The Role of Gas Pressure in Coal Bursts

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ABSTRACT

Rock and coal fractures and micro seismic vibration are common occurrences during development mining. It is very uncommon for coal and rock to be propelled into the roadway during normal mining operations. However, such occurrences do occur and appear to require significantly more energy than is available from strain energy release during coal cutting. The sources of energy, which can contribute to the propulsion of coal from the face or ribs, are typically strain energy from the surrounding ground, seismic energy from a rapid rupture of the ground in the vicinity, or rapid expansion of gas from within the burst source area.

The aim of this paper is to briefly review the bursts that could be related to strain energy or seismic energy. However, the greatest emphasis is placed on the effect that gas within the coal could play in moderate to gassy mines.

It has been found that the bursts related to the expansion of gas can occur in coal and stone. The volume of gas involved in coal bursts is typically lower than in gas outbursts; however, the process is generally similar.

INTRODUCTION

A coal burst is defined as a rapid expulsion of coal (and potentially gas) from the boundary of the roadway. The volume of a burst can be variable, but volumes above 10-50m^3 are noted and cause significant disruption to operations.

Rock and coal fracturing is common about roadways, particularly under the influence of elevated stresses, either tectonic or related to mining abutment stress. Shear fracture is very common; however, it is very uncommon that the coal is propelled from the face or ribs as a result of fracture of the material. The nature of rock fracture about roadways under elevated stress is presented in Figure 1.

A burst requires energy to propel the coal or rock from the rib or face of the roadway. The depth of material impacted may vary from 0.5m to greater than 3m inside the roadway boundary. The strength of the ground in this zone is variable depending on the nature of the coal seam (or surrounding material). Typically, this material has significant residual strength as confinement increases into the ribside.

The energy required to propel this material is typically in addition to that which is associated with normal fracturing about the roadway.

Figure 1. Normal fracture mode about development roadways. Primarily shear fracture through the rock and coal.

Experience with a number of bursts indicate that blocks of coal have been propelled 3–5m laterally and commonly hit the bolting platforms.

An example is presented in Figure 2, which shows large blocks of coal propelled over the roof bolting rigs on the continuous miner. The location of the rigs to the face is a least 3m.

A guide to the propulsion velocity to project a block under the action of gravity is presented in Figure 3, indicating that propulsion velocities of 8–10 m/s are typically required to match observed behaviour.

The energy sources available in coal mines are typically

- Stored strain energy in the coal and in highly stressed areas about the roadway
- Gas pressure from a desorbing zone of coal, or local pockets of gas within the pore space and fractured zones
- Seismic energy resulting from rapid slip on faults or structure. This form of energy results in the coal or rock being acted on by particle motions (p and s waves), which induce a peak particle velocity on the fractured coal (or rock).

Figure 2. Coal burst in development. Note: coal blocks on the miner.

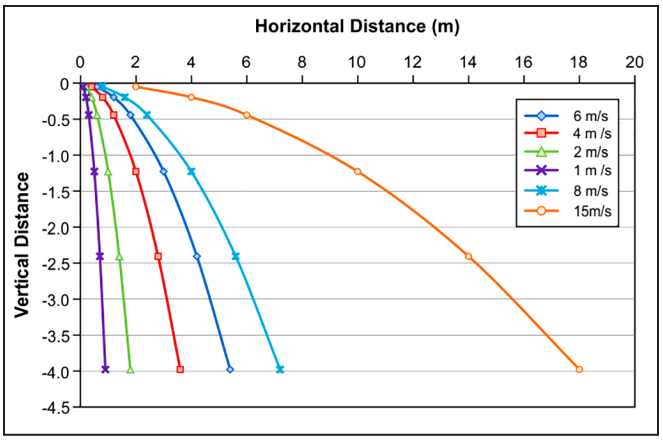

Figure 3. Block trajectory relative to burst velocity.

These sources of energy are often assessed as being independent, whereby the energy from gas pressure is associated with gas outbursts, and the stored strain energy in the rocks are associated with rock bursts.

In coal mines, it is possible to have multiple sources of energy available, and bursts can be related to a combination of energy sources, particularly in areas of elevated gas pressure in the coal. The relative contribution of each of the sources needs to be considered in order to better understand the nature and cause of bursts.

ENERGY RELATED TO POTENTIAL MECHANISMS

Strain Energy

The energy stored in the rock units and the coal is related to the stress and the stiffness of the materials. It can be visualised by viewing the rock as a spring, which is compressed by the in situ stresses. The stored energy is the amount required to have compressed the strata (spring) to the in situ state.

The general formula is

$$\text{Strain Energy} = \frac{1}{2E}\left[\left(\sigma_1^2+\sigma_2^2+\sigma_3^2\right)-2\nu\left(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_3\sigma_1\right)\right] \qquad (1)$$

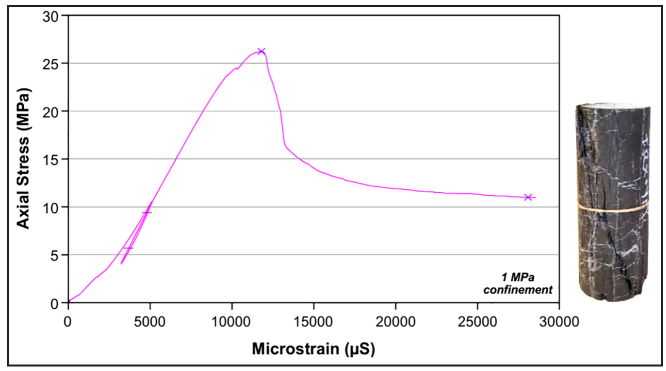

Figure 4. Typical coal, stress, strain behaviour at 1MPa confinement.

Where E = Young's Modulus, ν = Poisson's ratio and σ_1, σ_2, σ_3 are the principal stress components.

In sedimentary rock, the stored strain energy is consumed (rupture, friction, heat, seismic radiation) in the fracture process, and very little is available to dislodge or propel the coal.

This can be noted in the post-failure tests of the coal, where additional energy is required to take the coal from the point of failure through the process of fracture, linking and forming a continuous fracture surface. In the laboratory, this energy is provided by the testing machine, and, in the mine, this energy is provided by displacement of the surrounding coal (not fractured) or the roof and floor strata immediately adjacent to the rib.

A typical failure characteristic of coal samples is presented in Figure 4. The post-failure stiffness is typically 6-10GPa, which is 3–4 times the pre-failure Young's modulus.

In order to get the coal to rapidly dislodge or be propelled, additional energy is required. This is confirmed by the response of the coal ribs, which will commonly fracture and could slump under gravity, but, typically, they do not propel into the roadway.

The concept of additional energy being available can be taken further, in considering the effect of the roof and floor or surrounding coal on the failure process. The generalised concept is presented in Figure 5, which relates to the surrounding strata (or coal in a thick seam) as a spring. When it is unloaded by the failure of the coal,

the strata can rebound and provide additional energy to the system. This energy is commonly required to form macro fractures in the coal; however, depending on conditions, additional energy could be available. This could contribute to the energy level required to propel the fractured coal.

The additional energy available from the surrounding ground in the immediate vicinity of the fracture is

$$E = \text{stress drop}^2/2 * (1/E_r - 1/E_c) \quad (2)$$

where the stress drop is at the time of failure of the coal, E_r = unloading modulus of the surrounding rock, and E_c is the post-failure modulus of the coal (or rock units undergoing fracture). All units are in MPa, and the energy is in MJ/m^3.

Applying this approach and using a post-failure stiffness of the coal, (10GPa) and 8GPa of the surrounding ground results in approximately 7kJ of additional energy input into the failure process after the fracture of a cubic metre of coal. If the stiffness of the surrounding ground is greater than the post-failure stiffness of the coal, no energy is available to contribute to instability.

This energy can only propel the coal if it is sufficient to overcome the inertial resistance to movement caused by confinement of the coal in the rib and interlocking of the fracture zones in the rib. It is very rare to see coal propelled from the face or ribs during development mining in normal geometries and conditions.

In most cases, only the outside skin of a rib having loose coal would have a low inertial resistance, whereas the zone 0.5m–1.5m into the ribside resistance to movement increases, due to confinement and frictional interlock.

However, if one looks at the energy available in a pillar that fails suddenly, the energy levels can be significantly greater. Using the discussed approach and an extreme example of a highly loaded pillar separated by 180m of goaf, a stress drop of 30MPa is approximately 3MJ per cubic metre of coal pillar. This is due to the low overburden stiffness of 142MPa, which provides significant energy into the post-failure component of the pillar. The energy balance is presented in Figure 6. Such events are typically an issue for mine design. However, under certain circumstances, such failures and energy levels are available to contribute to a major burst.

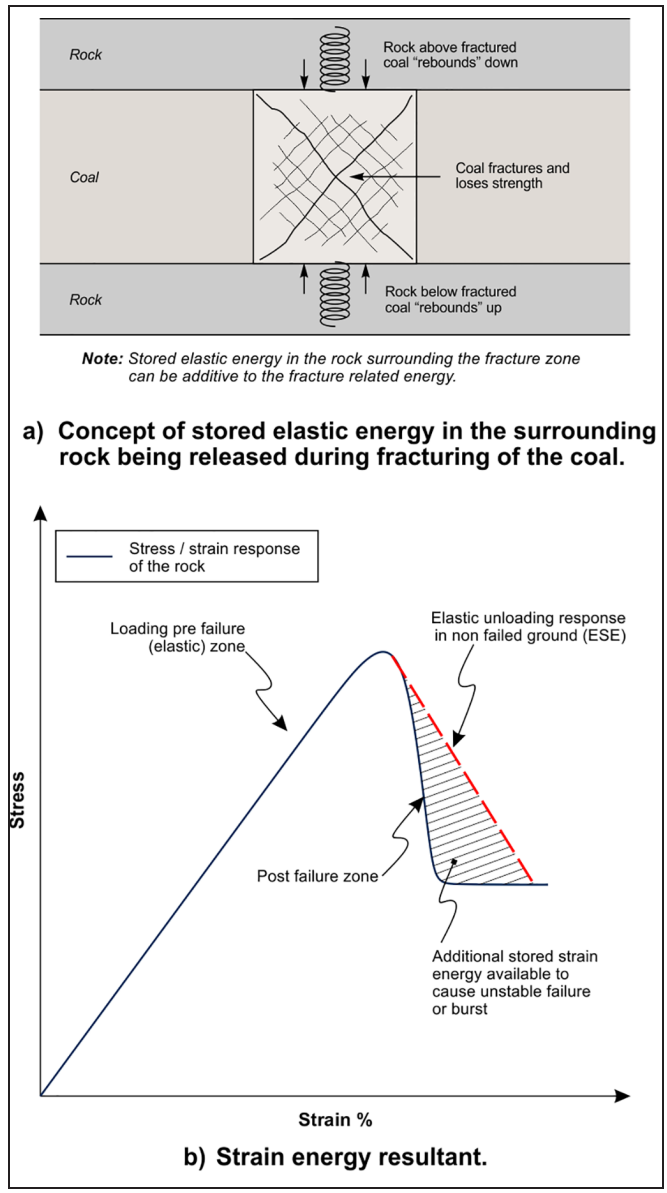

Figure 5. Concept of additional stored strain energy from surrounding strata.

Energy Related to Slip Along Bedding Surfaces or Fault Planes

The energy related to shear slip failure of such surfaces is determined by a similar energy expression of

$$\tau^2/2G \quad (3)$$

where τ is the shear stress drop, and G is the shear stiffness of the strata surrounding the structure on which rapid slip occurs. In cases of a confined plane that fails, the stress drop is the cohesion of the surface. If the normal stress across the plane drops because of the failure process, the stress drop will be the shear stress drop along the plane.

Examples of the energy for these surfaces is presented in Figure 7, for a range of stress drops and plane lengths.

The energy increases with the increasing plane length and stress drop. The energy available from the typical development of a roadway cases of average shear stress in the range of 2–3MPa, in the range of 40–60kJ per linear metre of roadway.

If the shear stress is elevated due to abutment loading, the energy can be significantly elevated in cases of strong coal to stone contacts. This is a potential mechanism for bursts about pillar edges with strong coal-stone contacts. The geological environment will dictate the potential energy under such cases.

Seismic Energy

Seismic energy is radiated from sudden rupture surfaces as part of the failure process. The radiated energy is related to the sudden displacement along the fracture surface, and, as such, the magnitude

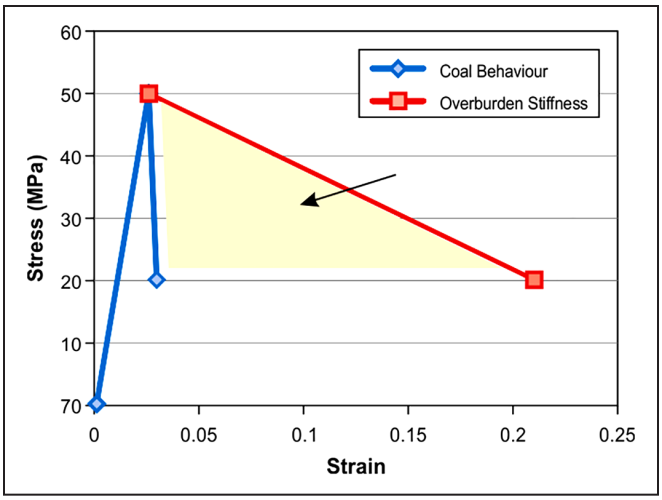

Figure 6. Energy available from overburden movement in case assessed.

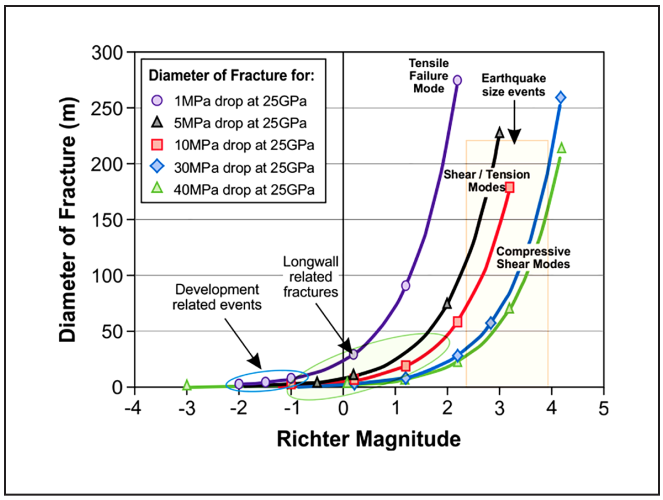

Figure 8. Relationship of Richter magnitude and fracture size.

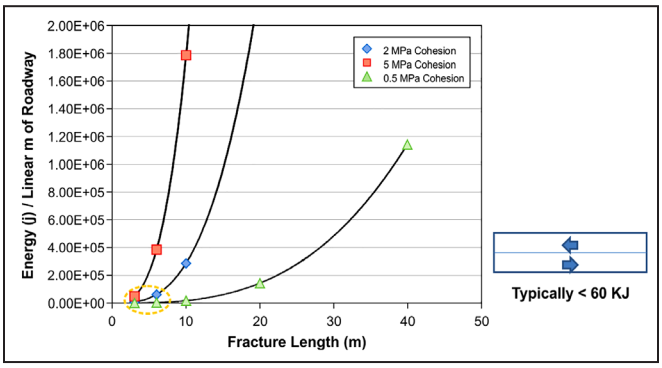

Figure 7. Energy from shear slip along a bedding or pre-existing structure plan.

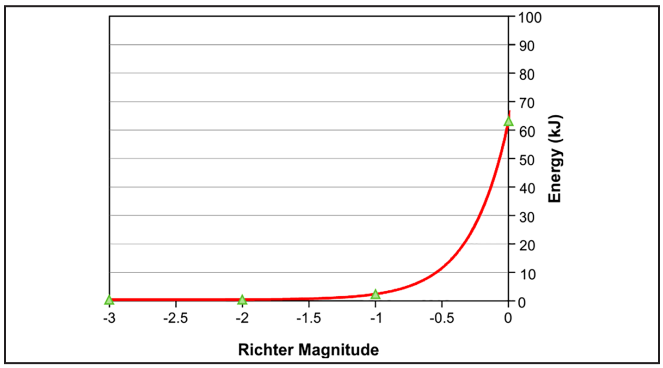

Figure 9. Energy available from seismic events on for development driveage.

is related to the stress drop and surface area of the rupture surface. The radiation pattern is complex; however, most analyses are based on generalised cases of a uniform radial pattern from the source.

The magnitude of seismic events is typically reported as Richter magnitude. The relationship of Richter magnitude, relative to the stress drop and fracture size, is presented in Figure 8 (after Gale et al., 2001; Gale et al., 2002), which also relates the fracture mode associated with the seismic event. The results of micro seismic monitoring in coal mines is generalised in this Figure 8 to depict the magnitude related to rock fracture during development and longwall operations.

During development, Richter magnitude is typically less than -1, but this can be elevated up to a Richter magnitude of 2–4 during longwall extraction. The magnitude of events about roadways on development relate to fracture surfaces, typically less than 0.5m in diameter. The energy related to longwall extraction is a function of the greater stresses and volume of rock affected by stress redistributions. This is consistent with observation.

The energy associated with the seismic events during development driveage is is typically less than 5kJ, as shown in Figure 9.

The energy around longwall panels can exceed 10–20MJ for large caving (fracture) events.

The impact of the seismic energy is related to the ground motions created via the seismic waves. Wave patterns are complex; however, in general, the ground motions are measured and analysed on the basis of peak particle velocity (PPV). The PPV is a function of magnitude of the event and the distance from the source.

Some examples are presented in Figure 10, showing the rapid reduction in PPV with distance from the source.

Various studies have been done on the effect of PPV on roadway stability. In general, most studies relate to metalliferous mines, for which there is a comprehensive micro seismic monitoring system. The effect of the PPV appears to be related to the nature of the ground about the roadway. If it is loose and unrestrained, the effect is maximised; however, if the ground is restrained or reinforced, the effect is minimised because the energy is transferred to the reinforcement rather than impacting on loose unrestrained blocks of rock.

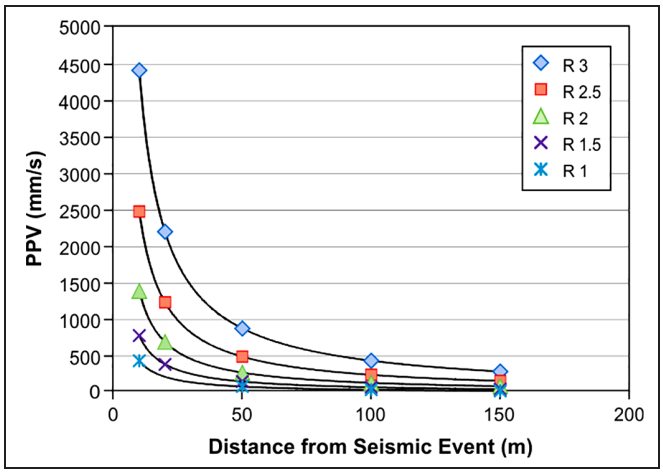

Figure 10. General relationship of PPV vs distance from a seismic source for a range of Richter magnitude events.

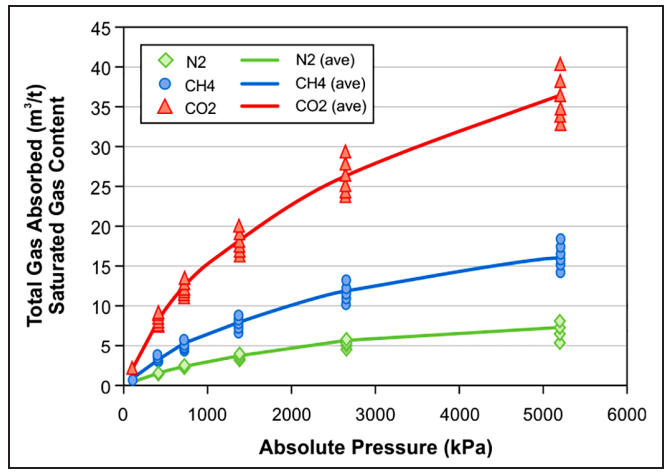

Figure 11. Gas adsorption characteristics used in the study.

In coal mines, the general wave radiation effect is modified by the anisotropic nature of the layered rock and coal, in general, PPV up to 250–500mm/s, with only minor effects on loose material. This can be seen in Figure 3, for a velocity of 500mm/s will only cause a localised "shake down" event.

In order to cause significant damage, it appears that PPV needs to be in the order of 1500–2000mm/s, which requires large seismic events to occur nearby to the roadway. Amplification of PPV can occur in broken material, which may contribute to the damage, but the nature of such amplification is difficult to predict.

Gas Energy

The energy relating to gas pressure relates to the gas desorbed, or diffused, from the coal structure. The gas is related to the desorption isotherm of the coal. A typical adsorption isotherm, used in this analysis, for the Bulli coal is presented in Figure 11. For the purpose of this assessment, the desorption isotherm is assumed to be the same as the adsorption isotherm. Methane has been used as the gas source in this analysis.

The energy provided by gas pressure is derived from the adiabatic expansion of the gas from within the pore space, fracture volume, and coal micro fabric. The volumetric expansion can also relate to the deformation volume of the fractures and voids created by movement of the rib.

The energy associated with the expansion of a gas is presented as Equation 4 (Gray and Wood, 2015).

$$W = \frac{V_1\left(P_1 - P_2 \cdot \sqrt{\frac{P_1}{P_2}}\right)}{\gamma - 1} \qquad (4)$$

P_1 is the initial absolute pressure	Pa
P_2 is the initial absolute pressure	Pa
V_1 is the initial volume	m^3
W is the work by adiabatic expansion	J

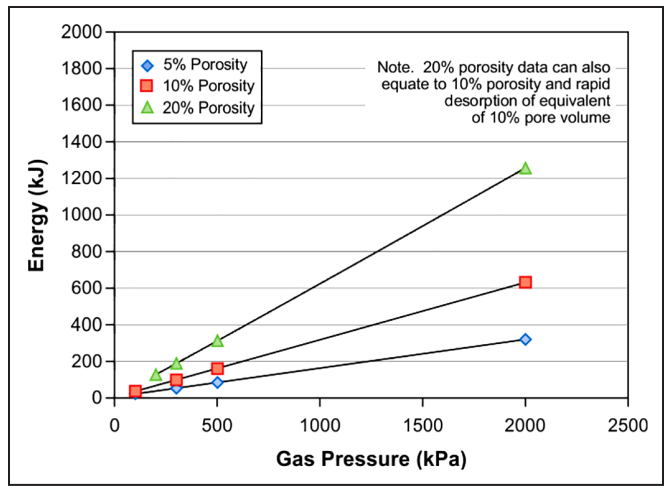

Figure 12. Energy related to gas expansion for Methane for various cases.

γ is the ratio of specific heats at constant presssure over constant pressure over constant volume for methane and carbon dioxide $\gamma \div 1$

The energy from a range of volumes of gas expanding, from an initial desorption pressure to atmospheric is presented in Figure 12.

It is clear that the energy available from gas can be very significant and much greater than that available from stored strain energy.

For example, if the coal porosity was 10% and the gas content was $12m^3/t$, then desorption pressure would be 2MPa. Using this input, the energy available from the initial gas from the pore space would be approximately 330kJ, which is many times greater than the additional energy typically available from about a development roadway resulting from stored strain.

The key issue is how much gas can be desorbed as part of the burst process. This is determined by the following:

- In-situ pore space volume in the coal. The pore volume is a function of maceral types, rank of coal, and de-volatilisation processes, such as coking about igneous intrusions. Typically, porosity is in the range of 2–5% but can increase up to 15% around igneous intrusions. Around fault structures, effective porosity may also increase due to fracture and strain; however, this is variable depends on the nature of the structure.
- Micro structure of the coal. If it is highly micro fractured, volumes of 2% to greater than 50% of total gas may be very rapidly desorbed. This is generally based on diffusion relationships determined by Fick's law.
- Deformation of the coal leading up to a burst. If the coal is not micro fractured, the gas desorption will be much slower. Time–dependent, volumetric changes in the coal ribside are required to develop gas volume. If the coal is fracturing and allowing volumetric increase to occur, free gas could fill the voids, increasing the potential energy of the system as a function of effective porosity (see Figure 12). A burst may take less than 1 second to occur; however, it is often noted that the ribs are "working" or bumping as pre-cursors to such events.

In order for gas pressure to develop, the volumetric rate of gas generation must significantly exceed the potential for flow through the coal to the roadway. This requires either

- A low permeability barrier zone to the roadway and moderate to high effective porosity for coals which desorb slowly
- The ability of the coal to desorb rapidly, which is at a significantly greater rate than can flow to the roadway

In order to have gas desorption or diffusion in a coal section, the water or gas pressure must be below the desorption value for that coal. In order to get high desorption rates relating to micro fracturing of the coal fabric, the confining pressure in the coal should be less than the gas pressure within the pore and micro fracture fabric.

The location of the energy source is where the phenomena noted in the above occur within the ribside.

Therefore, it is clear that there is a large potential energy source from gas adsorbed within the coal. The amount that can be realised to be part of a coal burst is dependent on a range of factors, which cannot be fully discussed in this paper.

It is also apparent that energy within the pore space can be significant and can also work with other energy sources, such as strain energy as part of the burst process. Strain energy is part of the process of fracture and weakening the resistance of the ribside and gas energy can also be part of this process, but is a key source of propulsion of the broken material.

ENERGY REQUIRED FOR A STRAIN OR GAS BURST

The effect of energy can be assessed in terms of propulsion of coal on the basis of kinetic energy. The relationship in terms of velocity is

$$\text{Velocity} = \sqrt{2 * \frac{(\text{Energy} - \text{Resistance})}{\text{mass}}} \quad (5)$$

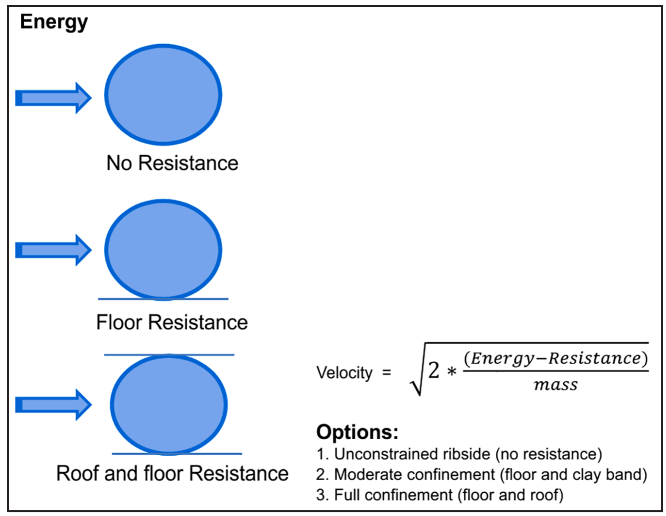

Figure 13. Concept of resistance to movement.

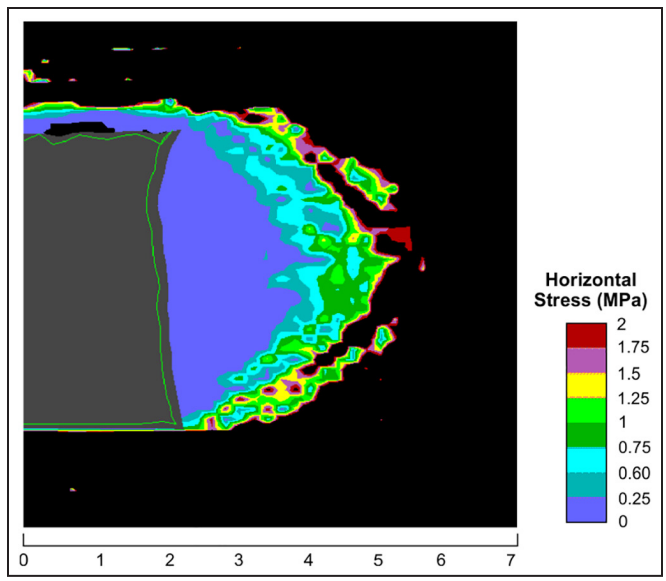

Figure 14. Horizontal confinement developed into a coal ribside.

The relationship is depicted in Figure 13, relative to what may be experienced in a roadway.

If, on the extreme ribside, there is no resistance to movement, the velocity, due to energy release (at that very point), can be significant. However, resistance is developed very rapidly into the ribside, due to confinement, cohesion, and friction of bedding and fracture surfaces. The resistance will depend on the thickness of the coal rib, existence of weak bands, and fracture density within the ribside. However, as an example, the simulated confinement developed into the rib of a 3m coal seam typical of the south coast area of NSW is presented in Figure 14.

The model geometry and properties are presented in Figure 15. The modelling approach is similar to that reported by Gale et al. (2004).

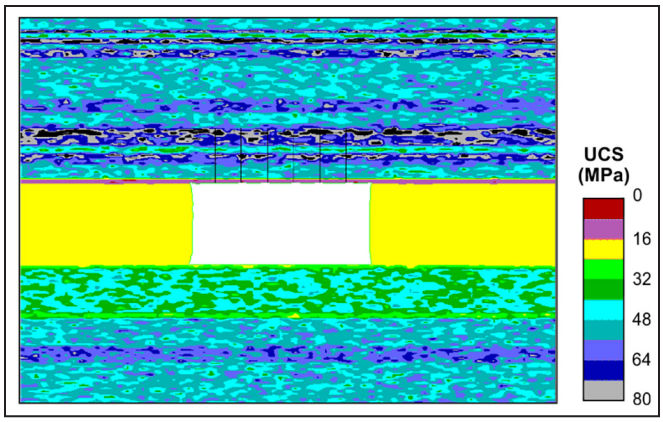

Figure 15. Model Geometry and properties.

The results shows deformation of the ribside, extending greater than 1.5m, but confinement and resistance to movement is rapidly developed. For a case of gas-pressure-related energy located approximately 0.4m, 1m, and 2m into the ribside, the gas supplied energy vs velocity relationship is presented in Figure 16. This shows, that for a source located 1m into the rib, approximately 175–200kJ of gas supplied energy is required to mobilise the rib and additional energy adds linearly to the burst velocity. A burst velocity of approximately 8–10m/s requires approximately 1–1.2MJ of energy.

For a source located at 2m into the ribside, the resistance developed is in excess of 1.5MJ, and the rate of increase is much smaller, due to the greater effective mass of material.

The resistance relative to distance of the gas energy source for the data is presented in Figure 17 and shows the clear increase from the surface into the ribside.

The resistance at 0.4m for a heavily fractured ribside is small and not significantly different to a free mass. It is very difficult for gas pressure to develop such pressures due to flow through the fractured ribside.

The modelling results are more complex than that related in the equation, but the same concept is clearly portrayed.

Therefore, resistance to movement is inherent in the ribside and will be related to geology, stresses, fracture mode, and fracture density within the ribside. Clearly, a different "resistance" will relate to different situations and coal seams.

However, it is clear that the volume of coal involved in a burst will be related to the energy available and the location of the source. The nature of application of energy is also a key factor.

An interesting observation from this modelled case is the amount of energy required to cause a burst relative to what is available from a number of sources.

It is clear that, for this geometry, energy from stored strain is unlikely to cause significant burst volumes, unless it is associated

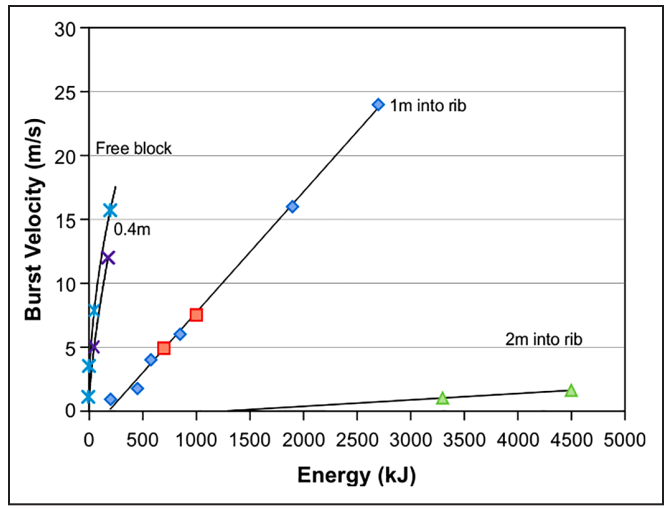

Figure 16. Burst velocity in the modelled coal rib vs energy and distance into the ribside.

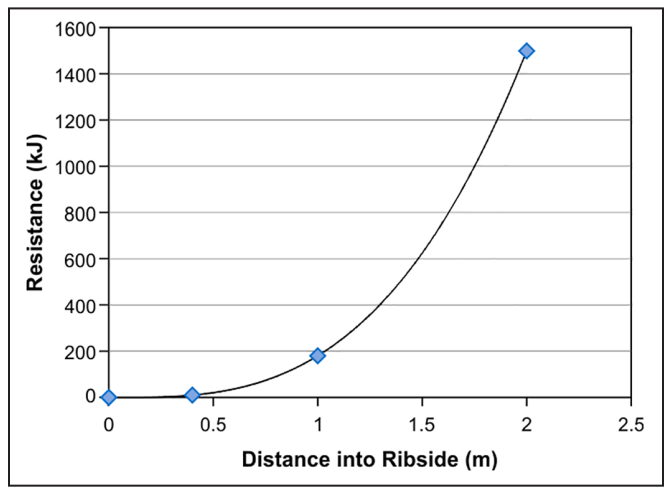

Figure 17. Resistance to burst vs depth into the ribside (modelled case).

with sudden failure of cohesive bedding planes, bounding the coal seam in highly loaded ribsides (4MPa), as noted in Figure 7.

Energy related to larger scale pillar failure is also a significant energy source, but that is considered a mine design issue, rather than a mechanism that should occur in normal development operations.

CASE STUDY OF A GAS-RELATED COAL BURST

This case study relates to a gassy seam at a depth of approximately 500m. The nature of the burst is presented in Figures 18 and 19.

A number of coal bursts occurred adjacent to a dyke structure that had the following characteristics:

- A significantly reduced mining induced fracture density as the roadway approached the dyke
- Apparent increase in pore volume within the coal near the dyke

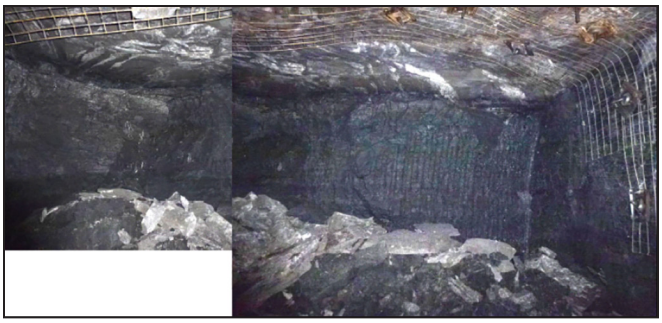

Figure 18. Burst area and block geometry after miner removed.

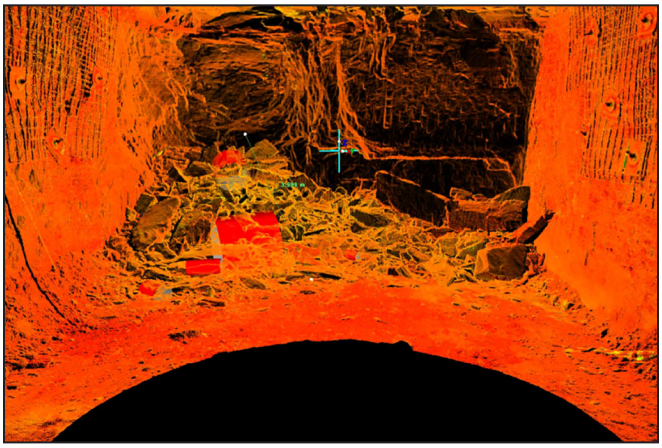

Figure 19. Laser scanned image of cavity and roadway face area.

- Variable gas content in pockets adjacent to the structure
- Increased micro fracturing of the coal matrix adjacent to the structure
- Increased gas in the ventilation (not apparent from development monitors)

No indication of any recent movement along its surface and no seismic events we recorded associated with the burst event. The locally elevated gas content in pockets of the coal near the dyke structure is presented in Figure 20.

Figure 21 shows an example of the gas volume monitored during mining and the burst. This data was obtained from analysis of the gas monitors in the panel after the event. The results show a "gas push" prior to the event and then a "normal" period followed by the burst, which occurred closer to the dyke.

The interpretation is that pockets of higher free gas in the coal were intersected during development in this zone. The gas in the initial pocket could flow into the roadway and not develop significant pressure to initiate the burst. The flow prior to the burst was low, and fracture formation in the coal about the roadway was noted to be minimal at the face. The depth of yield in the ribside was 1.5–2m. However, at the face, it is estimated to be less than 1m. In this situation, gas pressure could be maintained, as the permeability of the coal ribside was low (0.1–0.01md based on coal samples).

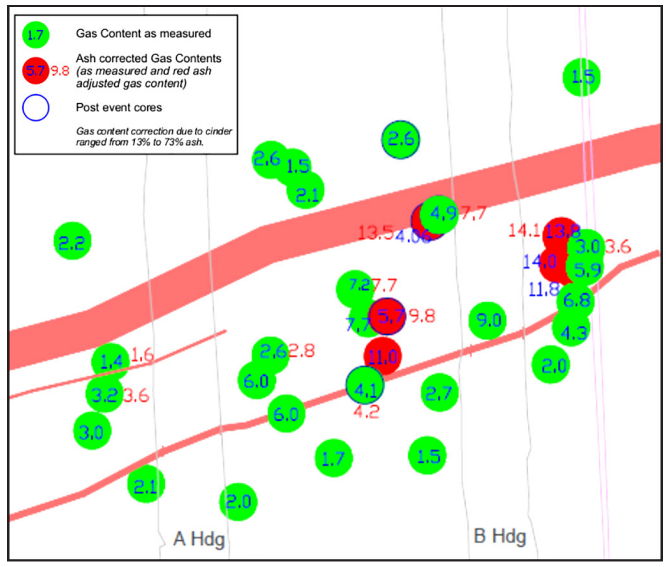

Figure 20. Gas content in samples about the zone. Note potential for "pockets" of high gas content coal.

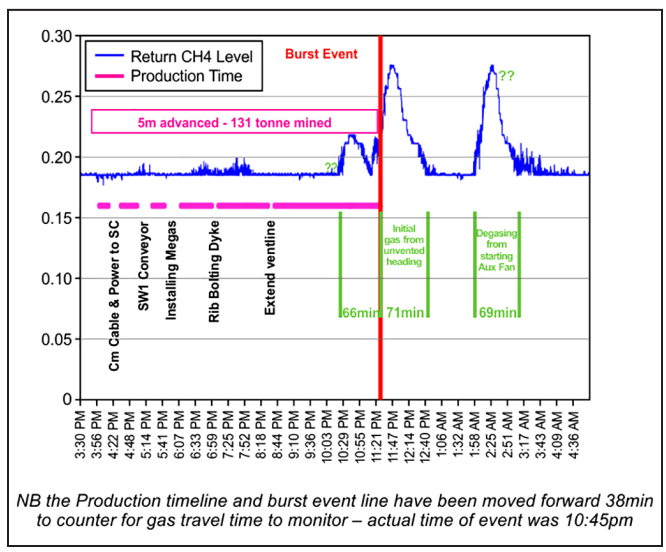

Figure 21. Gas levels pre and during burst event.

The end result was a burst of 10–15 cubic metres of coal that projected blocks, at least 0.5m width and height, of coal over the continuous miner. This is presented in Figures 18 and 19 and was approximately 2–3m wide, 2.5m high and 2–2.5m deep. The burst cavity was a broad cone, with finely spaced curved fractures paralleling the cavity. The burst coal comprised large blocks, moderate to small blocks, and fine dust.

The volumes of gas released during the event are presented in Figure 21. Approximately 60 cubic metres of gas was released during the initial gas event, and 120–140 cubic metres was released during the burst event. These volumes are estimated based on gas content measured and ventilation flow.

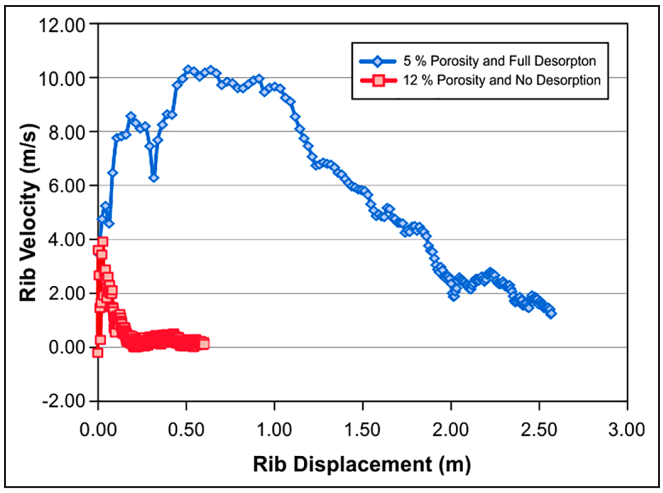

Figure 22. Burst velocity vs displacement for two cases.

Subsequent drilling indicated that while much of the area was drained, pockets of coal with gas content of approximately 8–12 cubic metres per tonne existed in the area. The anticipated pressure possible to be developed is in the range of 1.0–2.5MPa.

The velocity of the coal blocks would need to be greater than 10m/s to be located in the positions found.

Computer modelling of the range of scenarios indicates that a gas pressure, within a zone 1–2m into the coal, has the energy and capability to create the burst as noted. The results of the modelling are presented in Figure 22. The results indicate the velocity and displacement of the burst for two scenarios.

These are

- Gas pressure of 1MPa in 10% pore volume
- Gas pressure within 5% pore volume, but with very rapid gas desorption related to formation of fine fracture fabric in a section of the burst zone. A pressure of approximately 1MPa was developed.

These pressures are related to the lower bound of the anticipated gas content within the pockets of higher gas content coal. The actual case is likely to be somewhere between the end members.

The results show that high velocities are developed; however it is probable that gas, in addition to an initial pore volume, is required to drive the burst to the extent observed. The gas volumes recorded demonstrate that additional gas was available for the burst, but the timing of the gas desorption is not clear from the data. The nature of the gas flows indicate that the volumes are not generated by normal desorption but are most likely related to fracture assisted desorption.

The results indicate that, at least, 1.5–2 MJ of energy is required to cause such a burst located in the 1.0–2m zone within the face. This energy is available from gas within the coal.

DISCUSSION AND CONCLUSIONS

The results indicate that, if the ribside or face is fractured and has little cohesive strength, the coal immediately adjacent to the rib (0–400mm) could possibly be mobilised by energy associated with stored strain and seismic events of modest magnitude.

Computer modelling indicates that, once confinement and cohesive strength develops in the ribside, the resistive energy becomes much larger, and significantly greater energy is required to create a burst within the confined material.

It was found that, for bursts which are 1–3m in depth, much greater energy is required than the strain energy associated with normal development operations.

The energy required is related to

- gas pressure associated with moderate to high gas content coals
- significant seismic events nearby
- major stress changes associated with pillar failure or failure of structures bounding the coal seam

More work is underway to determine the energy available from various ground failure events; however, the aim of this paper is to demonstrate the potential impact that gas-related energy may have in the process.

It is likely that a number of sources of energy could operate together, which could facilitate the burst. The obvious sources are strain and gas energy, which are likely to operate together to create the ribside fractures and the energy required to overcome the ground resistance to movement.

Seismic energy is also conceivable in association with strain energy.

The timeframe of seismic wave forms is typically in the 4–100Hz. The energy could combine with free gas within the pore volume, but it is difficult to combine additional energy from desorption within this timeframe.

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