared with the older Q rods (lower detail)(courtesy Boart Longyear Australia)



There is room to improve in-seam drilling survey technology by incorporating devices to detect geological structures during drilling. Some devices which should enable detection of structures during drilling have been developed to prototype stage. However, support of the industry will be required to advance their development.

Drilling is usually conducted with sufficient lead time (6 to 12 months) to allow the holes to drain the longwall block and the next development panel of gas prior to mining. Drilling methodology was comprehensively documented by Hungerford (1995) and updated by Hanes (2002).

Advance drainage holes extend in front of developments and usually on the virgin coal side of the development. They are drilled incrementally with new holes superseding old holes as they are overtaken by the development. These holes are used to detect geological structures that strike sub-parallel to the across panel holes and they capture gas from the virgin coal before it can be emitted into the rib of the opening. It has not been practical to date, to use only long advance holes to drain a longwall block because of the current hole length limit of around 1600 m and the greater lead time required.

#### *Longwall or room and pillar extraction stage*

Strata exposure above the coal seam extraction area is greatly increased due to the creation of the goaf. The distance the relaxed zone extends in the roof is equal to or greater than the longwall width (up to 200 m). The distance the relaxed zone extends in the floor is up to half of the longwall width (down to 100 m). Large gas flows can occur from coal seams in the roof or floor and it is at this stage that sophisticated gas drainage systems are used to reduce hazardous gas conditions to safe statutory levels within the general mine ventilation system. Desorbed and released gas is emitted to the underground workings (mine atmosphere) and captured by the drainage system. Intensive desorption and emission (gas-outs or blowers) take place during longwall extraction. However, the quantity of released gas will decline with time, perhaps during several years after the longwall is completed.

The mapping of gas movement within a goaf was described by Balusu (2003). He concluded that the development of tracer gas mapping methods and the application of computer modeling enabled improved performance of goaf drainage which was supported by several case studies.

Inclined cross-measure drainage holes have been drilled from the gateroads, but usually only from the tailgate side, usually ahead of the retreating longwall face. These holes only commence to actively collect copious gas when the face reaches the vicinity of the hole. Most holes have been drilled into the floor and towards the centre of the longwall block at the horizon of the lowest seam to be tapped. In the case of Bulli Seam extraction in the Illawarra area, the underlying seam with most gas is the Wongawilli Seam some 40 m below the worked seam.

Overseas, upholes are more important and used in greater numbers than downholes because of unworked overlying seams, the greater upward relaxation of strata and the consequent increase in permeability. In general, upholes dissipate the natural gas pressure of any overlying seams, requiring negative pressure to capture the atmospheres existing near the tops of such holes. Downholes are less efficient than upholes mainly because the permeability of underlying seams is not increased by strata relaxation to the same degree as for overlying seams. Downholes can be adversely affected by a head of water from the working horizon to the seams. In Queensland, gas from coal seams which overlie the worked seam is typically captured by goaf drainage holes from the surface.

The upholes and the downholes bored from the companion gateroad are necessarily longer and flatter than their longwall advancing equivalent would be because of the need to traverse the roadway pillar width as well. It has been convenient in some instances to bore from the companion road though there is some apparent advantage in drilling laterally fanned holes by mobile machines from the cutthroughs and closer to the gateroad(s).

In any case, as longwall faces are made longer, the difficulty of maintaining holes in the target seam increases, thus the proportion of seam gas to be collected by upholes and especially downholes will be reduced.

Post-drainage practices have been described in general by Hargraves and Lunarzewski (1985), and in detail at Appin Colliery by Battino and Regan (1982), and at Westcliff Colliery, after pillar extraction, by Marshal et al (1982). Overseas practices have been described by Higuchi, Ohga and Isobe (1982); Lunarzewski (1982a); Lunarzewski (1982b); Highton (1982); and Bourquin and Martin (1982).

It is clear that the success of present post-drainage practices in Australia will ensure their normal consideration for any future deeper longwall retreating activities.

#### *Post extraction stage*

Longwall and room and pillar extracted areas can be efficiently sealed off after completion of the extraction process. The exposed cavities form gas reservoirs that can be extracted by post-drainage techniques at a predetermined controlled rate. The quantity of captured gas should be in equilibrium with gas desorption from the strata gas sources. Part of the gas usually leaks directly to the ventilation system. The extracted gas can be diffused into the ventilated mine workings or transported by a gas drainage network to the surface for controlled exhaustion to the open atmosphere and methane utilisation.

#### *Multi-longwall extraction stage*

This stage refers to the combined effect of many old extracted longwalls adjacent to an operating longwall in the same general area. The relaxation zones in this case extend much further into the adjacent roof and floor strata resulting from the combined effect of strata relaxation zones of each old longwall within a large extraction area. This can have much more serious consequences on gas emission problems associated with the operating longwall unless more sophisticated and complex gas drainage systems are introduced.

Apart from drainage through boreholes around an extracted area, as described above, accumulations of seam gas above the upper explosive limit, 15% CH<sub>4</sub> in air may be captured by pipes left for the purpose through stoppings and seals (Hargraves and Lunarzewski, 1985). This may apply to atmospheres behind stoppings in gateroad cutthroughs inby facelines in the case of retreating longwalls whilst access to such stoppings through companion roadways remains. It may also apply to sealed areas of mines, or to entire sealed mines where continuing make of gas provides a supply.

This technique can be applied to goaves of longwalls drained through pre-bored and cased surface holes drilled over longwall centrelines or to one side of the panel. Such holes bottom just above the seam, and become active shortly after the longwall face has passed and opened the strata around them. Such a hole, 125 mm diameter, over No. 2 longwall at Appin produced a peak of 6,800 m<sup>3</sup> of CH<sub>4</sub>/day under free flow conditions, (Hargraves, 1982). There was no other seam gas drainage in use in the area.

Goaf drainage holes have been successfully used in mines in NSW and Queensland to capture gas from the goaf.

#### *Mine closure*

This stage would normally require the mine either to be sealed off completely or with a special outlet to the open atmosphere, or with a coal mine methane utilisation system. Controlled gas drainage may still be required if the gas has some commercial uses. Safety precautions are required to protect specified areas from possible migration of gas from the mine's underground workings and relaxed strata to surface features.

#### **Natural drainage and suction**

At depths at which seam gas drainage is undertaken, say 300 m or more, virgin seam gas pressures are of the order of 2.5 to 4 MPa, or more. Barometric fluctuations are not likely to be more than 0.005 MPa. Thus if it is assumed that pre-drainage holes extend as far as the virgin gas condition, at time of boring, and if post-drainage downholes likewise tap pressure not much below virgin pressure, then there should be sufficient gas pressure available to drive drained gas through the pipe network to the point of discharge or use. Barometric fluctuations should not have any significant effect, but any significant head of water in drainage down-holes retards gas escape. Holes should be kept free of water. In the case of post-drainage through upholes the goaf and hole will act like an inverted manometer with the lower density CH<sub>4</sub>-charged atmosphere at the top and flow will need to be induced by a depression on the hole collar side. The slight ventilation pressure from maingate to tailgate should assist flows into holes bored from the tailgate side. With holes through stoppings and with virtual pressure equalisation of goaf and the outbye side of the stopping some depression on the outbye side will be needed to induce flow.

In these two instances the application of variable suction provides the advantage of control over output which in turn, provides control over purity of output and to some extent of the remainder and so the creation of explosive mixtures can be avoided.

In the case of drainage of goaves directly through boreholes to the surface, with CH<sub>4</sub> seam gas, the motive column due to differences in densities of air and CH<sub>4</sub> is sufficient to overcome main ventilation fan depressions and to allow natural flow to surface to occur. Thus in a mine with a main fan depression of 1.6 kPa at pit top, the 0.8 kPa say available from the base of a goaf hole to surface should favour such a hole downcasting surface air, but the motive column of say 300 m of pure air to 300 m of CH<sub>4</sub> ignoring any temperature differences, is approximately 1.5 kPa. Thus with such a hole open at the bottom to a volume of virtually pure CH<sub>4</sub> and shut at the surface, it would fill with CH<sub>4</sub> and would tend to upcast under a nett head of

$$1.5 \text{ kPa} - 0.8 \text{ kPa} = 0.7 \text{ kPa},$$

ignoring any back-pressure developed around the bottom of the hole due to impeded flow from there to the mine roadways. These considerations explain the surprising free flow of up to 6500 ml/day of essentially CH<sub>4</sub> through a 126 mm borehole from over the No. 2 Longwall goaf to the surface at Appin Colliery.

The real need for suction to operate methane drainage from upholes in longwall advancing has automatically included its use in the (overseas) less common downholes and, has virtually ensured the use of suction in the more usual downholes in the Australian context of longwall retreating and in pre-drainage. Given that Australian requirements for seam gas drainage are in pre-drainage and in downholes in longwall retreating, it is worth examining, in each case, the justification for suction. Although suction pressures are small in relation to the seam gas pressures applying in pre-drainage and in the downholes in longwall retreating aspects of post-drainage, any assumption of negligible effect of suction is erroneous. Hargraves and Lunarzewski (1985) and Marshall et al (1982), have shown a dramatic increase in net seam gas flow with suctions ranging up to 50 kPa. It is worth examining the comparative economics of the alternatives of suction from fewer holes and free flow from more holes. There are also the comparative safety aspects of gas, if CH<sub>4</sub> with possible dilution towards its explosive range with suction and risks with pipe breakage both with suction and free flow. For utilisation there may be comparative advantage of pure gas under free flow, and for instance a cryogenic purification can be made at a less extreme low temperature. Whether suction is used or not, where drained CH<sub>4</sub> is dissipated underground inevitably there will be the problem of a transition zone involving the explosive range. Where seam gas is largely CO<sub>2</sub>, corrosion problems may be less severe in plant which is static only.

Some situations may be visualised where the pre-drainage of development and post-drainage of longwall retreating are both considered, and the drainage is divided into pure gas freely flowing from in-seam holes and post-drainage downholes with suction applied to post-drainage up-holes and sealed areas only.

Drainage plants are complex, rigorously controlled and monitored installations, (Battino and Regan, 1982; Lama, Marshall and Tomlinson, 1982). For smaller duties, extractors have been sited underground where the problems of operating plant close to the face and dissipating discharges into return airways have been overcome.

The pipe ranges between drainage holes and exhaustor plants should be of adequate diameter to provide effective suction at holes. Undue pipe friction or constrictions due to water accumulations at valleys cannot be tolerated. Adequate valving and sampling and pressure measurement access allows control of concentrations and progressive isolation of low production holes. Water traps minimise entrained water and particulates. These and other details are covered by Hargraves and Lunarzewski (1985).

#### **Disadvantages of seam gas drainage**

Apart from the expense of seam gas drainage (when not recouped by utilisation) there are other problems introduced.

1. There is simultaneous drainage of moisture from the coal resulting in mining in a drier, harder, dustier condition. Usually the gassiest coals, those requiring seam gas drainage, are the least permeable and the most difficult to infuse with water to counter the aggravated dust problem. This applies particularly to pre-drainage, with infusion water competing with gas from virgin sources attempting to replenish the pre-drained coal.
2. Any cessation of pre-drainage prior to mining provides time for virgin seam gas conditions to be at least partly restored.
3. Closing of abandoned drainage holes may present problems for subsequent mining. This applies particularly in cases of pre-drainage in-seam and postdrainage by downholes to seams to be mined subsequently. Such closure may however be desirable or necessary to prevent gas blowing into workings, water entering workings and air and water interconnection between openings in successive seams, (Hargraves and Lunarzewski, 1985).
4. The general vulnerability of large pipes in the mining environment including near extraction areas, and problems with leakages both into and out of pipes.

In general these disadvantages do not prevent the use of seam gas drainage, where required, but heighten the awareness of the need for precautions to be taken against such disadvantages, particularly the requirements for strict monitoring and control.

## Utilisation

### *Purity and other aspects*

The need for seam gas drainage and the prospects of utilisation do not necessarily go hand-in-hand. Although Australian coal seam gases, have, on average, much more CO<sub>2</sub> than the global average, nevertheless most are flammable and major prospects of utilisation lie in heat and power applications (22% CH<sub>4</sub> in a CH<sub>4</sub> + CO<sub>2</sub> mixture is the lowest limit of flammability). Based on extraction plant gas with minimal CO<sub>2</sub> and largely air as the diluent, Hargraves and Lunarzewski (1985), listed the following various prospects for use of drained gas.

1. 40-35% of CH<sub>4</sub> - released into the atmosphere. It may be dangerous as a fuel,
2. 60-40% CH<sub>4</sub> - suitable as fuel for gas turbines' boilers, coke ovens, metallurgical furnaces and other uses,
3. More than 60% CH<sub>4</sub>- may be cracked and after enrichment used as admixture to coke oven gas,
4. Over 75% CH<sub>4</sub> - may constitute an admixture to natural gas, and
5. 80-75% CH<sub>4</sub> - suitable for catalytic cracking yielding gas, which after enrichment can substitute town gas."

The reasons for the choice of a minimum such as 35% to 40% CH<sub>4</sub>, are because it may be dangerous to attempt to use it as a fuel. The dangers of explosibility in approaching the nominal upper explosive limit of about 15%, are markedly increased by any in-leakages of air from long term leaks or accidental leaks. But explosive limits usually quoted are at ambient temperatures, and some uses of drained gas involve higher temperatures than ambient. The greatest example is in compression for use in turbines involving high fuel pressures in which adiabatic conditions involve considerable rises in temperature. As the range of explosibility ends on both the low side and the high side of the range because of the specific heats of the gases including the uninvolved portions of the explosive mixtures, and the difference in temperature between ambient temperature and the temperature for explosion, any reduction in this difference should broaden the range of explosibility. Thus the maximum temperature and pressure in the utilisation process must be known as data affecting the explosive range of drained gas for determining the lower limits of CH<sub>4</sub> in the extraction system. As there are components of seam gas other than CH<sub>4</sub>, always a little N<sub>2</sub>, sometimes flammable higher hydrocarbons especially C<sub>2</sub>H<sub>6</sub> and some CO<sub>2</sub> especially in the Australian context, even small proportions of these, if flammable, will tend to broaden the explosive range, and, if inert, to reduce it. All of these factors should be considered in the choice of a minimum percentage of CH<sub>4</sub> in any particular drainage system.

In Australia the prospect of the sale of drained gas to public utilities appears to be possible only at a purity of not less than 92% combustibles and not more than 2% CO<sub>2</sub> - gas of highest fuel value and with reduced corrosion risks to pipelines and equipment. Such purity is presently unattainable in gas drained to surface exhausters. Purity ranges between 50% and 70% CH<sub>4</sub>.

The composition of fuel for gas turbines at mine sites is set at a minimum of 40% CH<sub>4</sub> to keep reticulated gases well above the upper limit of explosibility and to give best control to the fuel-air ratio in the turbine, and maximum 2% CO<sub>2</sub> for corrosion control. Usually such turbines are small and tie in with the power grid of the state utility.

If pipeline distances are short there is a possibility of drained gas being used to supplement solid and liquid fuels and natural gas in industry furnaces.

Cryogenic plants for the purification of drained gases have been used overseas, but at high capital cost and high operating cost. The ultra low operating temperatures needed to remove air gases from drained gas is a prime contributor to high cost which would not apply in the case of free flow drainage to separate simple CH<sub>4</sub> - CO<sub>2</sub> mixtures. Depending upon composition, either pure CH<sub>4</sub>, dry ice, or both could be utilised. The noted occurrence of more than traces of He in Bulli Seam gas at some Illawarra Collieries presents another possibility of utilisation.

Prior to 1984, virtually all gases were vented to atmosphere, with dispersal assisted by positioning discharges over fan evasees. One pilot gas turbine was tested prior to the first major turbine commissioned in 1984. Now, any seam gas drainage considerations include utilisation of gas in power generation on site and possible sale of surplus power and/or gas to public utilities and other users.

### *Storage of drained gas*

In taking account of five day production and the seven day nature of seam gas drainage, with expected diminution of drainage, especially from post drainage work, over weekends and holidays, some storage facility may be required to provide more uniformity of supply where utilisation is practised. Because of the vast volumes of flammable gas involved in such storage, it is logical that some abandoned mines would be considered as convenient sites for storage. As well as the gas compressed in roadways on the basis of Boyles Law such a scheme, in a coal can involve huge volumes of seam gas being sorbed in pillar coal and ribside coal according to permeability and sorption isotherms.

Thus in an abandoned mine with say 20 km of roadway, there could be 320,000 m<sup>3</sup> of airways and 1.7 million tonnes of pillar coal and perhaps 60,000 m<sup>3</sup> of exposed virgin coal at ribsides. A reduction of storage pressure from 10 to 5 atm., could result in freeing 1.5 million m<sup>3</sup> of gas at atmospheric pressure from roadways immediately, and releasing perhaps 6 million m<sup>3</sup> of gas over a period from pillars and ribsides. With only small pressure differentials more likely in a utilisation situation perhaps 10 million m<sup>3</sup> of CH<sub>4</sub> sorbed into pillars and ribs would be tied up indefinitely.

### **Interactions**

Seam gas emissions and seam gas drainage have an important impact on other aspects of coal mining operations, including

1. ventilation which influences diffusion of gas from exposed coal, effects dilution of emitted gases and disperses gas layers,
2. monitoring control which is used to assess the explosibility of drained gases and the presence of explosive mixtures around mining machines, and
3. hazard assessment, usually by hand-held instruments, but including recognition of the modifying efforts of various component gases such as CO<sub>2</sub> and N<sub>2</sub> on explosibility and on the risk of oxygen deficiency.

It is clear that great advances have been made in pre-drainage over the past decade, no less in Australia than elsewhere. This has been a consequence of a considerable research effort which has produced a better understanding of the movement of gases through coal.

### **ACKNOWLEDGEMENTS**

The principal author gratefully acknowledges the financial support by the Australian Coal Research Projects (ACARP) for his role in facilitating communication about gas and outbursts throughout the Australian Coal Industry. Chris Harvey is gratefully acknowledged for his constructive editing of the text and contribution of ideas.

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