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MINING GASSY COALS

Ian Gray

ABSTRACT: This paper reviews the basic factors and practice of mining gassy coals worldwide. It then suggests how changes need to be made to Australian mining methods to deal with the challenges of mining deeper and gassier coals.

THE BASICS

Gassy coals are coals that generally contain methane generated in the coalification process but may contain carbon dioxide. Other gases may also be present in low concentrations. Carbon dioxide is normally introduced to the coal through igneous events. Many coals are wet and have a reservoir fluid pressure that is higher than the pressure at which gas would be released from the coal, referred to as the sorption pressure. This pressure is akin to the bubble point of a conventional oil reservoir which contains solution gas. The gases in the coals are principally stored by a process of multilayer adsorption. In the water saturated state the water in the coal contains solution gas. Some coals are, however, not water saturated and has free gas in their pore space. From a reservoir viewpoint the free pore space in coals is that which is interconnected in a cleat network.

Cleating

The cleat in coals is generally well recognised in Australian and US coals and usually takes the form of a fracture network which is near perpendicular to the seam. There is generally a major or face cleat and a butt cleat which is approximately orthogonal and less well developed. The cleats may be open or filled with clays, carbonates or other minerals depending on the history of the coal. This cleat pattern is however not a universal trend. Many coal seams in Russia and China have a cleat pattern that is not developed to any extent, or where present, is quite irregular. The presence or otherwise of a cleat pattern has a major influence on the mechanical properties of coal and in particular its drainage characteristics.

What is a gassy coal?

The definition of a gassy coal is a relative term. An Australian bituminous coal used for coking purposes might be regarded as gassy if its gas content is 10 m^3/t. If this gas content existed in a semi anthracite from Shaanxi Province in China it would not be considered to be particularly gassy. The reason for this is, in part, the sorption isotherm characteristic of the coal. This describes the volume of gas stored in a coal as a function of pressure at the seam temperature. Frequently, this gas storage is approximated by the Langmuir Equation (1).

$$V = \frac{V_L P}{P + P_L} \qquad (1)$$

Where:

V= Volume of gas stored in isotherm, m^3/t;
V_L = Langmuir Volume, m^3/t;
P= Pressure, MPa;
P_L= Langmuir Pressure, MPa.

More gas is stored in coals of higher rank for a given pressure. The higher the moisture level of the coal the lower the gas storage capacity. This may be seen as being due to the water and methane competing for storage on the coal surface. Sorption isotherms are generally regarded as being reversible and can be generated by measuring the uptake or release of gas from coal over a range of pressures. While Mavor (1990) suggests that the moisture content should be normalised to a level controlled by humidity there seems little justification for doing this. Rather, the process of testing at as close to an *in situ* moisture content as possible is needed. This is generally obtained by testing core as received. When mixed gases exist there is a further level of competition between the gas types and

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water. Clarkson and Bustin (2000) describe a process for arriving at mixed gas isotherms using the individual isotherms of the component gases.

It would seem that the order in which the gases came to exist in the coal may have an influence on the storage. The question may well be asked what has really happened to a coal that has generated methane under wet conditions; has lost most of that gas due to groundwater movement; has then had a carbon dioxide rich hydrothermal sweep move through the seam replacing the methane and leading to carbonate filling of the cleats and a raised temperature; this raised temperature then leads to the generation of more methane. This is a complex but real scenario for many coals.

There is, however, always a level of uncertainty in knowing the true nature of the sorption isotherm as recreated in the laboratory, due to a lack of knowledge of the precise moisture content and due to a lack of knowledge of the history of the coal. The measurement of what is termed the native sorption isotherm is therefore advocated. This is arrived at by placing coal in a sealed pressure vessel, either as part of the coring process or by the use of a sealed core barrel, though the latter is not commonly available. In the former case the pressure vessel is normally a close fit on the core and the small excess volume is taken up with water. Once sealed in a vessel, a pressure equilibrium is reached. Once this has occurred a quantity of gas is released and the pressure is once again allowed to reach equilibrium. This process may be repeated with measurement of the gas and water release and of the equilibrium pressure. As with all sorption isotherm or desorption measurements, this should be undertaken at the reservoir temperature. The correct knowledge of the sorption isotherm is vital in the assessment of whether coal is gassy or not.

Diffusion characteristics

Knowledge of the diffusion characteristics of coals is also important. Coals release gas at quite different rates. This release of gas from coals is generally thought of as Fickian diffusion down a concentration gradient though other types of diffusion such as Knudsen diffusion also may exist. In terms of Fickian diffusion, the rate of gas release from a coal lump is determined by the diffusion coefficient, the concentration of gas (gas content) and its size and geometry. Because coals are always to some degree heterogeneous and may contain fractures, the direct use of the theoretical equations of Fickan diffusion (Crank, 1975) seldom accurately describe the rate of desorption from a lump of coal or a core. They do however, seem to quite accurately describe the diffusion of small particles of coal (Gray, 2011a), when the effects of fractures and heterogeneity are removed.

Characteristically, the diffusion behaviour of lump coals show a more rapid initial gas release rate than would be expected if the coal followed Fickian behaviour. This means that an estimate of the diffusion coefficient made from the rate of early desorption will be of a higher value than one made at a later stage of desorption.

The use of Fickian diffusion equations are, however, the basis for determining the lost gas component of core that is retrieved during wireline coring operations. In this, the gas release is approximated by the first order term of the equation that describes the initial diffusion from a solid cylinder shown in Equation (2).

$$\frac{V_t}{V_\infty} = \frac{4}{\sqrt{\pi}}\left(\frac{Dt}{a^2}\right)^{\frac{1}{2}} - \frac{Dt}{a^2} - \frac{1}{3\sqrt{\pi}}\left(\frac{Dt}{a^2}\right)^{\frac{3}{2}} + \cdots \qquad (2)$$

Where:

V_t=Cumulative volume of gas released at time t (consistent units);
V_∞=Total volume of gas release (consistent units);
a=Core Radius. m;
D=Diffusion Coefficient, m^2/s;
t=Time, s.

The lost gas is typically derived by plotting the cumulative gas release versus the square root of time and projecting the straight line slope back to cover the time over which this gas loss occurs. While this period is usually poorly approximated as half the period it takes to retrieve a wireline core barrel (AS3980) the slope is in itself a very useful measurement. Using the slope and the final total gas volume it is possible to determine the apparent initial diffusion coefficient. This is given in field units in Equation (3).

$$D = 3.273 \times 10^{-3} \cdot \left(\frac{Sl.a}{V_{\infty}^{ml}}\right)^2 \quad (3)$$

Where:

Sl=Slope of the Initial Desorption Plot ($\frac{\mathrm{ml}}{\sqrt{\mathrm{min}}}$).

The apparent initial diffusion coefficient would be a precise measure if the core were a cylindrical solid of radius ***a*** with a uniform diffusion coefficient. If the core is substantially free of fractures this is an approximation to the early real value of the diffusion coefficient. However, if the core contains fractures that are significantly more closely spaced than the core diameter then a more useful measure is that of the slope of the plot of initial desorption versus square root of time, divided by the total gas volume and mass of core.

As an alternative to using a diffusion equation, Airey (1968) used an empirical equation to describe the rate of gas release from broken coals. This is shown in Equation (4).

$$\frac{V_t}{V_{\infty}} = 1 - e^{\left(-t/t_0\right)^b} \quad (4)$$

Where:

t_0=Characteristic desorption time (consistent units with time, *t*);
b=Shape factor (dimensionless)

The diffusion equations provide a basis for determining how coal will release gas in the broken state. This is important in determining gas make at the face as coal is cut and fragmented. It is also important in determining the propensity of the coal to outbursts. In either case, the gas release rate is determined by the particle distribution size, total gas content and the diffusion coefficient. In the case of outburst the ability of the coal to deliver gas at pressure into the spaces between fragmenting coal is a significant contributor of energy to the outbursting process.

Permeability

Coal permeabilities measured in Australia have been shown to vary over six orders of magnitude, from a few microdarcies to several Darcies. This variation is essentially a function of the frequency, interconnectivity and openness of the cleat network. The coal permeability varies spatially and with effective stress. The state of effective stress is affected by the fluid pressure and state of desorption of the coal as the coal shrinks as it releases gas or dries. The coal's response to shrinkage is highly dependent on the coal's modulus which tends to rise significantly with confining stress. These processes are described by Gray (2011 b). The variability of coals means that their gas conditions are quite different and therefore the methods to mine them must be varied to suit the conditions.

PROBLEMS WITH MINING GASSY COALS

The problems posed by gas in coal are several fold and include outbursts, gas make from ribsides into the roadways, gas make from coal when it is being cut, and the production of gas from coal seams that are in the relaxed zone of mining, whether the seams are relatively intact or substantially broken in the goaf. In some cases the gas released into coal mines may come from sources other than the coal itself. Contributors may be carbonaceous shales or porous sandstones.

Outbursts

Outbursts are the expulsion of gas and coal from the working face. The violence of the outburst is dependent on the energy release that occurs with it. This is a function of the size of the coal mass affected and energy release per unit volume of that coal. The energy release is derived from the strain energy stored in the coal and rock, the energy of gas stored in free pore space (cleats) and the gas that diffuses from the coal. Some of this energy will be absorbed by fragmentation of the coal. Thus, coals that are already broken such as fine fault gouge material pose a particular problem in that the energy required to fragment them is negligible while their ability to desorb gas quickly is high. This process is explained in more detail by Gray (2006).

The main way to prevent outbursting is to drain gas thus relieving this element of stored energy. The degree to which drainage must be achieved to avoid outbursts is dependent on the gas type, the initial diffusion coefficient, the gas content/pressure as related by the sorption isotherm, and the potential for the coal to fragment. These are the factors that should be taken into account in determining outburst risk. Drainage does not necessarily relieve a highly stressed coal of strain energy release when it breaks. It should also be appreciated that weak coals which are confined may be highly stressed behind a solid face and if that face suddenly fails, this energy may be suddenly released. Nevertheless, despite all these additional factors which should be taken into account, particularly in more stressed coals, the main factor used in determining outburst risk is gas content.

The value of the gas content at which it is safe to mine is dependent on the gas and coal. It may be that it is safe to mine an anthracite coal at 13 m^3/t, a value which would be likely to lead to a significant risk of outbursting in a sheared bituminous coal. The reason for this is principally the difference in the sorption pressure and coal toughness. Permeable coals are not generally considered to be a risk from an outburst viewpoint because the gas has drained from them ahead of the mining face.

Gas make into roadways

Gas make from the ribsides into underground roadways is a function of the reservoir characteristics of the coal seam. Many coal seams are wet and the water pressure must be lowered to below the gas desorption pressure before the gas is released from the coal. Once gas is produced in the cleat network, a two phase Darcy flow regime will exist in the cleats. The rate of Darcy flow is determined by the potential gradient and the permeability to either the gas or water phase. The potential gradient contains both pressure and gravitational terms. In many cases the gas release rate is determined by Darcy flow, however in a few coals the gas release rate is limited by the rate of diffusion from the coal solid into the cleat network. This is particularly the case where the cleating is widely spaced and the permeability high. Therefore, unless the rate of gas release is governed by diffusion, the coals that pose the most problems with gas make into roadways are those with high permeability and an adequately high sorption pressure to drive the gas through the cleat network. Gas drainage by in seam drilling is particularly effective in dealing with such situations. In some cases it is necessary to lower the water pressure significantly to achieve gas drainage and care needs to be taken to design the gas drainage system with adequate peripheral drainage to cut off water recharge to the block being drained. It is then possible to lower the seam reservoir pressure to a level that permits gas to be released and drained. Generally, dealing with high permeability coals is a comparatively easy process that can be accomplished not only by in-seam drilling, but also in some cases, by the use of vertical wells.

Coals may also be quite dry and behave as single phase gas reservoirs from initial drainage. This situation has been found in highly permeable coals of the Surat Basin in Queensland where it would appear that the free gas is essentially a gas cap in the traditional petroleum sense in what are otherwise water saturated coal seams. Essentially dry coal seams have also been found to exist in the very tight coals such as those of the Karaganda basin in Kazakhstan.

Gas make on cutting

As coals become less permeable the gas release from the ribside becomes less and the problem of gas make shifts from the ribside to that from the coal being cut. The limits of gas content to minimise outburst risk are frequently far lower than those that would be required to permit high production mining. The concern with gas make at the face, whether it is on development or on a producing longwall, is the risk of developing an ignitable mixture. The factors that control the rate of gas production are: the rate of cutting, the coal's gas content, its diffusion rate and the particle size distribution of the cut coal. The latter is determined by the cutting means and the nature of the coal. Some coals will break to produce a fine product no matter what the pick lacing of the cutting head. The measurement of coal core desorption rates is a very important basis for determining what the gas release rate on mining will be.

Experience in Russia would indicate that coals with higher moisture content desorb gas less rapidly. Thus, the use of water infusion may serve a far more useful purpose than dust control. This is worthy of investigation in the context of varying coal types as it may prove to be very important for face gas control elsewhere.

Gas make from relaxed zone

The drainage of the relaxed zone around a mined seam may be the key to being able to continue mining safely at economic rates as very large gas releases may occur from broken strata. If these releases occur continuously they are easier to deal with than where the ground breaks suddenly leading to a large release of gas which may expose the face to an explosive mixture. The general purpose of relaxed zone drainage is to draw the gas into boreholes or drainage galleries under the use of vacuum so as to reduce the face concentration. Care must be taken to not draw in excessive air thus causing the mixture that is being drained becoming explosive. Too much vacuum may also lead to spontaneous combustion if air is drawn through coal. How relaxed zone drainage is achieved is dependent on its exact purpose and the conditions existing in the mine.

One of the important uses of relaxed zone drainage is in draining the longwall block of gas prior to mining. In this situation the longwall block has usually been drilled from the gateroads prior to mining. These holes might serve a function of some pre-drainage. If however, the coal is highly impermeable then the gas quantity obtained in pre-drainage may be minimal. When the longwall approaches it causes a raised abutment stress with subsequent de-stressing as the coal passes its peak strength and yields. Under these circumstances the coal in front of the face may yield the bulk of the gas it contains to the in seam holes. These holes should be operated at a modest vacuum.

Such holes need not just be drilled in-seam. The practise of drilling above or below the seam and waiting for the stress changes to cause relaxation of the strata around the seam to permit gas release is fairly commonly used. The complications with the use of such holes is in keeping them open and in ensuring that they have an adequate gas carrying capacity as the volumes of gas liberated may be very large. In some situations the use of a drainage gallery above the seam being mined is used. This may be used on its own or with drainage holes drilled from it. In the case of either borehole or gallery their success is dependent on how well they stay open and what vacuum may be applied to draw gas away from the workings. To try and achieve the maximum level of openness of hole or drainage gallery these need to draw gas away from the broken ground toward solid ground. Under these circumstances, if the hole or gallery is sheared at the goaf end, then the remainder of it continues to operate.

In some mines goaf drainage can be achieved simply by the use of vertical holes which are usually cased and have vacuum applied to them. Such holes are usually drilled from surface to the location of the goaf for a seam which has not had mining take place above it. Where overmining has been used, drilling of surface gas drainage holes becomes much more difficult as it must pass through old goaf areas. The vacuum level applied to such surface holes is usually automatically controlled so that the gas composition does not fall below a prescribed level. There is no reason why such automatic control should not be applied to underground boreholes other than cost. The technology exists to implement it. The benefits of using such a system to minimise face gas make and minimise the risk of spontaneous combustion caused by drawing air into the relaxed area by excessive vacuum are considerable.

LOW PERMABILITY COALS

Gassy coals that have very low permeabilities pose particular challenges to economic mining. This state of low permeability may be caused by the infill of cleats with mineral matter or may be brought about by the high stress state of the coal. In either case, the only way to drain the coal is to bring about an increase in its permeability. There are essentially only two means to achieve this.

Shrinkage induced stress relief

If effective stress in the coal decreases readily with gas drainage due to shrinkage then inducing initial drainage will lead to improved permeability. This effect can sometimes be quite dramatic as at Leichhardt Colliery in Queensland (Gray, 1983 and 2011b) when the permeability appeared to increase by several orders of magnitude. Such cases are brought about by desorption pressures that are close to reservoir pressure, high shrinkage behaviour, stiff coals and low initial stresses. Where carbon dioxide is the seam gas the shrinkage with gas release may be greater than that with methane. Dartbrook Colliery in New South Wales epitomised this situation. It had a lightly stressed stiff coal with high levels of shrinkage associated with the carbon dioxide seam gas. Here in some locations, where dawsonite (a carbonate) filled the cleat system, the only way to bring about initial drainage was to hydrofracture the coal from in-seam holes. Once drainage was initiated, shrinkage brought about great improvement in permeability and drainage. The coal could then be mined with manageable gas levels.

Mining induced stress relief

Where the factors such as higher fluid pressure in the coal, reduced shrinkage, less stiff coal and sorption pressures that are significantly below reservoir pressures change, the situation may be reversed and the natural trend is for the coal to reduce permeability with drainage. Under such circumstances the method required to decrease effective stress is to remove material.

The traditional practice used in countries with tight coals is to mine one seam to cause relaxation of the adjacent seams thus reducing the stress in adjacent seams. Mining may be accomplished from the top down or from the bottom up. This sort of operation is, or has been, practised in China, Germany, Kazakhstan, Poland, Russia, Ukraine, and the UK. The extent of the zone relaxed by mining the first seam is dependent on the geomechanics of the situation but may typically extend 50 m from the seam being mined. The first seam to be mined is chosen because of its suitability to being worked first. Of prime consideration in this case is a low risk to outbursting brought about by the tough nature of the coal, its lack of geological structure, lower gas content and other related factors. It may also be chosen for its comparatively low working height so that excessive disruption of the adjacent seam to be mined next does not occur, especially if there is little interburden.

Drilling induced stress relief

Alternatives to mining an entire seam for removing material so as to facilitate de-stressing have come in a variety of forms. The most commonly practised has been the drilling of relief holes in a face. These have been drilled anywhere between 0.1 m diameter to the 1.3 m used at the Japanese mine of Akabira in the 1980's. Such holes serve only to drain gas unless conditions exist so that failure occurs leading to fracturing which propagates from the borehole. To do this the stresses must be sufficient that they cause significant failure of the coal around the boreholes. The practice of washing ouburst prone material from gouge zones has been tried in what was the Soviet Union but without the protection of some well control system. Drilling holes without some form of well control has led to uncontrolled emissions and outbursts.

In Australia, the process of water jet drilling followed by slot cutting to relieve stress has been tried. This has apparently not been successful because gas content remained high in the environment in which it was tried. There is however, no reason to reject the technique simply because it has not been successful in a single application, there needs to be an assessment of the reasons why the system did not work under the specific conditions that existed where the trial took place.

WHAT NEXT?

Coal mining has taken place in deep, highly stressed and gassy conditions for many years in a number of countries and methods have been developed for working in such conditions. Australia has developed underground mining in conditions that are, by comparison, relatively shallow and not as gassy as many other operations when considered on a world scale. The standard Australian approach has been to drain gas by in-seam drilling to lower the gas content to avoid outbursts or to de-gas a block prior to longwall mining. This has been permitted by permeabilities that are generally high enough (>1 millidarcy) that such techniques have been successful. The permeability has furthermore been seen to increase with drainage in many of the shallower coals. These conditions have allowed some gassy Australian coal mines to be highly productive.

Mines are now being planned to be worked at greater depth than is current practice. This means that instead of 600 m in New South Wales and 400 m in Queensland consideration is being given to working at 800 m and deeper. These depths bring with them challenges in terms of high stresses, higher fluid pressures and in some cases much lower permeabilities. Australian coal mining has seen glimpses of what may await it as it goes deeper through zones in existing mines that have had either extremely low permeability or borehole collapse, or both. There have also been situations where the permeability declines with drainage as fluid pressure is lowered and effective stress increases. It should be pointed out however that while there is a general trend to declining permeability with depth there are many coals that do not follow this trend as evidenced by experience in the testing of deep coals for commercial gas production.

Current Australian approaches to dealing with high gas and low permeability conditions have been to drill many holes through the zones that will not readily drain, to attempt hydrofracture, to remotely mine or to use permitted explosives to shotfire through difficult coals.

The drilling of multiple holes has been found in some cases to be completely ineffectual, either because the holes close or because the coal is too tight to permit any significant drainage. The consequence is large delays in production while the mine re-adjusts its plan to negotiate around the difficult zone. The problem here is as much a failure to take into account the real risk factors for outbursting as a lack of technology to deal with the drainage problem.

The use of hydrofracture from in-seam holes was applied successfully to Dartbrook mine in the Hunter Valley of NSW. This was however a shallow mine with strong coal and a high shrinkage that led to enhanced permeability. Attempts at hydrofracture in the Bulli seam have been unsuccessful because the coal has inadequate strength to support a packer and because casing in-seam is impractical both from the viewpoint of the difficulty in doing so and because leaving steel in seam is highly undesirable for future mining.

The use of remote mining has some benefits as it removes personnel from the immediate zone of outburst risk. However the possibility of the occurrence an outburst that will send a slug of explosive gas through the mine is a real possibility. The same comment applies to shotfiring through outburst prone coals except that there is the additional risk of an outburst catching unaware crew returning to the face after the shot. In either case, the potential exists for an outburst to come from the ribside behind the face as occurred behind a road header at Pervomayskaya mine in the Kuzbass in 2005.

Dealing with the outburst challenge

Australian mining has used gas content alone as an indicator of outburst proneness. While this approach has served the industry well in terms of there being no outburst fatalities for many years, it should be recognised that it is a simplistic approach developed empirically for the Bulli seam. There are many other factors apart from mere gas content that contribute to the occurrence of an outburst. To prevent outbursts occurring under changing conditions and indeed to save the industry the large cost due to unnecessarily lost production it is very important that new approaches be taken to determine the true risk of an outburst occurring. A system based on the total net potential energy available within a coal mass as being a far better indicator is advocated. This will take into account strain energy, adiabatically expanding gas derived from desorption or pore space, and the toughness of the coal. It is considered that this approach can be made sufficiently straightforward that errors due to its increased complexity can be avoided.

Safely mining an initial tight gassy seam

The problems associated with mining a single gassy seam or the first of multiple seams remain essentially the same. The seam must be mined safely and economically. In the case where the seam being mined is the first of multiple seams it may be considered that the de-stressing being brought about by mining it is the key to mining the adjacent seams and therefore the economics of mining this seam should be considered in the context of the entire mine economics. In this case, the first seam to be mined may be considered as being an essential part of the mine degassing and mining process.

Pre-drainage for development

The first consideration in mining is to be able to develop in safety. This means that outbursts should be prevented. Potential energy stored within the coal needs therefore to be brought to a safe level. A key component in this is reducing the gas level. If the coal has a very low permeability the drainage will be very slow and some process will be required to stimulate flows. If in addition, boreholes will not stay open because the stresses in the coal are sufficiently high, and the coal strength inadequate, then borehole collapse will occur. Under these circumstances the drilling of in seam holes for gas drainage is a pointless exercise. If however, conditions exist whereby large scale failure is brought about by drilling then, provided there is adequate control over gas and material discharge from that hole, systems such as large augers or water jet erosion may be considered as a useful tool for de-stressing and degassing, albeit on a local scale. Such localised techniques have great potential to permit mining to negotiate gouge zones that would be particularly outburst prone.

In the more general context of a highly impermeable coal seam that cannot be drilled because of hole collapse and is highly gassy, alternative means to drain the seam are needed. Hydrofracturing has great promise because the fracture is held open by the use of a propant, usually sand. The problem of hole collapse may, under the right circumstances, be avoided by not drilling in the seam the hole from which the hydrofracturing process is conducted. Rather the hole may be drilled in rock adjacent to the seam provided that the rock is of adequate strength to withstand the stresses therein. Doing this enables the hole to be cased and cemented so as to maintain its integrity. The casing can then be perforated and hydrofractured in multiple stages. By this process hydrofractures can be created at intervals that might be as close as 6 m. For the process to be successful the hydrofracture needs to propagate into the coal seam and transect the seam.

The fracture needs to propagate from the borehole to the seam in a direction that is usually vertical. If it were to extend horizontally then it would not extend into a horizontal seam. For it to propagate vertically from the borehole the minimum effective stress needs to be horizontal. This is a function of the local stress regime which is in turn dependent on the weight of the strata, the Poisson's ratio and Young's modulus of the rock and the tectonic strains that exist (Gray, 2011b). If the tectonic strains are sufficiently high in the horizontal direction and the rock is stiff then there is an increasing tendency for the horizontal stresses to be high. Rocks with high Poisson's ratios also tend to have higher horizontal stresses.

The development of the fracture from the borehole is dependent on the stress regime in the rock and nature of stress concentration around the borehole or the perforation. Good perforating techniques lead to reduced fracture initiation pressures and the rapid development of a fracture that is orthogonal to the minimum principal stress. Such a fracture will extend evenly outwards from the borehole until it reaches a lower stressed rock such as a coal in which it will thereafter preferentially propagate.

The techniques to permit such an operation have substantially been developed for the tight gas and shale gas industries. Their use in tight coals will however require some adaptation as it is envisaged that the fracture spacings are likely to be much closer than in the above industries. However, the need to extend the fractures is likely to be much less than those required in shale gas industries as the prime requirement is likely to be the degassing of development roads. It is envisaged that surface to in-seam drilling could be used with such a hydrofracture system for initial development but thereafter the process would be handled more cost effectively by drilling and casing from underground, quite possibly from roadways created in rock specifically for the purpose of drainage. In this case, the cement for casing, perforating jet sand fluid and hydrofracture sand fluid mixtures could be pumped at the surface and reticulated to the underground via a system of cased holes and high pressure pipework.

Whether the coal permeability decreases or increases with drainage merely affects the choice of the spacing of the hydraulic fractures along the borehole length so as to achieve drainage within a specific period. Too close a spacing may however lead to fractures coalescing and not adequately extending laterally.

Pre-drainage of the production block

Once development may be undertaken in safety then the problems of gas make on cutting need to be addressed. While it would be possible to employ the hydrofracture techniques discussed to de-gas an entire longwall block this may not be economic. If boreholes, which stay open, can be drilled in the coal and abutment stress changes create a de-stressed permeable zone in advance of the face then it may be possible to utilise this technique to drain the block with vacuum ahead of the face. This technique is not, however, applicable to the start of the longwall extraction when the abutment stresses have not been developed. Some other approach is required in this case. This could be by hydrofracture.

As the key to increasing the permeability of coal is to de-stress it, then the approach to achieving such de-stressing is to remove material. This might be done by cutting the coal to relieve stress, which could be accomplished in a variety of ways including the use of water jets. However, a simple chain cutter run between gate roads would achieve this function with minimal equipment cost. What is envisaged is a toothed chain pulled around drive wheels located in the gate roads with a leading and following chain. This would cut a slot of about 150 mm width parallel with the seam, thus de-stressing it. The gas quantity produced is likely to be significant and some means to collect this gas would be needed. This could be by pre-drilled holes, if these would remain open, or by a shroud arrangement drawing gas from the slot. The slot could be expected to close to some degree a few metres behind the passage of the chain unless it was filled with a propant. The question as to whether the chain would become trapped

by the slot closure needs to be considered in some detail, taking into account the force that could be exerted on the chain. The pumping of propant filled slurry behind the chain may be able to be used as a form of permeable stowing that would permit drainage.

Drainage of the relaxed zone

The production of gas from coal and rocks in the relaxed zone or goaf may be the single most important factor in determining whether production can take place at economic rates. While vertical goaf drainage holes may serve to drain the goaf in a single seam shallow mining operation, they are unlikely to be suitable for most multilevel seam mining. The reasons for this are the difficulty in maintaining a hole through multiple goaf formations and the extreme difficulty in drilling through old goaf areas.

Drilling holes into the roof or floor strata from longwall gate roads is a difficult and time consuming process. These holes often have to be drilled at close spacings to have adequate effectiveness as they frequently become blocked by rock movement adjacent to the gate road. In some cases, casing has to be installed for approximately the first 60 metres to avoid the hole closing. In addition, the volume of gas that is produced requires a significant number of holes or large hole diameters. Having to repeat the drilling process for each longwall block is a time consuming and expensive process.

One alternative is to create long boreholes in rock between seams. These can be drilled either along the longwall block so that the rear portion of the hole is being absorbed into the goaf, or they can be drilled across multiple longwall blocks in which case entire hole ends would disappear into the goaf as the face advances. In the latter case, the holes would need to be drilled at a reasonably close spacing to pick up the gas being emitted. The drilling of holes of 3 km length in rock requires significant underground drilling capacity, but is technically feasible.

The volume of gas that may be expected in some situations could require a hole of 0.5 m diameter to ensure that a vacuum is maintained to draw gas from the end of the hole. In some countries, such holes would be mined as drainage adits, a process that permits full support to be used. In the Australian context, the cost of this may be high and consideration should be given to the use of remotely controlled tunnel boring machines for this purpose. The prime challenge that these would face is one of ventilation, or more promisingly, intertinisation of the hole, and in making the equipment flameproof. As holes become larger the problems of support become more complex with joint related failure becoming increasingly important.

CONCLUSIONS

While some gassy coal seams will continue to be able to be drained for mining using various permutations of current practices of surface to in-seam or underground drilling, others will not. This particularly applies to the deeper, more highly stressed and impermeable coals. Under these situations, drilling in-seam can be extremely difficult due to hole failure which becomes more of a problem as the fluid pressure is reduced. In addition, the permeability may drop to a few microdarcies. In these conditions in-seam drilling is not an option.

Under these circumstances drilling needs to be conducted in more competent strata adjacent to the seam. These holes can then be cased, cemented, perforated and hydrofractured through to the seam so as to initiate drainage over a far greater area than that available to a borehole. This can be conducted through surface to in-seam holes or from underground. In the latter case, a system for the reticulation of hydrofracture fluid through the mine development would be useful. The hydrofracture spacing may be reduced to several metres to cope with low permeability coals. Whether the coal drains after fracturing will depend to some degree on the stress changes that the coal undergoes during drainage. These hydrofracture techniques are likely to be suitable to lower gas contents so that mine roadway development may take place. In this case, the hydrofracture borehole is probably best situated in the floor beneath the roadway or gate roads so as to avoid damage to the roof.

The main block of coal will also need to be drained before production takes place. This could be accomplished by the same technique as for development but is probably better handled by using the traditional approach of using abutment loading to break and de-stress the coal and thus promote drainage. An alternative approach of slot cutting the longwall block to de-stress it and promote drainage may be an option.

The use of mining to relax and de-stress adjacent seams so as to promote gas flow and permit the subsequent mining of that seam is considered to be a very important technology that will need to be utilised in Australia. Indeed, in some cases, its use is the only way in which mining may economically take place. In Europe, Russia and China the mining of an initial sacrificial seam at sub economic rates is often the only way to improve the permeability of other seams so that they may be drained and mined without risk of outbursts and gas outs of the face.

The traditional practices, of cross hole drilling from underground to collect the gas from the relaxed zone are however thought to be inefficient. Rather it is suggested that alternative technologies that permit the drilling of long, large diameter holes along longwall blocks or across multiple blocks could be beneficially used. Technology to drill such holes is available or may be readily developed.

The overall concept is presented in Figure 1 where drilling is accomplished from drainage adits driven in rock. Such adits could be fitted with pipe work for gas removal, or the entire adit be used for gas removal.

The total drainage process lends itself to an approach where a large block containing several seams and a number of longwall blocks are prepared for mining by drilling for pre and post drainage. In this respect the concept of the process is one of pre-conditioning prior to mining such as might be adopted in a block caving mine. This keeps production and gas drainage separate.

Finally Australian practice in determining outburst risk needs some fairly drastic overhaul to accommodate all of the real factors that influence outbursts. A potential energy based approach is advocated.

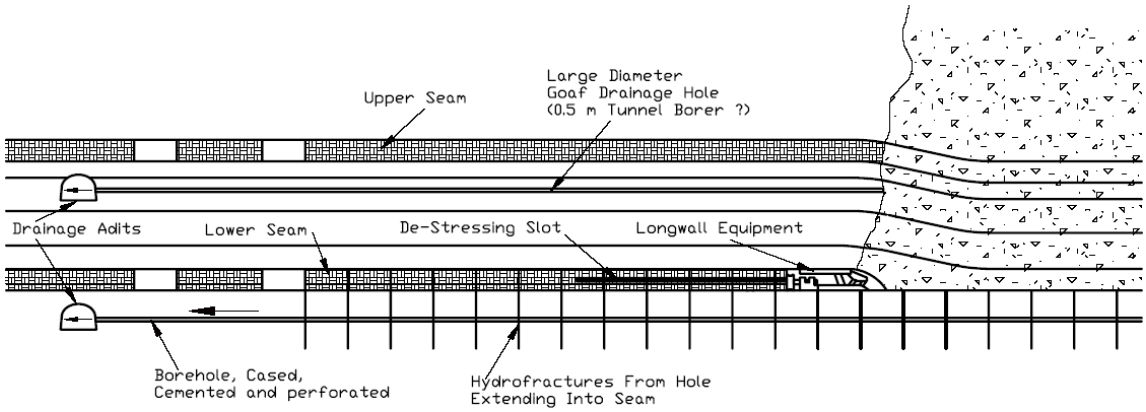

Figure 1 - Schematic elevation of mining the lower seam using pre-drainage by under seam holes with hydrofracture stimulation and slotting. Also a large diameter goaf drainage hole below the upper seam.

Aspects of the technologies described in this paper are patented or are the subject of patent applications.

REFERENCES

Airey, E M, 1968. Gas emission from broken coal: an experimental and theoretical investigation, *International journal of Rock Mechanics and Mining Sciences*, 5, pp 475-494.

Clarkson, C R and Bustin, R M, 2000. Binary gas adsorption/desorption isotherms: effect of moisture and coal composition upon carbon dioxide selectivity over methane. *International Journal of Coal Geology* 42 (2000), pp 241-271.

Crank, J, 1975. *The Mathematics of Diffusion*, 2nd Edition, Clarendon Press, Oxford.

Gray, I, 1983. Factors influencing outbursting and gas drainage in underground coal mines. Thesis submitted for the degree of Doctor of Philosophy, University of NSW.

Gray, I, 2006. Coal Mine Outburst Mechanism, Thresholds and Prediction Techniques. *Project No. C14032. Australian Coal Industry Research Program* (www.acarp.com.au).

Gray, I, 2011a. Gas content measurement and its relevance to outbursting. *11th Underground Coal Operators' Conference* (Eds. Aziz N, Kininmonth B, Nemcik J and Ren T). 10-11 Februrary, 2011, pp 291-296. University of Wollongong. http://ro.uow.edu.au/coal/335/.

Gray, I, 2011b. Stresses in sedimentary strata, including coals and the effects of fluid withdrawal on effective stress and permeability. In Proceedings of *11th Underground Coal Operators' Conference* (Eds. Aziz N, Kininmonth B, Nemcik J and Ren T). 10-11 Februrary, 2011. University of Wollongong, pp 297-306. http://ro.uow.edu.au/coal/371/.

Mavor, M J, 1990. Measurement and evaluation of coal sorption isotherm data. *SPE Annual Technical Conference and Exhibition*, 23-26 September, 1990, New Orleans, Louisiana. ISBN 978-1-55563-545-9.

Standards Australia, 1999. AS3980, Australian Standard for the determination gas content of coal - Direct desorption method.