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Dealing with bursts – a new approach

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DEALING WITH BURSTS – A NEW APPROACH

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ABSTRACT: This paper categorises the different types of coal bursts and gas outbursts in terms of their mechanisms. It is considered to be essentially impossible to predict when one of these events may occur. However, it is possible in many of the cases to predict the velocity of ejection and hence the distance with which particles may travel including bouncing and rolling and sliding. Keeping beyond this stand-off distance ensures the safety of workers from impact. Where gassy fault gouge exists there is no such safe distance. The material involved may be ejected in the form of a turbulent flow which has been described as a coal storm and which can travel great distances. This also involves large amounts of gas with the inherent problems of explosive mixtures. Locating, and determining the size of such geological features is therefore of great importance. Methods of doing this are discussed.

INTRODUCTION

Bursts are events that expel material with velocity at the time of ejection. This is usually coal but is sometimes rock. Unlike falls, where the velocity is gained through gravitational acceleration, the sources of energy that drive the material outwards are either strain energy of the rock or coal, or energy derived from expanding gas.

Rather than attempt to set predictive thresholds of whether a burst will take place or otherwise the approach taken here is that it is possible to predict how fast an ejection might be, and how far the material may travel, should it occur. Personnel should not be within the range of moving material and need to be withdrawn to a safe stand-off distance during mining. This is particularly applicable to coal bursts and outbursts in blocky coal.

The outbursts associated with gassy, finely ground coal are quite different in character as they are frequently not a single step process but occur in multiple stages. Mining through fault gouge requires a completely different and much more rigorous approach, as the consequences of an outburst associated with this material are much more serious, and the range of ejection well beyond any practical safe stand-off distance.

BURST TYPES

Bursts range from the sudden failure of the face with the ejection of coal driven by strain energy that may eject a few tonnes of material without any gas, through to the huge outbursts that involve erosion of fine material associated with a reverse fault. These occur in stages and may eject thousands of tonnes and a million cubic metres of gas. Because of the requirement for brevity in this document, burst forms will be described with minimal reference to individual cases. If the reader wants more detail with references they should refer to the research document (Gray, Wood, Gibbons and Zhao, 2021) and to its precursor (Wood and Gray, 2015).

All bursts are associated with failure that leads to the ejection of material at velocity. The sources of energy are strain energy of the rock or coal, and energy derived from expanding gas. If the energy that is available is consumed in the failure process then there is none left to drive ejection and what is left is a gravitational collapse.

COAL AND ROCK BURSTS

These are events that do not involve gas. The energy comes totally from the stored strain energy within the material that is being ejected and possibly from that surrounding it. In cases where the roof and floor are stiff, the strain energy is stored within the material that will fail. For this to be available to drive an ejection, the energy must not all be consumed in the failure process. Failure modes which do not consume a major proportion of the energy are therefore likely to lead to bursts. These include buckling

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and shear failure on discrete planes, rather than crushing of the block. An example of a wedge type failure is given schematically in **Figure 1**. **Figure 2** shows a coal burst affecting gateroads taken from Mark (2016). In this, the pillars have failed violently ejecting coal into the roadway.

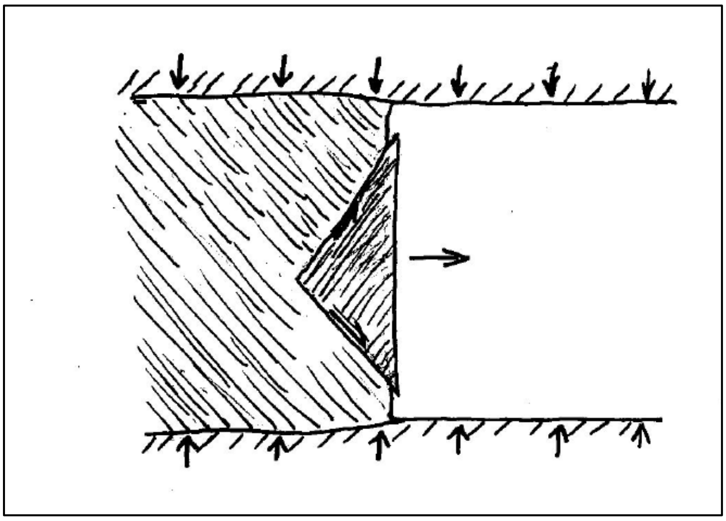

Figure 1: Wedge type strain burst failure

Figure 2: Effect of a coal burst on a gateroad before (top) and after (below) (Mark from an unspecified US mine in the North Fork Valley, 2016)

Figure 3 is a drawing of a normal outburst that occurred at Leichhardt Colliery. This showed buckling type failure. Gas was also involved in these events which typically ejected 10 tonnes of material at quite low velocities.

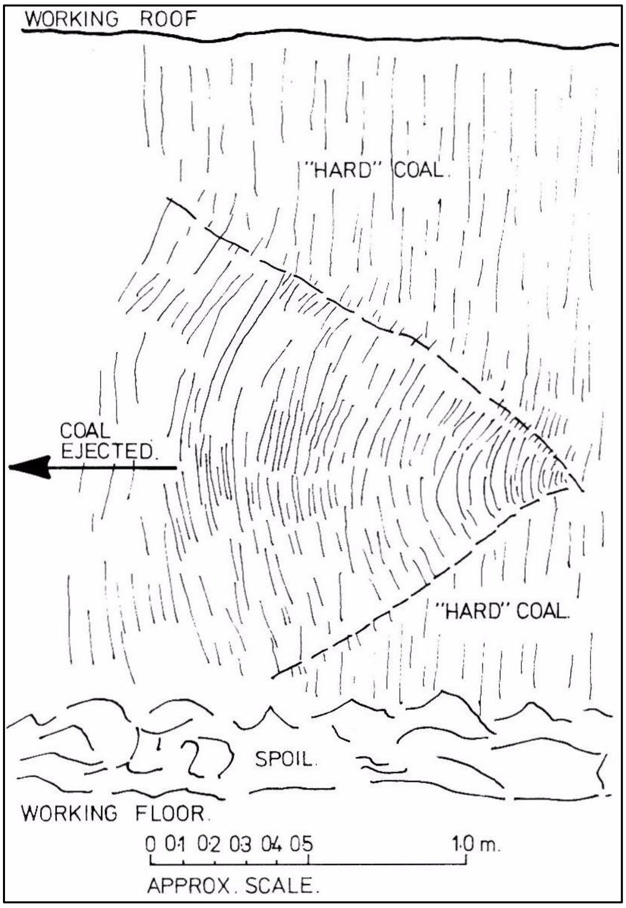

Figure 3: Elevational view of outburst cavity (Moore and Hanes, 1980)

STRAIN ENERGY AND VELOCITY EJECTION

In cases where the roof and floor are not involved, the strain energy available in a coal burst comes solely from the seam itself. Table 1 lists the theoretical ejection velocities in the various cases. In the top line is the theoretical maximum ejection velocity if all the strain energy in a one dimensional stressed case is converted into kinetic energy. The second line considers the case where there is a vertical joint behind the failure wedge shown in **Figure 1** and where two failure planes exist at 45 degrees minus half the friction angle to the vertical. These are the most likely planes for shear failure. The third line considers the case where the vertical joint does not exist. The fourth line considers the case of the maximum theoretical velocity if all the strain energy from a uniform biaxial stress state was converted to kinetic energy. The fifth line considers the velocity that might occur if a three dimensional cone type strain burst occurred with a release joint behind. The final case is taken from Qiu (2021) and considers the case where two dimensional plate buckling occurs. In this the tip velocity of the broken plate segment may be higher than that of the first case. This is theoretically possible as most of the rotating and translating plate is travelling more slowly than the tip.

Where u is the velocity of ejection

E is the Young's modulus

ρ is the density of the rock or coal

σ is the stress – uniaxial or biaxial depending on 1D or 2D case

v is Poisson's ratio

All these cases represent the case where no strain energy comes from surrounding material. It is also possible to have bursts where a significant proportion of the energy driving the event comes from the convergence of the roof and the floor. This is typically the case where pillar failure occurs as is shown in **Figure 2**. The time required for these wedge or cone type coal burst events to reach peak ejection velocity is of the order of one millisecond. Ejection velocities may lie in the range of 2 to 7 m/s. These velocities are reached with very little elastic deformation.

Table 1: Theoretical maximum ejection velocities for rock and coal burst events without contribution from surrounding material

CASE	EQUATION
1D stress theoretical maximum velocity	$u = \frac{\sigma}{\sqrt{\rho E}}$
1D stress, wedge with release joint behind	$u = \frac{1}{2}\frac{\sigma}{\sqrt{\rho E}}$
1D stress, wedge without release joint behind	$u = 0.45\frac{\sigma}{\sqrt{\rho E}}$
2D stress, theoretical maximum velocity	$u = \frac{\sqrt{2(1-v)}}{1}\frac{\sigma}{\sqrt{\rho E}}$
2D stress, wedge with release joint behind	$u = \sqrt{\frac{(1-v)}{2}}\frac{\sigma}{\sqrt{\rho E}}$
Plate buckling with full release joints	$u = \sqrt{3}\frac{\sigma}{\sqrt{\rho E}}$

THE EFFECT OF GAS

Once pressurised fluid is present, then, the situation changes. Fluid cannot contribute to failure unless it can alter the stress state within the coal or rock and become a component of effective stress.

The effective stress within a rock mass is given by Equation 1. The use of the Kroneker delta simply means that changing fluid pressure does not change the shear stresses and only affects stresses normal to the plane being considered.

$$\boldsymbol{\sigma'_{ij} = \sigma_{ij} - \delta_{ij}\alpha_i P} \qquad (1)$$

Where σ'_{ij} is the effective stress on a plane perpendicular to the vector *i* in direction *j*

σ_{ij} is the total stress on a plane perpendicular to the vector *i* in direction *j*

δ_{ij} is the Kroneker delta. If $i \neq j$ then $\delta_{ij} = 0$, while if $i = j$ then $\delta_{ij} = 1$

α_i is the poroelastic coefficient affecting the plane perpendicular to the vector *i*

P is the fluid pressure in pores and fractures

For fluid pressure to affect stability it must have some surface on which it may act. This can be within pore, cleat or fracture spacing. For the fluid to operate the surface must be open so that fluid can reach it.

The importance of the concept of effective stress cannot be over emphasised. Where fluids cannot act, they do not influence failure. If the effect of the fluid pressure, α_i, increases with reducing effective stress, as is the case in many coals, then the effect is magnified.

If the fluid is a gas, this has the ability to do work on expansion, causing the mass to accelerate as in an outburst. How much work the gas can do is dependent on its initial pressure, initial volume and final pressure. What is important is the concept that gas cannot contribute to a burst if it cannot operate within the coal. This means that if the coal does not contain some internal fracture surface that is open, or will open up with failure, then it will never outburst.

The theoretical ejection velocity that may be due to a gas expanding quickly, and therefore adiabatically, is given in Equation 2.

$$\boldsymbol{u} = \sqrt{\frac{2P_1\emptyset}{\rho(\gamma-1)}(\mathbf{1} - (\frac{P_1}{P_2})^{(\frac{1-\gamma}{\gamma})})} \qquad (2)$$

Where P_1 is the initial pressure

P_2 is the pressure that the gas expands to – atmospheric pressure

u is the velocity reached at the end of expansion

ρ is the coal density

$\emptyset$ is the void space fraction (porosity)

γ is the adiabatic index = 1.32 for methane, 1.28 for carbon dioxide

The key variables are the void space fraction and the initial gas pressure. The void space is the fraction of the total coal or rock volume that is open. In coal it is essentially the space within cleating, not space within enclosed pores in the microstructure of the coal.

Importantly this void space is very low in solid coal. Coal seam gas reservoir behaviour would indicate that such pore space is of the order of 0.5%, much of which is occupied by water, even after gas drainage. If all of this 0.5% was occupied by gas at a pressure of say 4.0 MPa gauge, the ejection velocity would be about 7.5 m/s. If however that void fraction volume is 3% then the velocity would be 18.4 m/s. At lower pressures the theoretical velocity of ejection drops. At 1.5 MPa gauge pressure and void ratios of 0.5% and 3% the velocities become 4.2 and 10.4 m/s respectively.

It may appear that this is a very simplistic model but it is shown by Gray et al (2021) that the concept of multiple blocks of coal separated by gaps equivalent the void space reach the same velocity. This model is described as a gun barrel model as it represents movement within a conduit of uniform sectional area without leakage. A significant difference from the idea of a gun barrel is that it contains multiple moving projectiles. The movement required to expand gas in a planar void, such as a cleat or fracture, is not very much. Consider a coal that contains parallel fractures which add up to 10 mm spacing in a 1 m thick slab - equivalent to 1% porosity and which is a lot of open space. If the initial pressure is 4.0 MPa gauge the fully adiabatically expanded combined width of these to atmospheric pressure is 174 mm. If the coal were not to disintegrate a vacuum would be developed in the expanding void. We assume for the velocity calculation given in Equation 2 that this is not the case. However this short distance of expansion is important as the coal may not have broken apart and become leaky before the peak velocity is reached. The peak velocity in this model is reached in a few milliseconds.

Blocky Outbursts

Outbursts are generally not events that take place in milliseconds. By way of example Bruggeman (2002) reports an outburst that occurred at Central Colliery, German Creek, Central Queensland, Australia on 20 July 2001. This was an outburst that occurred in coal with a higher frequency of jointing than had generally been apparent in the prior workings.

Just before the outburst, a loud bang occurred. This caused the continuous miner driver to put the miner into reverse high tram. The noise seemed to be deep and to emanate from the roof. Then cracking of the rib was noticed with some fretting. The miner had travelled backwards some 2 m in a few seconds when a second event took place accompanied by a louder bang than the first. Some small pieces of coal were thrown towards the miner followed by larger ejection.

Personnel reported a pressure change causing popping of their ears. When the majority of the coal had been expelled, there was a suction towards the face. Personnel in the adjacent heading also heard these three waves of noise and trammed backwards, thinking it was a roof fall about to happen or a coal mine outburst. About 90 tonnes of blocky coal was dislodged, fortunately without any serious injury occurring. A photograph of another blocky coal outburst from a Bulli seam mine in the Illawarra is shown in **Figure 4**. This was associated with jointing parallel to a dyke.

The precursor events to the ejection in this outburst are important and are common in others. These include normal outbursts at Leichhardt Colliery (**Figure 3**) where the outbursts could be predicted by the mining crews and would only eject a few tonnes, and those at Cynheidre (Davies, 1980) where outbursts were frequently preceded by a noise described as being akin to that of a “two-stroke motorcycle engine being revved up”.

Figure 4: Photograph of a blocky burst event from the Bulli seam before clean up showing left-hand rib – face intersection

These cases are important as they illustrate the time factor in these outbursts; they are not events that occur in milliseconds. The situation is considered to be one of failure, dilation of the mass to form void space, pressurisation of the void space followed by ejection.

Outbursts from Finely Ground Coal

The most dangerous outbursts come from finely ground coals that are part of fault gouge. In the worst situations they are encountered suddenly by breaching rock in a fault or by entry from solid coal. The worst of these encountered in Australia was the outburst of 1 December 1978 which occurred at Leichhardt Colliery in Central Queensland. This produced 500 tonnes of rock and coal and 12 000 m^3 of gas, and led to a dual fatality. The mining breached a reverse fault containing gouge material along its strike. It was reported as an event that was accompanied by a series of double bangs that were quite distinctly separated.

Worldwide many other major outbursts of this type have occurred. One of these major outbursts occurred on 7 April 2002 at Luling Colliery in Anhui Province, China. In this a very large coal and gas outburst occurred as an inclined drive was being advanced by “air picks” through rock towards a faulted zone containing sheared coal. The rock barrier broke up and what ensued was an outburst that produced an estimated 8730 tonnes of rock and coal and 9.3×10^5 m^3 of methane. This material filled many hundreds of metres of roadway, with finer material being transported further in what has been described as a coal storm.

If we make the assumption that what occurred was a series of erosional cycles each followed by a blockage and a process of pressurisation before failure and further erosion, it provides an explanation of the process.

This cyclic process is shown schematically in **Figure 5**. Here a continuous miner hits a patch of fault gouge which begins to erode. The outlet to this blocks off and the void behind it pressurises. When the pressure is adequate to cause failure of the blockage, this material is then ejected and the erosion process then re-starts. This process may continue until the blockage remains in place or there is no more material to dislodge.

Events such as that shown in **Error! Reference source not found.** have the potential to eject gas and material at very high speeds. It only takes a pressure of approximately 1.8 times higher on the inside of a nozzle than on the outside to cause choked flow and the gas ejection to reach sonic velocity. This is about 450 m/s in methane. High velocities will entrain particles within them to form the coal storm used to describe the Luling outburst, the large outburst at Leichhardt Colliery and many other large outbursts that have occurred as listed in the Appendix of Gray and Wood (2015).

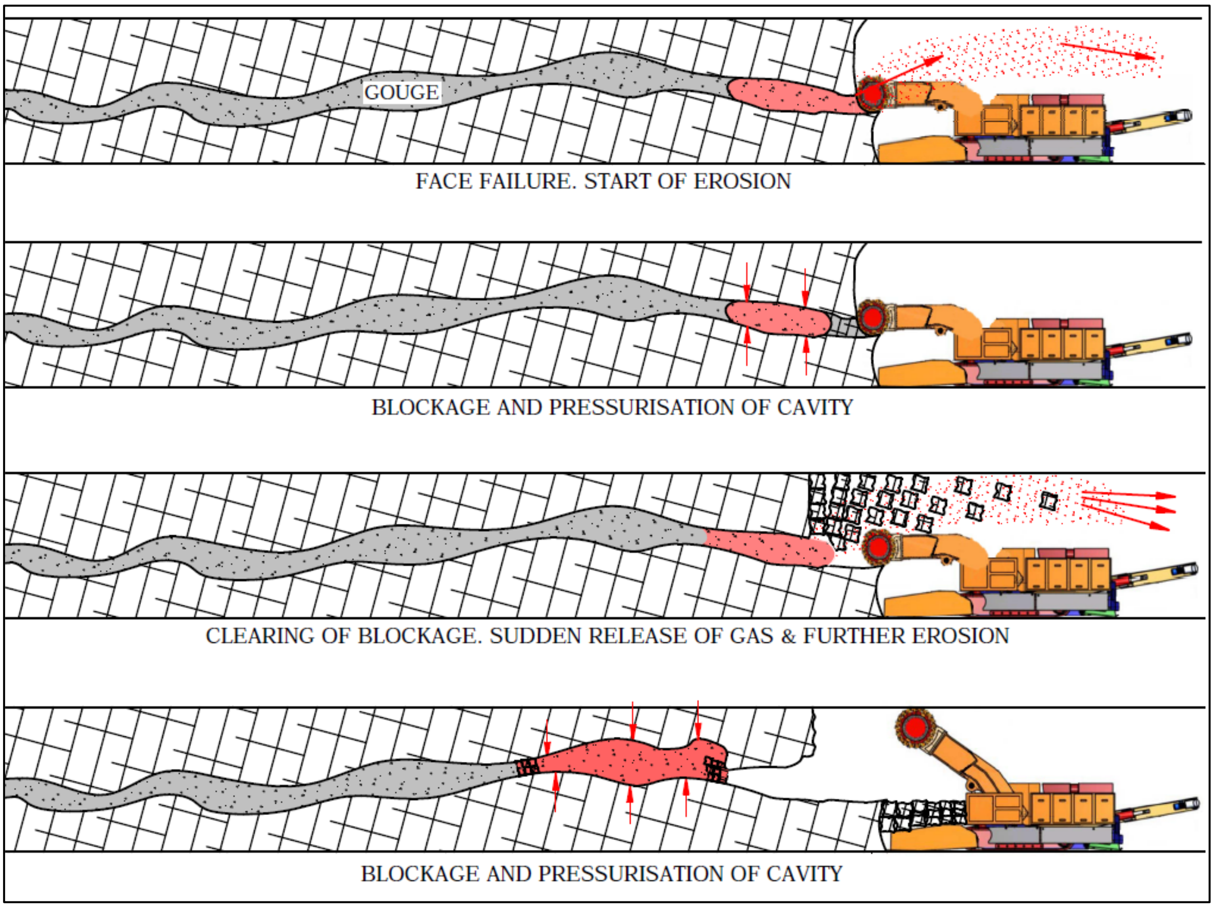

Figure 5: Cyclic process of a major outburst on a fault

What Pressure is the Gas in the Void Space?

In a zone unaffected by mining or drainage any gas can be expected to be at the sorption pressure of the gas within the coal. In many cases there will be no free gas as the water pressure in the seam will exceed the sorption pressure. Once some drainage has taken place water will be partially drained and space will exist for gas. This gas will diffuse from the coal solid through a complex process of desorption.

This process of diffusion may be a mixture of Knudsen flow, Darcy flow and other possibilities but it can be approximated by that of Fickian diffusion down a concentration gradient. If we use the mathematics of Fickian diffusion (Crank, 1975) we can approximately calculate what the rate of diffusion from the coal into the void space may be. This is important because if it is too slow then the gas is likely to leak off into the face.

The pressurisation of a void depends on its volume and the rate at which gas can desorb into it. The coal is considered to be made up of fragments which for mathematical convenience we will treat as spheres. These spheres may diffuse by the process of Fickian diffusion into the void. This problem is solved by numerical simulation of a set of cases. The model is described further by Gray et Al (2021). The diffusional behaviour is normalised in terms of the time function shown in Equation 3.

$$f(t) = \sqrt{\frac{Dt}{a^2}} \qquad (3)$$

Where D is the diffusion coefficient in (m^2/s)

t is the time of diffusion in (s)

a is the radius of the sphere in (m)

Figure 6 shows the pressure within the void or the pore space for a case with an initial seam pressure of 3 MPa and fairly normal sorption isotherm shape. If we consider the case of a sphere diameter of 0.02 m, a diffusion coefficient of 10^{-9} m^2/s and a period of 0.2 seconds then the value of the time function is 0.0014 and the pressure that could be developed in a 3 % porosity coal is 2.0 MPa.

While 0.2 seconds is one to two orders of magnitude longer than the time taken for pure adiabatic expansion to accelerate the simple gun barrel outburst model to high speed, it is still not very long to pressurise a dilated coal mass or void prior to expulsion in an outburst. Indeed, the time difference would not be able to be discerned by an operator near the face.

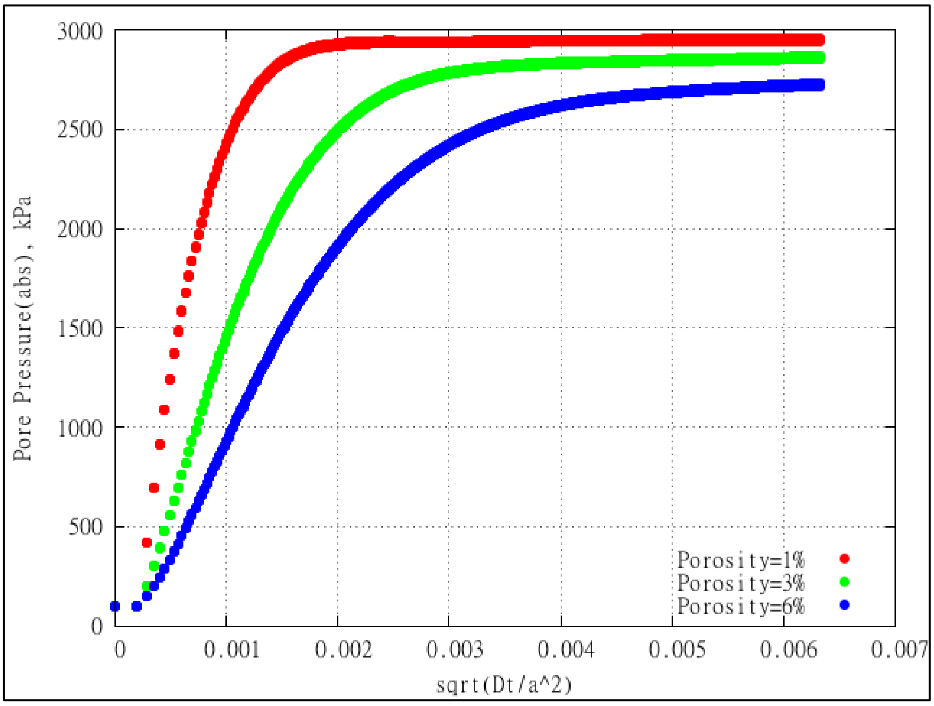

Figure 6: Pore pressure change when the initial pressure is 3 MPa

If, however, we consider the case of a coal with 1% void space the dimensionless value of $\sqrt{\frac{Dt}{a^2}}$ required to reach 2.0 MPa is approximately 7.5×10^{-4} . If the coal is blocky with a characteristic dimension block size of 0.1 m and a diffusion coefficient of 10^{-12} m^2/s the time to pressurise is 23 minutes. It is therefore extremely unlikely that such a coal would ever pressurise to the extent that an outburst may occur following failure and dilation because the gas would leak off.

If we work with a void ratio of 3% and pressurisation to two thirds sorption pressure and take an extended period of 15 seconds for pressurisation prior to an outburst we can re-arrange Equation 3 into Equation 4 which describes the value above which the risk of pressurisation may be expected to be significant.

$$\frac{D}{d^2} > 3.7 \times 10^{-8}\ s^{-1} \tag{4}$$

Where d is the characteristic lump dimension (m)

D is the diffusion coefficient (m^2/s)

This shows the importance of characteristic particle size and diffusion coefficient in leading to pressurisation of the dilated mass. The use of the 3% void ratio and the maximum of a 15 second pressurisation period following dilation are somewhat arbitrary but are expected to be of the right order to act as limits for determining whether diffusion rates are likely to be adequate for an outburst to occur.

A gouge material with a characteristic particle size of 0.5 mm and a low diffusion coefficient of 10^{-13} m^2/s would have a value of $D/d^2 > 4 \times 10^{-7}$ s^{-1} which is an order of magnitude higher than the suggested value in Equation 4 and might therefore be considered of being at risk of an outburst. Historically this correlates with outburst prone coals such as the lower portion of the D6 seam in the Karaganda Basin of Kazakhstan (Gray et al, 2021).

Diffusion Coefficients in Coals

The measurement of the diffusion coefficient can only be conveniently and reliably made on initial desorption. This means, obtaining coal samples with gas in them and measuring their desorption rate over a period of time. Once this has been completed, a measurement of the coal particle sizes can be made and the diffusion coefficient may be determined. This can be done on cuttings from open hole drilling or on core. In both cases, the coal should be retrieved as quickly as is possible so that the maximum amount of the desorption process may be measured. Experimentally it has been found that the diffusion coefficient is larger for larger particles (Gray at al, 2021). To what extent this is a function of fracturing that exists within the larger particles, their odd shapes or the inadequacy of the Fickian diffusion model is uncertain. The calculation of the diffusion coefficient from particle desorption is described by Gray (2017).

One useful measurement is that of the Apparent Diffusion Coefficient, D_A. This may be measured from the desorption of core retrieved for gas content analysis. It can be calculated using Equation 5 from Wood and Gray (2015).

$$\boldsymbol{D_A = 3.273 \times 10^{-3} \;.\left(\frac{Sl\ a}{M_{ml}^{\infty}}\right)^2} \tag{5}$$

Where D_A – apparent diffusion coefficient, m^2/s

a – radius of the core, m

Sl – slope of the initial desorption curve derived from a plot of

M_t vs. $t^{1/2}$ in $\frac{\mathrm{ml}}{\sqrt{\mathrm{min}}}$ where M_t is the total desorbed gas.

M_{ml}^{∞} – total gas content of core in ml

The value of D_A tends to be one or two orders of magnitude higher than the small particle diffusion coefficient and represents lump behaviour as opposed to that of small fragments. Diffusion coefficients range from 1×10^{-13} m^2/s for slowly diffusing small particles up to $1 \times 10^{-7.5}$ m^2/s for the most quickly desorbing cores. This is a huge range and fundamentally affects outburst behaviour.

WHICH COALS WILL COAL BURST AND WHICH WILL OUTBURST?

For a coal to suffer from a coal burst event, it must be stressed to near failure and then be taken over the threshold of failure with an associated strain energy release. For a coal to be at such a high stress, it must have significant strength. This strength may be thought of as coming from cohesion – as in the Mohr Coulomb failure criterion. Once cohesion is destroyed, the strength is limited by friction. Without the cohesive component, the coal has no strength next to an unconfined face. Thus coals that are prone to coal burst are either not cleated or jointed, though they may be sparsely jointed parallel to the structure, or if these do exist they have been cemented. Strain burst type wedge, cone or buckling bursts cannot occur unless stress exists at the face. The potential still exists for the core of a pillar to contain some joints that are confined, so that they may sustain stress, to burst given a sufficiently energetic seismic event to trigger their failure.

Coals that do have jointing and cleating and contain gas must be considered an outburst risk. If the cleating or jointing is sufficiently closely spaced, and the diffusion coefficient sufficiently high, then a blocky coal outburst must be considered a possibility. If the coal is finely broken such as in the form of gouge material and it is gassy then the danger posed by an outburst is extreme, albeit in a different form of outburst.

Most Australian coals have cleats and joints. This coal is benign after drainage. The coal with a risk of blocky outburst is usually characterised by joints and cleats with directions that are related to fault or dyke elements rather than the systematic directions characteristic of the particular seam.

THE SIZE OF THE BURST EVENT

In considering the seriousness of a potential burst event it is necessary to consider what size of event is likely. Thus a strain burst is likely to be a small event and its consequences are therefore limited. If the chain pillars of a longwall are strong and can become excessively stressed then the potential exists for a large failure that may propagate over several hundred metres of pillar length. This can also apply to the main development of a mine. An example is that of Crandall Canyon mine in Utah in the USA (Gates, 2007). In 2007 the mine was recovering main development pillars between two mined out groups of longwall panels. Despite plenty of warning, in the form of bumps, mining continued with the result being a major pillar failure that caused the failure of 800 m of pillars and which killed six. A subsequent rescue operation was caught by a continuation burst which killed three and injured six more.

Outbursts from the face are much smaller events that affect a volume of dilated failed coal. If this is a blocky event the volume of the burst is small and so is the distance of projection. Where the outburst is from finely ground gouge material associated with a fault the failure may proceed along the fault zone and also gather adjacent coal and rock. In this case the fine material is entrained in gas in the form of turbulent flow forming a coal storm, and the distance of projection of this fine material is a lot further than the larger lumps. These are the most dangerous outbursts. The volume of material in these is limited by the size of the fault zone and what the failure of this may entrain.

THE CONCEPT OF A STAND-OFF DISTANCE

It is impossible to actually determine whether the precise events associated with mining will lead to an outburst or coal burst. Either event is an unstable failure with energy release. The uncertainty is associated with the variability of geology, the associated material properties of the coal and rock and the variability of the mining operation.

In the cases of blocky coal outbursts or strain burst type coal bursts the basis for determining the ejection velocities lies in the equations in **Table 1** and Equation 3. It is likely that the timing event of the strain burst is somewhat quicker than that of an outburst and that a strain burst event is likely to eject material and may be followed by an outburst. Nevertheless for the sake of being extremely conservative the velocity of ejection may be determined by adding the strain energy and gas expansion energy and equating this to the kinetic energy. The velocity from this is combined energy approach is given by Equation 6.

$$\boldsymbol{u} = \sqrt{\frac{2}{\rho}\left(\frac{1-v}{kE}\boldsymbol{\sigma}^2 + \frac{P_1\emptyset}{\gamma-1}\left(\mathbf{1} - \left(\frac{P_1}{P_2}\right)^{\left(\frac{1-\gamma}{\gamma}\right)}\right)\right)} \qquad (6)$$

Where E is the Young's modulus of the coal

k is a factor to deal with the fraction of theoretical potential energy transfer to kinetic energy (approximately 4).

v is Poisson's ratio of the coal

σ is the stress in the coal – assuming UCS unless measured

P_1 is the initial pressure

P_2 is the pressure that the gas expands to – atmospheric pressure

u is the velocity reached

$\emptyset$ is the porosity fraction

γ is the adiabatic index = 1.32 for methane, 1.28 for carbon dioxide

If the velocity can be computed using Equation 6 and it is assumed that a lump of coal is projected from the top of the face then the distance it travels may be calculated simply as given in Equation 7 and shown in **Figure 7**.

$$\boldsymbol{x} = \boldsymbol{u}\sqrt{\frac{2h}{g}} \qquad (7)$$

Where x is the distance of ejection before impact with the floor

g is the gravitational acceleration

h is the height of the mining face

u is the ejection velocity.

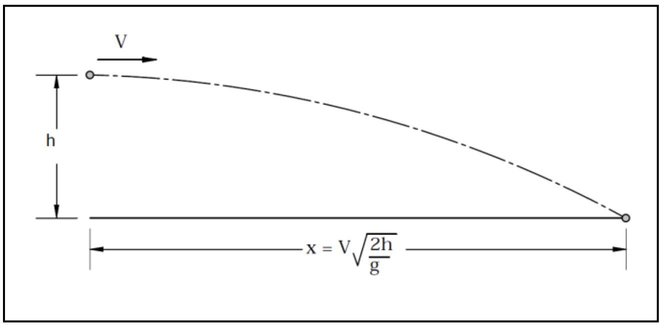

Figure 7: Distance particle with horizontal velocity travels before hitting the ground

After impact the material is likely to bounce several times and then slide or roll for double the flight distance. Thus the total distance the lump will travel is about three times its flight distance. The safe stand-off distance is beyond this.

Figure 8 shows a plot of what is thought to be a safe stand-off distance from the 3 m high face for cases which are not gouge and are not likely to disintegrate into fine material.

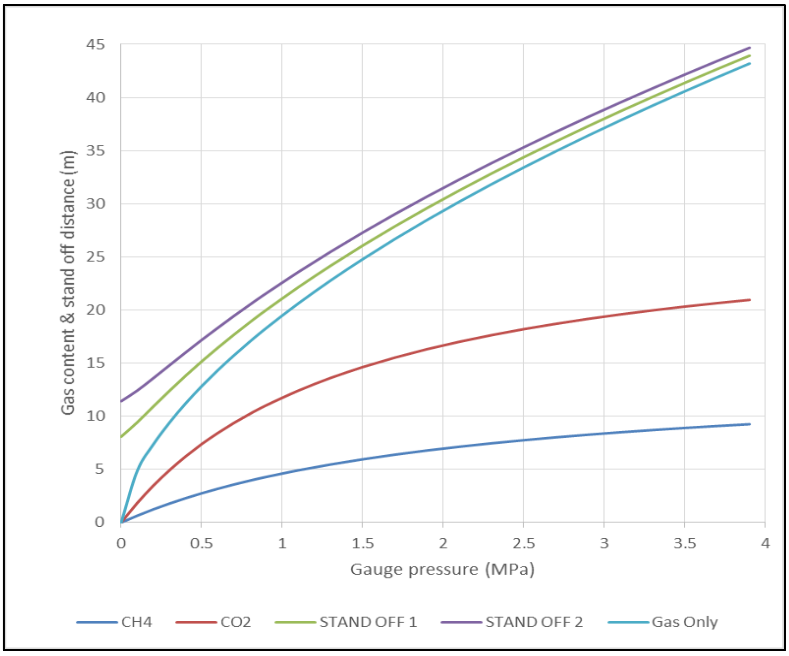

Figure 8: A plot of stand-off distance

The other assumptions used in this are a void ratio (porosity) of 3%, a density of 1350 kg/m^3; 2.5 GPa Young's modulus with 10 MPa stress for the case STAND OFF 1 and 5 GPa Young's modulus with 20 MPa stress for the case of STAND OFF 2. In both cases the Poisson's ratio used is 0.2. The case of stand-off distance where there is no strain energy contribution is also plotted as Gas Only.

The isotherms of gas content above atmospheric pressure for two gases are also plotted with respect to gauge pressure. These are average numbers from a range of tests on different coals. The first is for methane where the Langmuir volume is 14.80 m^3/tonne and the Langmuir pressure is 1.96 MPa absolute. For carbon dioxide the Langmuir volume and pressure are 30.86 m^3/tonne and 1.34 MPa absolute. These plots show the importance of pressure rather than gas content. Carbon dioxide content will be far higher for a given pressure than methane.

If the outburst is likely to be from fine gouge material of some volume then the concept of a safe stand-off distance does not apply. This is a very dangerous situation. It is also pointless endeavouring to calculate stand-off distances if pillar or longwall face failures from highly stressed coal are a possibility. They should not be allowed to be a possibility and no one should be in the vicinity of such a potential event.

MANAGEMENT STRATEGY

Exploration to Determine Outburst and Coal Burst Risk

In the mine exploration stage it is important to determine the state of stress and fluid pressure within the coal. It is also necessary to determine the sorption pressure of the gas within the coal, the diffusional behaviour of the coal and the geological structure within it. This can be achieved by the use of core drilling, core desorption and its subsequent examination for structure and testing for strength including the coal’s failure characteristics.

The measurement of isotherms on the coal is valuable as it relates gas content to pressure. In the case where mixed gases exist in the seam Native Isotherm measurements should be taken and compared to those derived from laboratory measurements with individual gases that are subsequently combined to form a mixed gas isotherm. The Native Isotherm (Wood and Gray, 2015) is determined on initial core desorption with all the gas species and water being involved.

The use of acoustic televiewer (ATV) images is also valuable as it gives another view of the coal structure and an indication of stress from breakout patterns or drilling induced tensile failure. Direct stress measurement in coal is limited to hydrofracture in most coals. It generally only reliably measures the minimum stress within the coal, though when used with ATV images that display breakout it provides some basis for determining major horizontal stress. ATV images can be examined along with core for fracture density and orientation.

The use of gas content measurement should be augmented by the installation of piezometers as these can provide long term continuous records of fluid pressure within the seam during drainage and up to mining. Once drainage had dropped the water pressure in the seam to the sorption pressure, gas is released and the piezometers will measure the gas pressure. This is a far more relevant and lower cost option compared to drilling multiple gas content compliance holes. Pressure is what matters, the gas content is of far lower importance.

Permeability measurement is also relevant because it directly influences the ability of the coal to drain either into gas drainage holes or the workings. High permeability coals do not generally outburst as the gas pressure has been relieved by gas drainage. Where gas remains in the coal the pressure within the coal near the face is a function of the permeability and advance rate.

UNDERGROUND IN-SEAM DRILLING

Open Hole Drilling

Underground in-seam drilling is the most important exploration tool for use to assess outburst and coal burst risk in an operating mine. The identification of fault zones is most important. The normal process is by drilling open holes using down hole motors powered from the drilling fluid. Drilling difficulties such as bogging of the drill string is an important indicator of problems. This is caused by the production of large coal fragments that may come from breakout in the hole wall due to stress concentration. The information that is currently obtained from such holes is limited. As a large amount of drilling is normally or could be conducted the information retrieved could be significant. The information that could be obtained falls into three categories.

The first of these is information on the progress of drilling and the torque and thrust response of the drill to penetration. For this to be meaningful it must be obtained from as close to the drill bit as is possible otherwise the information from the bit is lost in the frictional effects of the drill string in the borehole.

The second main source of information should come with the cuttings and gas release from the hole. The problem with getting information from cuttings is that these do not travel in a regular fashion from the drill bit in normal down hole motor directional drilling. They become part of the cuttings bed in the hole and are released from this at uncertain times. This is a problem associated with a failure to rotate the drill string and an inadequate flushing rate. The use of a rotary steering tool which is steerable during rotation, and higher fluid flushing rates, overcome such problems. This should enable the collection of cuttings so that their size distribution may be determined. Doing this requires development of continuous cuttings size assessment systems. The collection of cuttings also enables the determination of gas content from them. As holes become longer gas loss from desorption of cuttings limits the accuracy of this method. The use of gas flow rates from the hole as an indicator of conditions also becomes limited in long holes because the incremental flow from the newly drilled section of the hole is lost in emissions from the remainder of the hole.

The third method in which information from open holes, were obtained by logging them after drilling. Currently geophysical tools are limited by intrinsic safety constraints but such tools can be developed with adequate resources. Current development is focused on a multi-arm calliper tool to detect overbreak of the hole caused by an intersection with gouge material or borehole breakout. A development whereby a packer system can be deployed into the hole to test for gas pressure, a key indicator of outburst severity, and to measure permeability, is available. Other tools can be expected to follow, though intrinsic safety needs and the mixed gas and water environment in the hole will always be significant constraints on using a normal geophysical suite of tools.

Where coring can be used the opportunity to measure structure within the hole is increased immeasurably. Detailed structural analysis of the core becomes possible enabling the determination of jointing and cleating. Core loss indicates potentially dangerous gouge zones associated with faults. However, coring is currently only used for gas content measurements at isolated locations within underground drill holes. Sudden changes in gas content can indicate inhomogeneity of the seam and a reason for caution. Compliance coring is a measure of the efficiency of gas drainage and can, if the core is examined properly, be an indicator of areas of potential burst conditions.

The reason for this limited coring is the time it takes to pull the drill string, run a core barrel, take a core, pull the drill string, and run it back into the hole. Continuous conventional coring is too slow. Wireline coring brings with it the risk of having to extract the core barrel from a pressurised drill string.

Information Gained from Mining

While the process of exploring by mining is not good practice obtaining every bit of possible information from where mining has taken place highly desirable. Observation gives direct experience on the mining conditions and enables the location of structures within the seam to be extrapolated. Features that may be observed are described below.

- The stability or otherwise of the rib and face. Here a lack of failure indicates a coal that may be strong and carries a higher stress and which may therefore be coal burst prone. The measurement of stress is needed to accompany this to determine whether stress is an issue. This is most readily observed through examining boreholes for breakout. If the face ‘spits’ fragments, it is also a direct indicator of small failures that may become a large one.
- The state of fracturing within the coal as an indicator of changing stress direction and as a direct risk factor in blocky outbursting.
- Changing gas make in the ventilation. However, low gas may be a precursor to an outburst as can increased gas make which indicate the presence of structural features in the coal that are releasing gas.
- Any signs of sheared zones containing gouge material.
- Bumping felt by the mining crew or recorded by microseismic processes. This is frequently a precursor to a major burst event.

Where coal bursts or outbursts occur this information can be invaluable and should not be ignored, however small the event. All these observations indicate the current risk of bursting when viewed in the light of the mechanisms discussed above. Fine tuning of the management strategy can be achieved by the correct interpretation of these indicators.

CONCLUSIONS

This paper presents a description of coal burst and outburst events and endeavours to explain their mechanisms. Coal bursts are divided into events akin to strain bursts in metalliferous mining and major pillar bursts. Outbursts are divided into blocky coal outbursts and those that occur from gouge associated with faulting. The ejection velocity from strain burst type coal bursts and blocky coal outbursts are considered to be able to be estimated. The key parameters here are stress, gas pressure, the characteristic block dimension and the void ratio that may occur on dilation. The stress can be approximately estimated from borehole breakout. The gas pressure can be measured directly or inferred less accurately using gas content and isotherm information. The characteristic block dimension most easily comes from core examination. That leaves the most uncertain parameter which is the dilation that may occur on failure prior to an outburst. A value of 3% void space is considered a conservatively large value. Another parameter of importance is the diffusive behaviour of the coal, as it affects the ability of the dilated mass of coal to pressurise and therefore outburst. A basis for determining the importance of this is presented.

The use of a safe stand-off distance for mining is put forward. It use is intended to place operators out of the range of ejected material from coal bursts or outbursts. The most effective controls on the severity of coal bursts is by destressing through the removal of material or by destroying cohesion away from the workings so that strength and therefore stress is lost. The control on outbursting is primarily by gas drainage. Other options are discussed in Gray et al (2021).

The case of outbursting from fine gouge material poses a completely different problem, and if this is gassy then every effort should be made to determine the volume of such gouge material that may be intersected. Mining should then be either avoided, or only be undertaken when very low gas pressures have been achieved. A value of 0.5 MPa gauge pressure is suggested as the upper limit of mining through gouge. The key to dealing with potential major pillar bursts is to ensure that large groups of pillars are not critically stressed. This may mean mining to the extent that pillar failure is ensured but that the post yield strength of the pillar is controlled by suitably ductile reinforcement.

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