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Review of methane emission and prediction research in longwall coal mines

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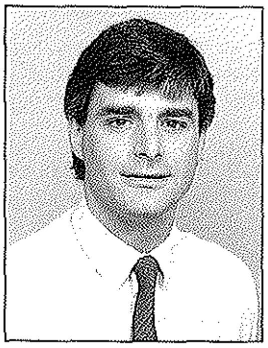
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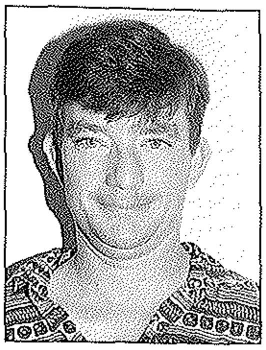
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ABSTRACT

There are a number of current theories in relation to methane migration and emission into workings following underground coal mining activity and some controversies do exist. Mining causes changes in the stress regimes in surrounding strata and results in fracturing. Permeability increases and methane flows into workings under a pressure gradient. The effects of stress on permeability depend on the physical properties of the coal and surrounding strata. Methane emission also depends on the original methane content and the proportion which will be liberated. There are several methods for determining in situ methane content and desorption characteristics of coal samples and several methane prediction methods but clearly more research is necessary to achieve an adequate predictive model.

INTRODUCTION

The high production rates associated with longwall mining are accompanied by high rates of methane emission into mine workings. The literature indicates that methane entering excavations originates from fractured material in the peripheral zone of relaxation. Relaxation and the resultant fracturing of strata in the vicinity of mining activity increases the rate of emission as a result of increased permeability which opens flow paths for gas to move into the lower pressure environment around workings. Material which does not lie within the zone of relaxation nevertheless has an inherent permeability, and even if this is comparatively much lower, the volume of methane seeping towards the excavation may be considerable because of the large surface area of the relaxation boundary and the relatively high seam gas pressure.

Many organisations have contributed to the development of techniques which aim to predict methane emission into mine workings, although there are considerable variations in the approaches taken and in the underlying assumptions. For example, methods differ in their consideration of methane emission from adjacent non-coal strata such as sandstone and shale, and there are opposing opinions with regard to the strata methane content values that should be used. Other differences appear to reflect the fact that methods have been developed in several countries with different geological conditions and mining techniques.

CURRENT THEORIES AND METHODS

The formation of coal results from a chemical transformation of vegetable matter. Fluids including water, methane and carbon dioxide are liberated. The gases are collectively referred to as firedamp. Firedamp is generally composed of 90 to 95 per cent methane, up to five per cent carbon dioxide, and traces of ethane, propane, butane, carbon monoxide, hydrogen sulphide and hydrogen (Boxho *et al*, 1980). Because of the high proportion of methane in firedamp, and the legal significance of the concentration of methane in return mine ventilation, the terms are often used interchangeably.

Methane in an excavation poses the following problems.

1. When methane enters the excavation it lowers the concentration of oxygen in mine air. This is a potential health risk for workers.
2. The emission of methane into excavations enables methane to mix with air. A concentration between 5.0 to 15.0 per cent methane in air forms an explosive mixture which can be ignited by a spark. Sparks can be produced by electrical equipment, picks striking rock, and frictional ignition between falling rocks or between roof bolts and falling rocks.
3. If the concentration of methane in return mine ventilation reaches the maximum statutory level (which may be about 2.0 per cent and varies from country to country and state to state), the law requires that mining must stop and the mine be closed until the methan concentration is reduced. This disruption to the mining operation is expensive. Since methane concentration in the mine ventilation is used as a criterion of mine closure, prediction of methane emission is an important component of mine planning.

The high production rates of longwall mining are accompanied by high rates of methane emissions into workings. If mine ventilation cannot control methane concentrations to below statutory levels in the return air, then other methods for controlling methane must be used to allow the mine to operate continuously.

In the context of methane drainage, the permeability of a sedimentary rock can be considered to be the fluid conductivity, that is, the ability to transmit a fluid when a pressure or concentration gradient exists across it. A brief review of terms and applications has been undertaken.

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sample (Curl, 1978). The same steps have been identified by underground measurements. A fall in the gas pressure within strata is associated with the approach of mine workings because of loss of free gas and relaxation. The adsorption equilibrium is disturbed and some adsorbed methane is desorbed. The methane desorption front moves slightly ahead of the strata movement front of an advancing face (Curl, 1978).

Two mechanisms can stop methane desorption.

1. If the free gas equilibrium pressure in coal approaches the atmospheric pressure in mine workings, the net desorption rate becomes insignificant (Boxho *et al*, 1980).
2. Behind the face, recompression gradually occurs. The resultant increase in resistance to gas flow allows methane pressure to build up, enabling a new equilibrium between free and adsorbed methane to arise. When this happens, net desorption becomes zero (Boxho *et al*, 1980).

Only methane in the free gas state can flow into workings. The flow occurs in a two step process, namely, diffusion through the micropore structure of the coal to a fissure, and flow along interconnected fissures in the coal bed. The volume of methane entering workings by flow through fissures is generally far greater than that resulting from diffusion alone (Curl, 1978). The flow of methane from non-carboniferous beds such as sandstones and mudstones occurs through fissures between particles.

The concentration gradient provides the energy for migration of methane. Methane moves by diffusion from the desorption site through solid coal until it intercepts a fracture. Kolesar and Ertekin (1986) have examined the time-dependent response of concentration gradients in the micropores to changes in fracture pressure, and have compared quasi-steady state and unsteady state matrix formulations as models for gas transport. A quasi-steady state model uses the average concentration gradient in the matrix elements over a discrete time step to calculate the matrix-to-fracture gas transfer rate. An unsteady state model implements a non-uniform micropore concentration gradient in determining the matrix-to-fracture transfer rate.

Ertekin, King and Schwerer (1983) have presented a detailed review of the mechanisms of gas diffusion through porous media. Three flow mechanisms can act individually or simultaneously. The mechanisms are

1. bulk flow, where intermolecular interactions dominate,
2. knudsen flow, where molecule/surface interactions dominate (for example, the flow through a capillary), and
3. two-dimensional surface flow of adsorbed gas.

Resistance to methane migration is inversely proportional to the macro-permeability of the medium. A study of the methane flow through coal discs by Thimons and Kissell (1973) indicates that concentration gradient is the driving force behind diffusional flow, and laminar flow occurs in response to the pressure gradient.

Curl (1978) indicates that flow within the fissures is considered to be laminar in accordance with Darcy's flow equation. However, Darcy's law requires fluid flow to be viscous, with the fluid adhering to the walls of fractures through which it flows. With a gas flow, this does not occur. Gas slip occurs along fracture walls. This gives rise to a flow in excess of that predicted from Darcy's law, and an apparent dependence of permeability on gas pressure. This is known as the Klinkenberg effect. Some researchers have modified Darcy's law to compensate for gas slippage (Ertekin, King and Schwerer, 1983).

The rate at which methane enters an excavation is called the methane make. The processes which determine the rate are summarised below.

1. Methane in fissures connected to the excavation migrates to the workings. The loss of this methane from the fissures affects the equilibrium between free gas and adsorbed gas in the coal, and methane desorption from the coal occurs. The desorbed methane also migrates towards the workings. When methane is desorbed from coal, the coal shrinks, and fissures in the coal become wider. The permeability of the coal consequently increases enabling a greater flow of gas through it.
2. Relaxation of strata involves formation of fissures. Some fissures connect reservoirs of free gas to the excavation causing an instant decrease in the resistance to gas flow. If the decrease in resistance is very large, gas can suddenly be ejected into the excavation. This is called an instantaneous outburst.

Curl (1978) reported that the overall gas emission rate from a coal seam is determined by either the diffusion rate or the laminar flow rate depending on which is the slowest. The slowest process is called the Rate Determining Step (RDS). Curl (1978) outlined a graphical method by which the RDS can be determined from borehole measurements. RDS measurements, however, should be interpreted with care. Coal seams are not homogeneous, so it is conceivable that the RDS is the diffusion rate around some parts of an excavation and the flow parameter around other parts of the same excavation.

The methane make of an excavation can be considered as the sum of flows through the floor, roof and ribs of each drive, added to the make from cut coal which is still within the excavation, and the make from the goaf. During retreating longwall mining, methane make tends to be high along the face as the roadway has a wall of freshly exposed coal on one side and a region of goaf on the other. Methane tends to flow from the goaf into the face roadway near the tailgate end caused by the lower ventilation pressure at the tailgate.

Methane make into the face roadway is affected by the rate of progress of the longwall. Noack (1970) describes the gas make as having inert (emission at zero coal output) and energised (increase in gas make per unit of production) components. Noack's scattergram of methane emission in relation to daily output from a German mine shows an increase of methane make with production. However, his insertion of three parallel "lines of best fit" is not mathematically justifiable, and is questioned by Curl (1978).

A subsequent graph of daily output against methane emission (that is, emission per tonne of coal produced) indicates that specific emission decreases as output of coal increases. The reasons for this reduction in specific emission could include the following.

1. The relationship between coal production and methane make is not linear.
2. During period of low production, the abutment zone moves slowly and may become more fractured than coal which is subjected to abutment loadings for a shorter time. When the coal is subsequently relaxed it has a relatively high macro-permeability and emits methane faster.
3. The ratio of inert emission to energised emission initially increases as coal production decreases.
4. Low coal production may have been associated with stoppage or slowing of the conveyor, so the degree of emission from cut coal in the mine was increased.

A comprehensive study in Germany showed that emission correlates better with saleable coal output than with face advance (Curl, 1978). Reasons for this may include

1. non-uniform extraction thickness,
2. emission and saleable coal output are dependent because the saleable coal contains most of the methane. If a face intersects a region which contains little saleable coal, the advance rate may be unchanged, but emission may drop, and
3. non-uniform density of extracted material.

Prediction of the rate of methane flow into workings is complex because of the large number of variables which have been found to affect the rate of methane flow. Some of these variables are listed below.

1. Variables of geological origin

   pressure gradients around the excavation

   effects of non-homogeneous seams

1. The term micro-permeability refers to the fluid conductivity of the porous matrix of a solid (unfractured) particle of coal. Methane can be transmitted through this matrix by diffusion.
2. The term macro-permeability refers to the fluid conductivity of the fissures between particles of coal or other sedimentary deposits.

Undisturbed coal has indigenous fractures distributed through it. Disturbance of the coal results in an increase in the number of fractures (De Villiers, 1989). If relaxation occurs the average width of fractures increases. Both of these changes increase macro-permeability.

The flow capacity of fractured coal depends on the number and width of fractures and their continuity in the direction of flow. The fractures in a given coal are not of uniform size or spacing, especially during the mining process. As the coal face moves, the strata load originally supported by the extracted coal is redistributed through the surrounding coal seam. Strata immediately above or below the excavation are subject to stress relief. As the face advances, collapsed waste will eventually reaccept the strata load.

Researchers are not in general agreement regarding the effects of stress redistribution on permeability in the abutment zone. Airey (1971) related macro-permeability to distance from the abutment zone. He observed that coal particle size decreases as the particles approach the face, and permeability increases as a consequence of the larger size and number of fractures. Dabbous *et al* (1974) performed permeability measurements which showed that coal permeability exhibits a stress hysteresis effect. Indications are that the flow of methane in coal is dependent on the stress history of the coal. Hargraves and Lunarzewski (1985) found that constraint dramatically reduces macro-permeability of coal; for instance, increase of hydrostatic constraint from 1 to 10 MPa in one coal decreased permeability from 10 to 0.04 microdarcy. Mordecai and Morris (1974) undertook laboratory work which showed that when a vertical load was applied to a hydrostatically stressed specimen, the stress first closed the pores and reduced permeability. With further loading, the permeability increased as a result of fracture propagation.

Extreme variation in the permeabilities of coal samples from a single bed has led to the proposal that a permeability distribution is more reliable than a specific value for a coal (Curl, 1978). Curl proposed that at the boundaries of the abutment zones there is a region of stress relief in which induced and indigenous fractures open up and give a greatly increased permeability. A high permeability zone along ribsides and faces appears to be a common feature of all US mines.

Khodot *et al* (1967) estimated the fissure space to be ten per cent of the coal volume when the seam is destressed. Recompaction results in a decrease in permeability, although this permeability is considerable greater than that of the virgin seam.

De Villiers (1989) found that permeability varies with shrinkage of coal. As the coal seam loses gas, coal particles decrease in size, opening up the fissures between particles and thus increasing permeability. A report by Ertekin, Sung and Schwerer (1988) shows a declining curve for production from a drainage well. This supports de Villiers' finding, and also shows the effect of depletion of micropores on well production.

There are several problems associated with the measurement of permeability and the application of the measurements obtained. Curl (1978) concluded that owing to fractures induced during the sampling of the coal the accuracy of such methods is suspect. Laboratory determinations may, however, be of value for comparisons of permeability between strata. It would appear that any permeability measurement must be associated with a stress history of the sample, a description of the method of measurement, the origin of the sample, and an assessment of the effect of induced fracturing in the specimen.

Curl (1978) indicated that the consensus of opinion from published literature is that the micro-permeability of coal is reduced by increased strata load. However, when coal fails under this loading, fractures are formed and macro-permeability increases. The effect of stress on the overall permeability of the coal will thus depend on the physical properties of the coal and whether the flow through the micropores or through the fractures constitutes the major part of the total flow.

Methane moves through fissures by laminar flow. Some authors accept Darcy's Law for gas flow. Others refute it on the basis that there is evidence that gas slippage occurs on the walls of the fissures (Curl, 1978). Empirical measurements have indicated that macro-permeabilities of undisturbed strata are non-uniform, and these are typically very low.

Battino and Hargraves (1982) measured macro-permeabilities of unconstrained Australian coals. The different results obtained with methane and carbon dioxide indicate that permeability is not a simple physical parameter. The diffusion coefficient is strictly dependent on the mobility of molecules according to the Einstein relationship, and consequently, at a given gas pressure the permeabilities for different gases should increase as the mean free paths increase. This has been borne out experimentally by Klinkenberg (1941). The mean free path is inversely proportional to gas pressure. Consequently the experimental method must also be considered. Whether tests were performed underground or in a laboratory can be an important consideration.

Porosity is the ratio of the void volume to the bulk volume of a material (Zhao and Harpalani, 1989). Porosity governs the free methane storage capacity of coal (Curl, 1978). Free methane emission rate is apparently dependent on diffusion rate, laminar flow rate, and the net flow rate of methane which moves towards the workings by each mechanism.

Boxho *et al* (1980) maintained that significant amounts of methane are retained in the coal and surrounding strata as

1. free gas in fissures and pores of the coal and other strata, and
2. adsorbed gas on the internal surfaces of the coal.

Dunmore (1980) found that direct evidence of gas in non-carbonaceous strata is not available. It is difficult to measure because the high permeability of destressed rock samples permits rapid release of gas during retrieval. Dunmore did not address the fact that methane in coal exists in equilibrium, so free gas is available to disperse into adjoining materials if they are permeable.

Sorption is the process of methane retention in coal. Sorption is sub-classified as absorption, adsorption, persorption and chemisorption. Adsorption is a surface effect whereby one substance is physically held on the surface of another. It is a reversible process. At normal coal bed pressures, most of the methane present is adsorbed on the coal surfaces. Methane exists as a free gas in the pores and fissures in coal in equilibrium with the adsorbed gas on the surfaces. The release of adsorbed methane from coal particle surfaces is called desorption (Curl, 1978).

Pressure is the critical parameter affecting adsorption. Adsorptive capacity is directly proportional to gas pressure. Pressure and adsorptive capacity are usually defined graphically by absorption isotherms. These plot the volume of gas adsorbed against pressure at constant temperature (Curl, 1978). Adsorptive capacity is inversely proportional to temperature. At a pressure of ten atmospheres for a given rank of coal, the relationship is linear. At other pressures, the relationship is non-linear (Curl, 1978). The percentage of sorption relative to dry coal is inversely proportional to moisture content, gas pressure and temperature. Ettinger *et al* (1958) gave an expression for the sorptive methane capacity of coal which included moisture content, gas pressure and temperature. Khodot *et al* (1967) proposed a formula to allow for the reduction of adsorption capacity with increased moisture content. A moisture content of 0.5 per cent can reduce the capacity to adsorb methane by nearly 25 per cent (Curl, 1978). A graph of methane adsorption isotherms in Curl (1978) shows distinct differences in adsorption when moisture content changes from 0.5 to 5.0 per cent. Adsorptive capacity is also proportional to coal rank. The relationship between adsorptive capacity and volatile content is shown graphically in Curl (1978).

Laboratory measurements have shown that methane emission from coal samples is a composite process involving desorption, diffusion, and flow through the macropores to the exterior of the

effects of water content
proximity and nature of faults
temperature and temperature gradients
indigenous permeabilities
variations in gas content within each seam
dip angle
degree of emission
contributions from adjacent seams
coal rank
volatile content of coal

2. Variables arising from the mining process
   face length
   history of face advance rates
   effect of advance rate
   the volume of the gas emission space
   the distribution of coal particle size in each region around the excavation
   the fracture systems which occur near the excavation
   rates of change of permeability, such as those caused by the interface between zone 1 and zone 2 subsidence boundaries (defined below) or coal shrinkage
   depth of mined seam
   gas content
   water drainage rate
   other water induced effects
   methane drainage rate
   bulk factor of goaf
   conveyor clearance rate
   residual methane content
   residual methane pressure versus strata dip and distance from the worked seam
   thickness of extracted seam
   distance from abutment zone
   coal particle size (this is inversely proportional to the distance from abutment zone)
   coal shrinkage rates
   emission from adjacent coal seams
   effects of non-coal strata
   strength of surrounding strata
   time-dependent rates of change of many of the above variables

Four approaches to solving the problem of methane prediction have been identified in the literature. Each method is described below, and then Methods 1 and 2 are discussed in more detail. The methods are

Method 1 This method models the zone of gas emission, measures the gas content and estimates the degree of gas emission for each stratum, and multiplies the expected emission per tonne of coal by the average coal extraction rate to obtain the rate of methane make.

Method 2 This Mining Research and Development Establishment (MRDE) method is based on the theory of gas emission of Airey (1971) and is unique within Europe in that the dimension of time is introduced (Curl, 1978). The problems associated with incorporating time as a variable are overcome by application of graphical techniques. Graphs are used to correlate

1. degrees of emission with weekly face advance,
2. total emission with age of district and degree of gas emission,
3. distance from working with depth and degree of gas emission, and
4. coal clearance time with degree of gas emission..

The graphs enable calculation of the,

1. emission from the worked seam,
2. emission from underlying and overlying seams, and
3. emission from broken coal during clearance.

These quantities are summed to give total gas emission.

Method 3 The use of this method is confined to Poland and the USSR. The method involves subtraction of the predicted residual methane after mining from the original methane content of each seam. Curl (1978) has claimed that residual pressure prediction methods are more site specific than Method 1.

Method 4 This method has been used by a number of researchers to mathematically model methane flow into the excavation from the worked seam, or the worked seam and surrounding strata. Typically, Darcy's law and Fick's second law are used to generate flow equations which describe the behaviour of water and methane in strata affected by the mining process.

Owili-Eger and Ramani (1974) developed a model which assumed relatively constant mine temperature and steady-state methane flow. The final flow equation was in the form of a second order non-linear partial differential equation and the solution was implemented by numerical methods. The model was subsequently extended to cover both steady and unsteady state solutions, although the benefits of implementing an unsteady state solution were negligible.

Comparison of the accuracy of the prediction methods is difficult for several reasons as outlined below.

1. The available literature gives little information about comparative testing of prediction methods.
2. Significant errors are known to occur in underground measurement of air flow and gas content. These measurements are used in many methane prediction methods to calculate actual emission values.
3. The size and some other properties of the zone of gas emission are unknown.
4. Coal mine conditions are variable to the extent that methane flow can vary widely during mining.
5. Methane prediction models generally do not incorporate enough variables.
6. The cumulative effect of modelling-induced errors is not discussed by many authors of models.
7. Assumptions may be over-simplifications, or based on insufficient information.

Discussion of Method 1

Various forms of this method have been implemented in Belgium, France, Germany, Poland, the United Kingdom and USSR. The basic parameters are

1. the stratigraphy above and below the worked seam,
2. the desorbable gas content of all relevant seams,
3. the zones of gas emission in the floor and roof, and
4. the degree of gas emission from adjacent seams and strata (Curl, 1978).

The basic steps are as follows.

1. Select the expected zone of gas emission and subdivide it into zones of similar gas content (usually regions of strata), called sources.
2. Establish initial methane content of each source in cubic metres per tonne of source material.

3. Predict the degree of methane emission as a per centage of the original gas content which is expected to be emitted into the workings from that source.
4. Establish the ratio of thickness of source to thickness of extracted material. This ratio is used to convert the calculated emission quantity into cubic metres of gas per tonne of coal extracted.
5. Calculate the average methane flow rate, that is, emission multiplied by average coal extraction rate (Dunmore, 1980).

The degree of emission is the percentage of methane contained within a stratum which is expected to flow to the workings. Curl (1978) emphasised that no prediction of methane flow to mine workings can be more accurate than the accuracy of the gas content determination. The measurement of methane content is most commonly achieved by either a direct method or an indirect method. The unit of measurement for total methane content is cubic metres per tonne of rock at standard temperature and pressure. The total methane content includes free methane and adsorbed methane (Curl, 1978).

The direct method was originally developed by Cerchar[1] in France. Samples of coal are collected from boreholes, and the quantities of methane liberated from the coal over time are summed to find the original methane content. The coal is crushed to obtain as much of the methane as possible. Estimation is required because the coal sample begins to lose methane before it can be enclosed in a sealed canister. Implementations of the direct method vary. Researchers disagree on the pressure at which the sample should be allowed to desorb, the crushing of the sample, and how to compensate for the fact that desorption is an equilibrium process so residual methane remains in the sample. Curl (1978) has suggested that the average temperature and pressure of the working is probably optimal for degassing a sample using the direct method. The MRDE allows samples to desorb in nitrogen to limit oxidation.

The methods of application of the final result to the methane drainage problem are varied. Different assumptions are made concerning the residual methane content of in-situ coal. Many researchers apportion the methane content of in-situ coal into desorbable methane and residual methane. In the United Kingdom it has been found that methane can desorb to zero partial pressure from large blocks of coal. Hence, an extra 1.0 m^3 per tonne is typically added to the desorbable methane content to give the total adsorbed methane content (Curl, 1978).

Kissell, McCulloch and Elder (1973) have obtained good correlation between methane content (measured directly) and specific emission for mines which are deep, large and which have had a sustained coal production of more than 2000 tonnes per day.

The indirect method of measuring methane content involves collection of a coal sample from a borehole and measurement of the seam gas pressure at the collection site. The sample is taken to a laboratory and subjected to increasing pressure at the temperature of the seam. An adsorption isotherm is subsequently plotted. The pressure measured in the borehole is applied to the isotherm to find the original methane content. Kissell, McCulloch and Elder (1973) stated that indirect measurements of methane content are affected by water in coal strata as the water contributes a hydrostatic component to the pressure reading. Paul (1971) showed that the water and methane pressures can be distinguished by a graphical method. A series of comparative direct and indirect measurements was undertaken in Europe. Two thirds of the 51 values measured differed by less than 20 per cent (Curl, 1978).

The use of methane content measurements must be judicious. Curl (1978) has reported that variations in gas content occur in continuous seams, and that large variations in gas content can occur on either side of faults.

The gas emission space is defined as the body of rock which delivers its entire content of gas or part thereof to the air current or to the gas drainage system as a consequence of mining operations (Mucke and Koppe, 1975). Assuming that a coal bed is of infinite size and the excavation is of constant, finite size, the application of this definition to a methane flow model relies on a clear understanding of the following points.

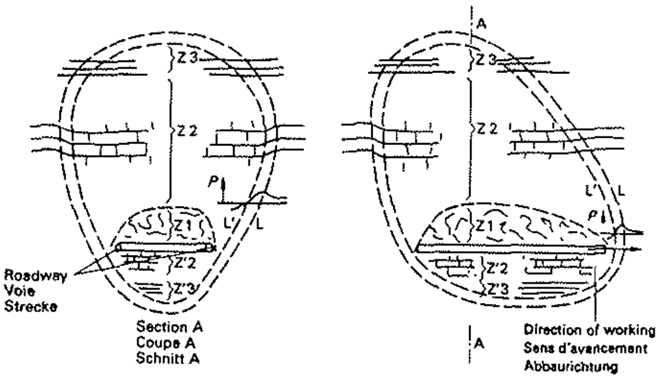

FIG 1 - Face and side views of relaxed zones around a goaf (after Boxho *et al*, 1980).

1. The boundaries of the gas emission space move away from an excavation over time and eventually approach a finite limiting position.
2. The methane make may initially increase for several reasons associated with the initial presence of free methane in the strata.
3. Methane make will peak when desorption rate first becomes equal to the laminar flow rate.
4. The resistance of flow paths to the excavation increases as they lengthen.
5. The pressure gradient decreases as the flow paths lengthen.
6. After diffusion becomes the rate determining step methane make will decrease over time, but will never totally cease.

The following observations have been made when isolated boreholes have been drilled into a coal bed for the purpose of methane drainage.

1. The size, shape and contents of the gas emission space change over time.
2. An underlying assumption is that the gas emission space can be identified at a given time.

The boundaries of the gas emission space are theoretical boundaries and may not be clearly identifiable in a physical sense. Some authors have assumed that the zone of maximum compression surrounding the zone of relaxation forms a relatively impermeable barrier. The assumption of a finite gas emission space can then be used to simplify calculations as the gas emission space is the same as the zone of relaxation. Relaxation increases permeability. Surrounding the zone of relaxation is a zone of compression. The compression is presumed to reduce permeability, and for this reason the zone of relaxation is treated as an isolated gas reservoir which is the gas emission space (Boxho *et al*, 1980).

The front boundary of the gas emission space (near the working face) has been investigated by Noack and Janas (1984). They measured gas emission from boreholes before, during and after undercutting by a coal face. At the site studied, the front boundary intersected the level of the seam being worked approximately 30 m ahead of the face and was parabolic in vertical section, the curvature of the parabola being less above the area being worked than below it. At the edges of the coal face, the front boundary clearly lies behind the position in the middle of the face. Noack and Janas have approximated the boundary of the emission space to a pair of parabolic sections. The curve could also be approximated using two oval or elliptical sections. Certainly the parabolic sections will become grossly incorrect at a finite distance from the face. Distorted ovate boundaries are shown in Boxho *et al* (1980)

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[1] French Coal Mining Industry Research Establishment.

to describe the shapes of the zones of relaxation surrounding an excavation. The use of ovate boundaries in a predictive model would be complicated because of discontinuities between boundaries and a current lack of knowledge of the exact shape of the relaxation zone. Ellipsoidal approximation is feasible and is probably adequate given the uncertainty regarding the boundary of the relaxation zone.

Boxho *et al* (1980) have subdivided the zone of relaxation into three pairs of constituent zones. A diagram is reprinted in Figure 1.

The first pair are referred to as Z1 and $Z'1$, and are nearest the excavation. ($Z'1$ is too small a dimension to be seen on the diagram.) Z1 is composed of material from above the excavation and $Z'1$ is composed of material from below it. In these zones, beds fracture into blocks which are displaced relative to each other. Macro-permeability is high, even after recompression. Boxho *et al* (1980) consider the zone to be isotropic. The second pair of zones are called Z2 and $Z'2$. They lie above and below Z1 and $Z'1$ respectively, and are characterised by rock fracturing and bed separation. After recompression, macro-permeability is more than virgin permeability, although considerably less than it was during the period of maximum relaxation. Macro-permeability is anisotropic, being greater parallel to the bedding plane than in the plane normal to it, according to Boxho *et al* (1980). This observation may be interpreted as a consequence of the degree of bed separation which occurs and the closure of fissures during recompression. The third pair of zones are called Z3 and $Z'3$ and lie above and below Z2 and $Z'2$ respectively. In zones Z3 and $Z'3$, the rocks are relaxed although relatively unfissured. This relaxation is sufficient for coal seams to become more permeable and for gas to escape providing there are outlets such as roads or boreholes. Permeability between bedding planes in $Z3/Z'3$ is zero. However, it is sufficient to allow escape of gas if a flow path (for example a borehole) intersects a seam.

The zones of relaxation are delineated by a zone of maximum stress. This has a distorted ovate shape, as shown in Boxho *et al* (1980).

The critical size is defined as the maximum size for a working which does not cause surface subsidence. If a working is above the critical size, either alone or in combination with other workings the zone Z2 opens out at a decreasing rate as time passes, becoming higher and wider. As this zone increases in height, the mass of material within the zone increases, compressing the lower part and decreasing macro-permeability.

At a certain distance behind the face, Z1 is completely degassed, and the permeability of $Z2/Z'2$ decreases as a result of recompression. Gas pressures are low as a result of depletion of the reserve, and the drainage rate decreases to a negligible value (Boxho *et al*, 1980). Boreholes which are connected to the drainage system increase the possibility of drawing more air than methane because there is no connection to a significant methane reserve. An exception is boreholes near the starting line of a face. These may have a long service life. This is possibly because these drain gas from strata beyond the zone of maximum stress.

The relaxed zone may extend 20 m laterally from the workings and into the rib sides. It narrows near each end of the panel. Boxho *et al* (1980) also indicate that $Z'1$ is approximately 2 to 5 m deep, and $Z'2$ is approximately 20 m deep.

Discussion of Method 2

This method is based on the theory of gas emission from coal of Airey (1971). It involves calculation of the extent of degassing of overlying and underlying seams, and calculation of the degree of emission from each seam. Degree of emission is assumed to be dependant on distance from the worked seam and the age of the working district. A computer program calculates the predicted emission rate as a function of time. Expected ventilation air flow and face advance rates are input parameters. Total methane emission is considered to be divisible into three categories.

1. emission from the worked seam
2. emission from overlying and underlying seams
3. emission from broken coal during clearance

The degree of gas emission from the worked seam before the coal is cut is a decreasing function of the rate of face advance. Because of the stress distribution around workings, the distribution of degrees of gas emission is regarded as asymmetrical above and below the worked seam. Results are presented graphically for ease of interpretation. The ordinate axis shows weekly advance and output of coal. Two abscissas show methane drainage flow and required air quantity. A third abscissa shows the amount of additional ventilation flow which would be required if drainage was not used and emission was steady. Average and peak required air quantities are plotted for the return end of the face, and for outbye in the return. Peak quantities are determined by multiplying the average quantities by a coefficient of irregularity.

The general pattern of emission is predicted assuming a five-day working week and a constant rate of face advance. The variation in emission is attributed to irregularity in face advance rate by varying the degree of degassing. The calculation of emission rate from adjacent seams allows for the effects of recompression of the goaf.

Curl (1978) examined and compared the following methods of prediction

1. Barbara method (Poland)
2. Cerchar (French Coal Mining Industry Research Establishment) methane prediction method
3. German methods: Flugge; Winter; Jeger
4. Gunter's method
5. INIEX method (from Belgium)
6. Jana's method
7. Kissell's method of estimation of methane emission into workings
8. Lidin prediction method
9. MRDE method
10. Stuffken's method
11. United States Bureau of Mines model

His conclusion was that the MRDE method alone was based on a coherent physical theory. The methods of Flugge, Jeger, Winter, Schultz and Lidin gave results of the same order of magnitude, although they tended to be lower than MRDE predictions. A major difference between methods was their treatment of non-coal strata. Differences between methods may be largely due to the fact that they were developed in different countries with different mining conditions.

The advent of computer modelling methods, and particularly finite element techniques, enable predictions based on the nature and extent of the relaxation zone surrounding longwall workings to be made from basic stratigraphic and geomechanical data. Such a model is currently being developed and evaluated at The University of Queensland for Bowen Basin (Queensland) conditions (Anderson and Gillies, 1990).

CONCLUSIONS

Methane emission into longwall coal mines is a complex problem which is influenced by many variables. Clearly, the need for an understanding of the mechanisms of methane emission and, more importantly, prediction, has led to considerable research on the subject. However, the predictive methods developed in several countries with different mining conditions generally include simplifying assumptions which result in a degree of site specificity for each model, and to date there is no universally accepted method available. The trend in recent years to adopt longwall mining has made the need for such a predictive model more urgent. More research is clearly necessary to achieve this end.

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