

CONTROL AND MANAGEMENT OF OUTBURST IN AUSTRALIAN UNDERGROUND COAL MINES

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ABSTRACT: Outbursts represent a major safety hazard to mine personnel working near the coal face in areas of increased outburst risk. There have been over 878 outburst events recorded in twenty two Australian underground coal mines and most outburst have been associated with abnormal geological conditions.

Details of Australian outburst incidents and mining experience in conditions where gas content was above current threshold levels is presented and discussed. Mining experience suggests that for gas content below 9.0 m³/t, mining in CO₂ rich seam gas conditions does not pose a greater risk of outburst than mining in CH₄ rich seam gas conditions.

Mining experience also suggests that where no abnormal geological structures are present, mining in areas with gas content greater than the current accepted threshold levels can be undertaken with no discernible increase in outburst risk. The current approach to determining gas content threshold limits in Australian mines has been effective in preventing injury from outburst however operational experience suggests the current method is overly conservative and in some cases the threshold limits are low to the point that they provide no significant reduction in outburst risk.

Other factors that affect outburst risk, such as gas pressure, coal toughness and stress and geological structures are presently not incorporated into outburst threshold limits adopted in Australian mines. These factors and the development of an Outburst Risk Index applicable to Australian underground coal mining conditions is the subject of ongoing research.

INTRODUCTION

Outburst has been defined as the sudden release of gas and material from the working place that can vary in magnitude and intensity (NSWDMR, 1995). The occurrence of an outburst is preceded by failure of the coal and during an outburst, the failed material is ejected with energy and with gas. The difference between a rockburst and an outburst is the gas that is emitted. The gas contributes in a major way to the expulsion of the coal and is generally thought to be the main contributor to total energy release (Gray and Wood, 2013).

Outbursts of coal and gas have been experienced in underground coal mines in many countries, including Australia (Lama and Bodziony, 1996). Outburst vary in size and intensity, from small bumps equivalent to rib failure without discernible gas release to violent ejections of thousands of tonnes of coal and rock releasing tens of thousands of cubic metres of seam gas. The sudden release of a large volume of seam gas into a mining place following an outburst can create significant potential risks to personnel safety which include: (a) danger of asphyxiation due to oxygen deficiency, (b) poisoning by noxious gases, (c) explosion by inadvertent ignition of the resultant explosive mixtures, (d) injury resulting from the violent ejection of coal and gas, and (e) exposure to dense coal dust.

Gas, geology and stress have been identified as dominant parameters that combine to create outburst conditions and provide the energy required to expel coal from the working face (Black *et al.*, 2009). Outbursts are usually, but not invariably associated with faults, dykes, seam variations and dislocations. In some mines, such as Leichhardt colliery in Queensland some outbursts occurred in areas with no abnormal geological structure or with structures which elsewhere in the same mine had been quite benign (Hanes, 1995).

The general nature of the outburst risk is such that it may be continuously variable, not only between mines but also within an individual colliery's workings. A single, unchanging approach to the management of the risk is, therefore, inappropriate. A degree of discipline is also warranted to identify, and effectively act upon, changes in the mine operating environment, which may be subtle, which may be associated with the potential for outbursts (NSWDMR, 1995).

AUSTRALIAN OUTBURST HISTORY

The first recorded outburst in Australia occurred at Metropolitan colliery on 30 September 1895 and in the 122 year period to 2017, over 878 outburst events have been recorded in twenty two Australian underground coal mines. Mining operations in the Bulli seam, located in the southern Sydney basin, have the longest history of outburst in Australia, with fourteen collieries recording over 641 outburst incidents. Ellalong colliery, working the Greta seam in the northern Sydney basin, recorded five relatively small-scale outburst events, and is the only non-Bulli seam mine in New South Wales to record an outburst event. Seven collieries operating in the Bowen basin, Queensland, have recorded over 232 outburst incidents, with the largest number of events recorded during development mining in the Gemini seam at Leichhardt colliery. Table 1 provides a summary list of recorded outburst data compiled from extensive review of published reports and Mines Department records.

The lives of twenty-one men and five horses have been lost in eight outburst incidents in Australian underground coal mines. The largest outburst event recorded in Australia, which claimed the lives of seven men and three horses, occurred at the Collinsville State mine in Queensland on 13 October 1954. In three separate outburst incidents, seven men and two

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horses were killed at Metropolitan colliery. Table 2 provides a summary list of fatal outburst incidents that have occurred in Australian underground coal mines.

Table 1 – Summary of Recorded Outburst Incidents in Australia

Mine	State	Seam	Recorded Outburst Events	Recorded Outburst Event Date Range	Max. Coal Outburst (tonnes)	Max. Gas Outburst (m ³)	Gas Type CH ₄ - CO ₂	Associated Geological Structure	Gas Drainage Status
Appin	NSW	Bulli	67	May 1966 - Feb 2017	150	5,100	Mostly CH ₄	Strike-Slip, Thrust, Normal Faulting. Dykes	No or Inadequate Drainage
Brimstone (closed)	NSW	Bulli	2	1992	<40	Unknown	Mixed	Fault	No Drainage
Coal Cliff (closed)	NSW	Bulli	2	1961	20	Unknown	CH ₄	Dyke	No Drainage
Corrimal (South Bulli)	NSW	Bulli	9	Oct 1967 - Sep 1983	40	Unknown	CH ₄	Shear Fault with Mylonite	No Drainage
Darkes Forrest (closed)	NSW	Bulli	2	1989	10	Unknown	Mixed	Dyke	No Drainage
Ellalong (Austar)	NSW	Greta	5	1994	<30	Unknown	Mostly CO ₂	Bedding plane shear. High Stress	No Drainage
Kemira (closed)	NSW	Bulli	2	May 1980 - May 1981	100	Unknown	CH ₄	Thrust Fault	No Drainage
Metropolitan	NSW	Bulli	169+	Sep 1895 - Jan 2017	250	11,500	Mixed	Thrust Faults & Dykes. Shotfiring Induced.	No or Inadequate Drainage
North Bulli (closed)	NSW	Bulli	1	1911	1	Unknown	CH ₄	Faults	No Drainage
Oakdale (closed)	NSW	Bulli	1	1996	<10	Unknown	Mixed	Fault	No Drainage
Bulli (closed)	NSW	Bulli	3	1972	30	Unknown	CH ₄	Faults	No Drainage
South Bulli (Russell Vale)	NSW	Bulli	7	Feb 1985 - Apr 1996	120	6,000	Mostly CH ₄	Strike-Slip & Thrust Faults. Dykes	No Drainage
Tahmoor	NSW	Bulli	99	May 1981 - Mar 1992	400	4,500	Mixed	Faults & Dykes	No or Inadequate Drainage
Tower (Appin)	NSW	Bulli	21	Jul 1981 - Dec 2000	80	Unknown	CH ₄	Strike-Slip Fault & Dyke	No or Inadequate Drainage
West Cliff (Appin)	NSW	Bulli	256	Dec 1976 - Apr 1998	350	Unknown	Mostly CH ₄	Thrust Faults & Dykes	No or Inadequate Drainage
Central (closed)	QLD	German Creek	1	20 Jul 2001	80	1,500	CH ₄	Oblique Strike-Slip Fault	Inadequate Drainage
Collinsville State (closed)	QLD	Bowen	13	Mar 1960 - Mar 1961	500	14,000	CO ₂	Strike-Slip, Thrust & Normal Faulting	No Drainage
Collinsville No.3 (closed)	QLD	Bowen	2	Mar 1972 - Apr 1972	1	Unknown	CO ₂	Strike-Slip & Thrust Faults	No Drainage
Collinsville No.2 (closed)	QLD	Bowen	7	Sep 1978 - Nov 1978	35	380	CO ₂	Strike-Slip & Thrust Faults	No Drainage
Leichhardt (closed)	QLD	Gemini	200+	1975 to 1982	350	13,500	CH ₄	Thrust Faults High Stress	No Drainage
Moura No.4 (closed)	QLD	C seam	3	1980 to 1983	Unknown	Unknown	CH ₄	Major Joint Planes	No Drainage
North Goonyella	QLD	Goonyella Middle	6	Oct 2001 - Jan 2015	150	5,000	CH ₄	Shear Zone. Mylonite In-fill	Inadequate Drainage

Table 2 – Summary of Fatal Outburst Incidents in Australia

Mine	State	Seam	Date	Loss of Life	Outburst Size (tonnes)	Gas Volume Gas Type
Metropolitan	NSW	Bulli	10 Jun 1896	3 men, 1 horse	Unknown	CH ₄
Metropolitan	NSW	Bulli	27 Jun 1925	2 men, 1 horse	220	Mixed CO ₂ & CH ₄
Collinsville State	QLD	Bowen	13 Oct 1954	7 men, 3 horses	500	14,000m ³ CO ₂
Metropolitan	NSW	Bulli	02 Dec 1954	2 men	90	CO ₂
Leichhardt	QLD	Gemini	01 Dec 1978	2 men	350	13,500m ³ CH ₄ + CO ₂
Tahmoor	NSW	Bulli	24 Jun 1985	1 man	400	4,500m ³ CO ₂ + CH ₄
South Bulli	NSW	Bulli	24 Jul 1991	3 men	300	6,000m ³ CO ₂ + CH ₄
West Cliff	NSW	Bulli	25 Jan 1994	1 man	350	CO ₂

Virtually all outburst events in the Bulli seam have been associated with geological structures and have occurred in areas where no substantial gas drainage has been undertaken (Lama, 1995). The highest number of outburst events have occurred at West Cliff, Metropolitan, Appin and Tahmoor collieries which all work the Bulli seam and Leichhardt colliery which worked the Gemini seam. Brief summaries of the outburst histories at these five collieries are provided.

West Cliff Colliery

West Cliff colliery commenced coal production in October 1976 and longwall mining was introduced in 1982 (Eade, 2002). The first recorded outburst occurred at West Cliff on 20 December 1976 and two hundred and fifty four (254) outburst events were recorded at West Cliff prior to the mine ceasing production in 2015-2016. The size of outbursts varied from four to over 300 tonnes, with the majority being related to zones of strike-slip faulting. Outbursts at West Cliff typically occurred in association with pulverised coal in shear zones running through the coal. The shear zones were also regions of high gas pressure, which when intersected, resulted in displacement of pulverised coal into the excavations (Marshall *et al.*, 1980). Walsh (1999) reported that of the approximately 250 outbursts recorded at West Cliff, 70% occurred on strike-slip faults, 4% on dykes and faults, 1% on thrusts, 3% on normal faults; and 19% on bedding slips.

The largest outburst at West Cliff, reported to have displaced 320 tonnes of coal, occurred at the northwest end of a normal fault where the gas drainage holes had not penetrated. There was a major joint zone 3-4 m wide in the roof associated with this outburst site and a mylonite band some 30-mm thick. The gas composition had been predominantly methane. In the north-eastern part of the mine, outburst events had occurred in areas with high gas content ($>16 \text{ m}^3/\text{t}$) and high concentrations of carbon dioxide ($>95\% \text{ CO}_2$) (Harvey, 1994).

Marshall *et al.* (1980) reported the time taken for an outburst to manifest at West Cliff varied from several seconds to almost a minute. In the opinion of Harvey (1994), mining operations at West Cliff had been possible through the use of gas drainage and specified outburst mining procedures.

On 03 April 1998, West Cliff became the first mine in Australia to record an outburst on a retreating longwall face. Two outbursts of approximately 17 tonnes were identified on the longwall face (LW23) at Chocks #45 and #54 during the flit run of the cutting cycle (Walsh, 1999). The outbursts, comprising some fines but mostly blocky coal (Piper, 1998) were identified as cones extending into the face ($>1.0 \text{ metre}$) at the top of the 2.5 metre Bulli seam. Two hours after the outbursts, gas continued to be liberated from the cavities and could be heard as an audible hiss and a visible haze (Walsh, 1999). No abnormal structures, such as strike-slip or thrust faults were noted at the outburst sites, however a bedding plane slip was present in the seam, approximately 100 mm below the roof. There was also no prominent cleat noted at the outburst sites (Walsh 1999).

Metropolitan Colliery

Mining operations at Metropolitan colliery commenced in 1888 with the Bulli seam being mined by hand, with some single round shotfiring (Ward, 1980). Metropolitan was the first colliery in Australia to record an outburst, which occurred on 30 September 1895. The mine has since recorded over 169 outburst events.

The highest incidence of outburst occurred during the mining of the 2 South District between 1961 and 1968, where over 100 outburst events were reported to have been induced by shotfiring. The largest reported outburst ejected 250 tonnes of coal and an unknown quantity of predominantly CO_2 (Lama, 1995).

On 23 December 2016, Metropolitan became the second mine in Australia to record outburst events on a retreating longwall face. A total of three outburst / slump events occurred in quick succession as the longwall (LW27) retreated through a significant thrust fault zone. The largest of three outburst events occurred on 04 January 2017, ejecting approximately 200 tonnes of coal and releasing approximately $11,500 \text{ m}^3$ of CO_2 (Hyslop, 2017).

Gas content at Metropolitan has been recorded above $20 \text{ m}^3/\text{t}$ and the seam gas composition in the current mining area is predominantly CO_2 . Early outbursts were recorded as fire damp (CH_4) and recent outbursts are of black damp (CO_2) (Chatterjee, 1982).

A review of relevant reports and information indicates that the majority of the outbursts occurred on structures, especially a zone known at the mine as the "soft outburst zone" (Harvey, 2002).

Appin Colliery

Appin commenced operation in 1962 and longwall mining was introduced in 1969 (Eade, 2002). The first recorded outburst occurred in May 1966, ejecting 50 tonnes of coal and an unknown quantity of CH_4 . The outburst occurred in a zone of joints that were evident in the immediate roof (Harvey, 2002). A total of 67 outburst have been recorded at Appin. Twenty outbursts events were recorded in the 27 years to 1994, the largest occurred in July 1969 when development mining intersected a strike-slip fault with mylonite displacing 100 tonnes of coal and an unknown volume of CH_4 (Lama, 1991).

In the years following 1994, 47 seven outbursts have been recorded at Appin, the largest reported in May 2009 while operating a remote controlled continuous miner to develop through a known thrust fault zone that had been difficult to drill and drain gas below the outburst threshold. The outburst displaced 150 tonnes of coal and released $1,140 \text{ m}^3$ of predominantly CH_4 .

The largest reported outburst to have been induced while shotfiring through a dyke associated with strike-slip faulting occurred in January 2013 and released an estimated $5,100 \text{ m}^3$ of predominantly methane. The mass of coal displaced by the outburst, in addition to the planned shotfiring excavation, was not reported.

Outburst events at Appin typically occur in areas where prominent geological features have been intersected. Such features include faults, particularly strike-slip and thrust faults, adjacent to dykes and associated cindered coal.

Harvey (2002) reported five small outbursts, four being less than eight tonnes and one of up to 20 tonnes, had occurred in areas where 'no prominent geological structure' had been identified.

Gas content at Appin has been measured at levels exceeding 16 m³/t and an extensive gas drainage system is used to prevent or minimise the risk of outbursts and manage gas liberated during mining. Composition of the gas is predominantly CH₄, however high CO₂ has been recorded adjacent to faults and dykes (Harvey, 2002).

Tahmoor Colliery

Mine development commenced at Tahmoor in 1978 and longwall mining was introduced in 1986 (Newman, 2005). Ninety-nine (99) outbursts have been recorded at Tahmoor colliery in the years following the first recorded outburst in 1981. The mine identified the developing outburst problem, with events progressing in significance from slumps and pressure bumps to large outbursts occurring on geological structures, particularly dykes and strike-slip faults (Stone, 1991, Newman, 2005 and Wynne and Case, 1995). Wynne and Case (1995) reported that all outburst events at Tahmoor had occurred during the cutting phase of the development mining cycle. Table 3 lists the structural association of outbursts recorded at Tahmoor (Stone, 1991).

Table 3 – Summary geological structure association with outburst at Tahmoor colliery (Stone, 1991)

Geological Structure	No. of Outbursts	Violent Outburst	Size of Outburst
Across Dyke	3	3	5 - 400 t
Strike-Slip Fault / Dyke	27	17	5 - 120 t
Strike-Slip Fault	49	15	5 - 60 t
Reverse Fault	4	1	5 - 40 t

Following the fatal outburst incident that occurred in the 204 Panel on 24 June 1985, Tahmoor worked to modify the Joy 12 continuous miner to provide increased protection for the miner driver in outburst conditions. A completely enclosed cabin was built which was protected by one-inch thick bulletproof glass (Figure 1). Inside the cabin, the operator, who wore an air mask, communicated through radio control with the shuttle car driver and the crew at a fresh air base. The enclosed cabin was ventilated with two sources of fresh air supply, along with two additional sources of emergency air supply. Air pressure in the cabin was maintained to stop potential gas seepage into the miner's cabin. The outburst miner was replaced in 1992 with the introduction of the remote controlled Alpine Bolter Miner (ABM20).



Figure 1. Joy 12 CM 20 machinery equipped with an outburst protection cabin, Tahmoor Colliery (Lama and Bodziony, 1998)

Wynne (2002) listed critical events and stages in the evolution of outburst management at Tahmoor, which include:

- 1981 – first recorded outburst;
- 1985 – continuous miner driver killed by outburst whilst cutting dyke;
- 1985 – encapsulated continuous miner introduced for cutting outburst structures;
- 1982 to 1992 – averaging 10 outbursts per year crossing structures;
- 1992 – introduced ABM20 continuous miner capable of being remotely operated;
- 1992 – commenced pre-drainage of coal around structures;
- 1992 – draft Outburst Management Plan;
- 1992 – remote mining through fault, last recorded outburst;
- 1992 to 1997 – ongoing refinement of drilling techniques;
- 1994 – Outburst Management Plan formalised;
- 1999 to 2001 – shotfiring (grunching) through “tight” coal zones

Wynne (2000) reported there had not been an outburst event at Tahmoor Colliery since 1992, due to effective pre-drainage and the Outburst Management Plan.

In 2003, Tahmoor introduced increased gas content threshold levels for outburst control, which included among other management controls, (a) increased drilling for pre-mining gas content reduction and compliance core sampling, and (b) limited rate mining.

Leichhardt Colliery

Leichhardt colliery was the most outburst prone underground coal mine in Australia, with more than two hundred outbursts reported between 1973 and 1978. Leichhardt colliery commenced operations in the Gemini seam in 1973 and, following the fatal outburst in December 1978, the mine was placed on 'care and maintenance' and operated as an experimental mine for four years before closing in December 1982.

The average thickness of the Gemini seam was 6.0 m and the mine operated at a depth of 350 to 410 m. Within the mine, shallow dipping reverse faults of minor displacement and associated slickensides were common. Seam gas was predominantly CH₄ (95% CH₄ / 5% CO₂). Characteristics of the Gemini seam included high desorption rate, high gas pressures, low permeability and the gas content was around 15 m³/t (Truong *et al.*, 1983 and Hanes, 2001).

Mining was done by continuous miners, shotfiring and an Alpine Roadheader. Drilling large diameter boreholes in advance of mining was used for a period to reduce stress and gas emissions and was considered to improve the mining conditions. The practice was later abandoned due to a belief that large diameter boreholes were no more effective than smaller diameter holes and operational problems were associated with drilling large diameter boreholes. Other preventive techniques such as shotfiring, and delayed action shotfiring were also practised which generally reduced the frequency of outburst occurrences (Truong *et al.*, 1983).

Mining induced cleavage was typical in the coal at Leichhardt. It curved around the face forming large sheets of coal which easily spalled or at times, burst. Outbursts had not occurred in the western workings of the mine due to changes in the gas and/or structural regime and the coal which was free from bursts lacked the mining induced cleavage (Moore and Hanes, 1980 and Hanes, 2006). In the eastern part of the mine, outbursts occurred frequently (daily) from the rib (Moore and Hanes, 1980). The outbursts were typically small and occurred as the violent buckling of a few tonnes of the cleated coal into the opening. At times, the miner driver could "turn on" an outburst for visitors (Moore and Hanes, 1980).

Typically, outburst prone coal was intensely cleaved around the mine opening. Outbursts were partly controlled by stress and by the cleats. Drives near parallel to the maximum principal stress were free from outbursts and other mining strain, whereas drives nearly perpendicular to the principal stress were highly strained and outburst prone. The rib which first intersected the cleat was the focus of most bursts, which projected perpendicular to the cleat (Hanes, 2001). Outburst cavities in the Gemini Seam were typically oriented such that their axes were perpendicular to the face cleat direction and the bursts occurred from the ribs or face generally on the side which first encountered the cleat (Moore and Hanes, 1980). Some outbursts occurred with their axes perpendicular to prominent induced cleavage and many bursts occurred from coal roof with their axes perpendicular to the bedding planes (Hanes, 1979).

The orientation of the fatal outburst that occurred on 01 December 1978 was apparently controlled by cleat orientation. The axis of the burst cavity was approximately perpendicular to the dominant cleat direction over most of its length. Also, the axis of the burst cavity was nearly parallel to the mean strike of slickenside planes in the burst cavity walls (Hanes, 1979).

Tight ribs preceded most outbursts. Pick marks were obvious for the full height of the seam. The face at the fatal 1978 outburst had very hard coal ribs which "rang" when hit with a hammer (Hanes, 2006).

Measured gas pressure gradients showed that gas pressure was the controller of outbursts. When the pressure gradient in the face was high, outbursts occurred (Hanes, 2001). Gas flow measurements showed that on drilling, gas did not flow from drainage holes until the holes had stood for 2 to 3 months (Hanes, 2001). Figure 2 shows the results of pressure measurements in the coal ahead of the working face in outburst and benign conditions reported by Hanes (1995).

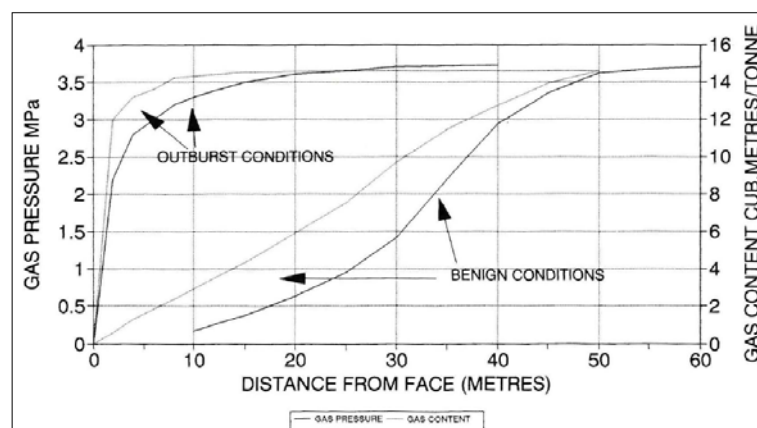


Figure 2. Gas pressure and content gradients recorded in the Gemini seam, Leichhardt colliery (Hanes, 1995)

INTRODUCTION OF OUTBURST THRESHOLD LIMITS IN BULLI SEAM MINES

The earliest attempts to develop safe threshold values for mining the Bulli seam were based upon measurement of gas emission rate from freshly cut coal (Lama, 1995). A version of the French, Belgian and Polish gas emission meter was introduced to Australian mines by Hargraves, where a 4.0-gram coal sample of -14 to +25 mesh fraction was collected and gas emission measured over a 2 to 6-minute period (Lama, 1995). Indices were developed which showed that if the gas emission was greater than 1.5 cc/g for CH₄ and 1.2 cc/g for CO₂, then the face was liable to outburst (Lama, 1995). The method required indices to be developed for each site, to suit local conditions, yet based on work in French mines the index value CO₂ areas was dropped to 1.0 cc/g (Lama, 1995). There were several problems with this method which affected the accuracy and repeatability of the measurement, which included moisture, variability of coal ply and depth of drill hole from which the sample was sourced. These issues, combined with the introduction of high performance roadway development systems to support the introduction of longwall mining rendered the method, which required frequent gas emission measurement of coal samples collected from 2-3 metres holes drilled ahead of the advancing working faces, unsuitable as it adversely affected productivity and the results were considered unreliable (Lama, 1995).

Early attempts at drilling larger diameter boreholes, up to 300 mm diameter, ahead of the working face as a means of reducing stress also aided in draining gas and reducing gas emissions thereby reducing outburst risk (Lama, 1995).

Lama (1995) reported gas drainage investigations at Tahmoor showed that when an area had been drained to gas levels between 9.0 - 10.7 m³/t, with CO₂ percentage 40 - 45%, there were no violent outburst events, even when structures such as dykes were present in the area. Lama also reported an outburst with the emission of almost 3000 m³ of gas occurred in an area where gas content was between 11 - 12 m³/t, with gas pressure of 1700 kPa. When gas levels were dropped to 6.0 m³/t, no outbursts occurred. Work at Metropolitan colliery found the Bulli seam had been mined without outburst in areas where the gas emission value was below 0.6, with desorbable gas content of 4.0 m³/t in 90% CO₂ (Lama, 1995).

It should be noted that gas content values reported by Lama were desorbable gas content (Q₁ + Q₂) as the gas content test method did not routinely measure the Q₃ residual gas content component. The test method used by Lama to determine the desorbed gas content involved measuring gas desorbed from coal samples over a maximum 48 hour period, or the time when at least one negative gas emission value was observed as a result of minor pressure and temperature changes causing resorption of gas from the surroundings into the coal sample (Lama, 1995).

Lama (1995) provided a brief description of work to measure the residual gas content of a selection of Bulli coal samples which, with some corrections, average Q₃ values of 2.01 m³/t for CH₄ and 2.4 m³/t for CO₂. The approach taken by Lama was to add the average residual gas content values (Q₃) to the measured desorbed gas content (Q₁ + Q₂) values to report total gas content (Q₁ + Q₂ + Q₃). Results of gas emissions from slow desorption testing of coal samples by Black (2011) raises concerns for the accuracy of Lama's approach to determining total gas content, as indicated by gas emission measurements of two coal samples, shown in Figure 3, which show gas desorption occurs for a substantially longer period than 48 hours with Q₃ greater than 2.0 m³/t being measured from coal core after slow desorption testing for a period of 600 days.

Based on the results of gas content measurements and a review of gas content threshold values used by other countries, such as Poland, Russia, Germany, Bulgaria and China, Lama proposed gas content threshold values based on desorbable gas content (1991) and total gas content (1995), having added the average Q₃ test results to the desorbable gas content threshold values. The gas content threshold values proposed by Lama, for both desorbable and total gas content, are presented in Table 4.

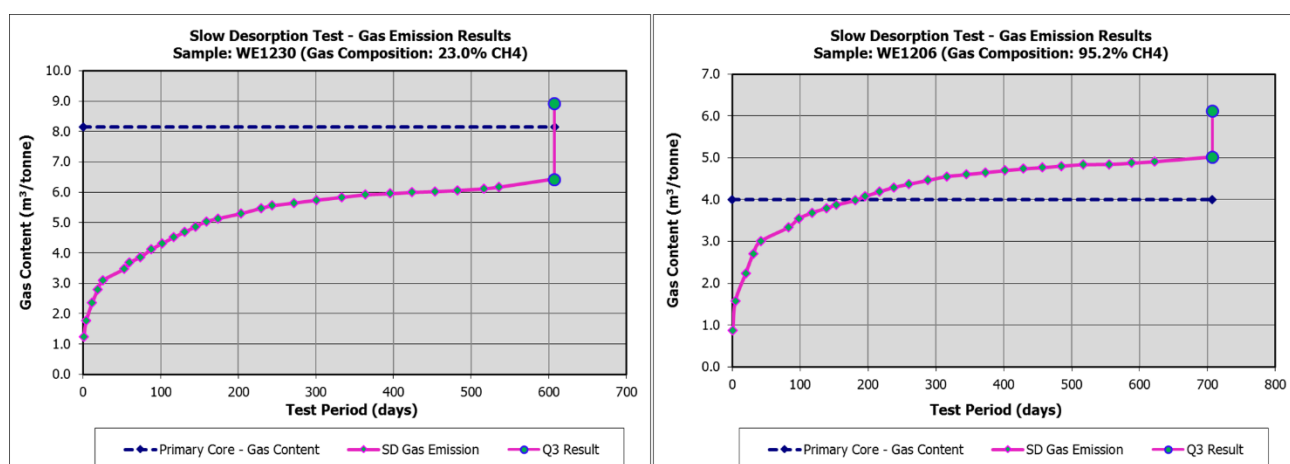


Figure 3. Examples of gas emission rate from coal core during slow desorption testing (Black, 2011)

Table 4. Lama's recommended gas threshold values for safe mining of Bulli seam (total gas content) (Lama, 1991 and 1995)

Proposed Outburst Threshold Limits [Seam Status]	Desorbable Gas Content (m ³ /t) (Lama, 1991)		Total Gas Content (m ³ /t) (Lama, 1995)	
	100% CH ₄ (Q1 + Q2)	100% CO ₂ (Q1 + Q2)	100% CH ₄ [(Q1 + Q2) + Q3]	100% CO ₂ [(Q1 + Q2) + Q3]
Level 1 TLV: Presence of Structure	8.0	4.0	8.0 + 2.0 = 10.0	4.0 + 2.4 = 6.4
Level 2 TLV: No Structures Present	10.0	7.0	10.0 + 2.0 = 12.0	7.0 + 2.4 = 9.4

In 1992 the NSW Chief Inspector of Coal Mines (CICM), concerned about the increasing number of outburst incidents, indicated by data presented in Figure 4, reported in Annual Reports of the NSW Department of Mineral Resources, and the apparent lack of effective management of outburst risk, formed specialist work groups to identify the regional characteristics of outbursts and develop the most appropriate means of protecting mine workers (Harvey, 1994). The working group identified the need for management plans, and all mines operating in the Bulli seam were requested to prepare outburst management plans to specify how they would manage outburst risk (NSWDMR, 1992, Harvey, 1994). The objective of the NSW Department of Mineral Resources (DMR) was that all Southern Coalfield mines would be operating under auditable outburst management plans by 30 June 1993. However, the plans submitted to the DMR were generally regarded as inadequate and were returned to the mines for further development. During 1992 and 1993, the CICM was considering the introduction of gas content threshold limit values as a means of reducing outburst risk. During this process, gas content TLVs as low as 6.0 m³/t in 100% CH₄ conditions and 3.0 m³/t in 100% CO₂ were considered.

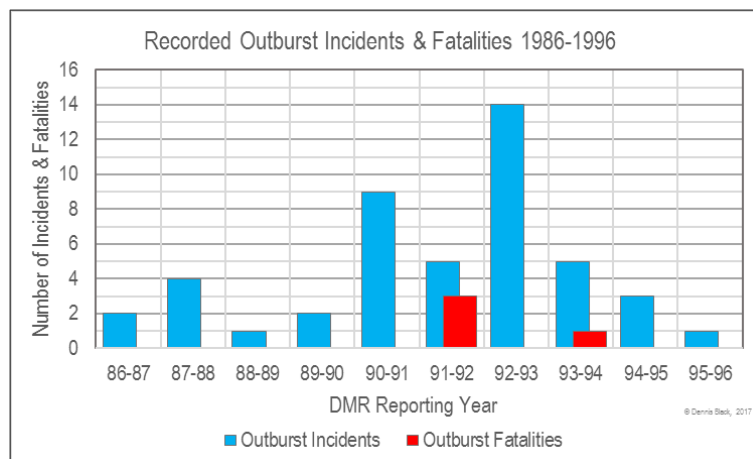


Figure 4. Recorded outburst incidents and fatalities 1986 to 1996, reported in NSW Department of Mineral Resources Annual Reports (NSWDMR Annual Reports, 1986 to 1996)

Following the fatal outburst at West Cliff colliery on 25th January 1994, the DMR issued a notice to all mines operating in the Bulli seam pursuant to Section 63 of the Coal Mines Regulation Act 1982, detailing actions to be implemented to prevent further outburst related fatalities. Arguably the most significant of these actions was the stipulation of limits on seam gas content prior to mining, known as outburst threshold limit values (TLV). Figure 5 shows the Bulli seam TLV prescribed in the Section 63 notification (Clarke, 1994). The TLV varied linearly based on gas composition, with the presence of CO₂ seam gas considered a significantly higher outburst risk than CH₄ seam gas. The Level 1 TLV for 'normal' mining was 9.0 m³/t in 100% CH₄ conditions and 5.0 m³/t in 100% CO₂ conditions. If gas content was not reduced below the Level 1 TLV, mining was only permissible under outburst mining procedures. The Level 2 TLV for 'outburst' mining was 12.0 m³/t in 100% CH₄ conditions and 10.0 m³/t in 100% CO₂ conditions. If gas content was not reduced below the Level 2 TLV, mining was only permissible using remotely operated equipment, with all personnel remaining clear of the outburst risk zone.

The introduction of TLV resulted in a significant increase in the intensity of drilling and gas drainage to identify geological structures and reduce gas content below threshold limits. Mine operators developed comprehensive outburst management plans which included standard drilling patterns and routine management controls to deal with the issue of gas content reduction. However, these TLVs preceded the introduction of intensive in-seam gas drainage drilling and the capability of directional drilling technology to aid in locating geological structures and other outburst risk zones.

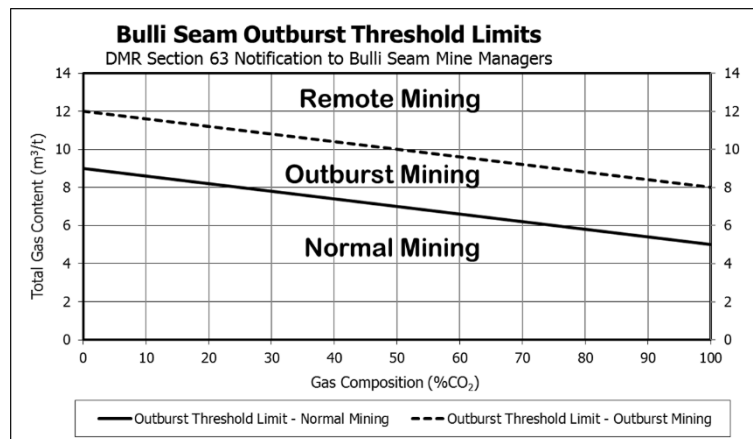


Figure 5: Prescribed Bulli seam Outburst Threshold Limits (Clarke, 1994)

Lama (1995) presented gas content data collected over a three (3) year period from sites where headings had been mined through structures with and without outbursts. With reference to the gas content and outburst data, presented in Figure 6, Lama proposed the two threshold limits lines; solid TLV line for areas with structures present and dotted TLV line for areas without structures. Lama stated the proposed values were safe and the safety factor of 19% ($1.1 \text{ m}^3/\text{t}$) was greater than the error associated with gas content measurement. Points lying between the two TLV lines show small outbursts occurring on structures. Details of the size of the outburst events, stated by Lama to be “*too small to cause any major damage or endanger life*”, are also presented in Figure 6. The gas content TLVs proposed by Lama for safe mining of the Bulli seam, based on the presence or absence of geological structures, and based on the work presented in Figure 6, have been summarised in Figure 7. The proposed Level 1 TLV of $6.4 \text{ m}^3/\text{t}$ for CO_2 and $9.4 \text{ m}^3/\text{t}$ for CH_4 was considered safe under all circumstances, i.e. when mining near geological structures with a development advance rate up to 50 m/d . Lama also suggested that if the rate of development advance was reduced to $10\text{--}12 \text{ m/d}$, the Level 1 TLV could be safely increased by 20%. The Level 2 TLV of $10.0 \text{ m}^3/\text{t}$ for CO_2 and $12.0 \text{ m}^3/\text{t}$ for CH_4 was proposed for development mining in areas where no geological structures were present within 5.0 m of the excavation.

Details of the outburst incidents referred to by Lama (Figure 6) have not yet been located for review and verification of prevailing conditions. While details of the timing and proximity of the gas content sample locations relative to the outburst reference points A to I were not reported by Lama, the description of “*Material thrown out = nil*” suggests the incidents may have been gas blowers rather than outbursts. Also, given the gas content testing method used by Lama involved measurement of desorbed gas content and the addition of average residual gas content (Q3) values to determine ‘total gas content’, it is suggested potential error may be present in the reported gas content values.

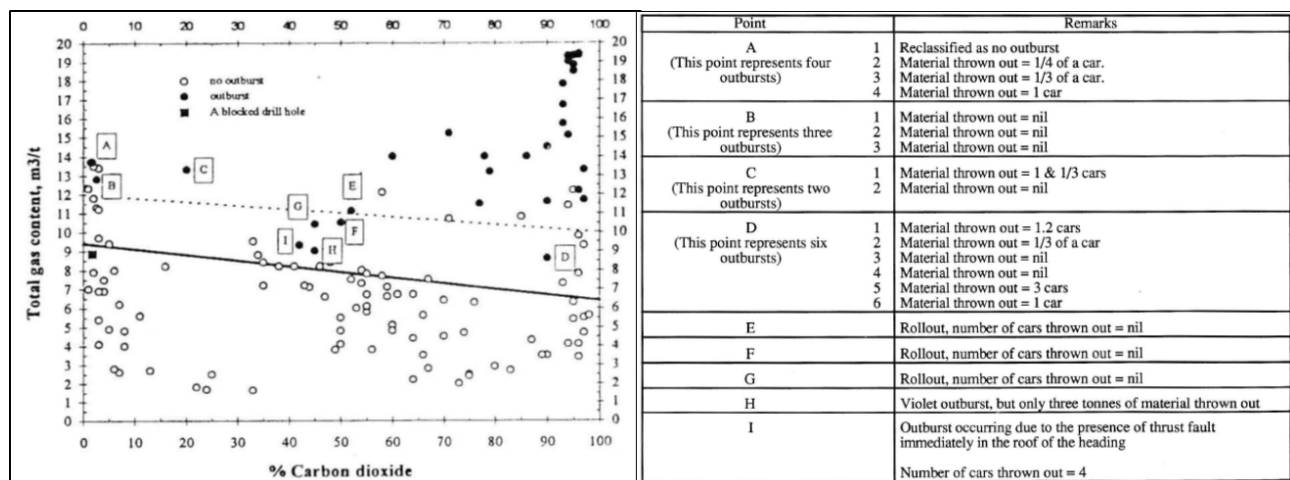


Figure 6. Recorded Total gas content data close to structures, Tahmoor and West Cliff mines (Lama, 1995)

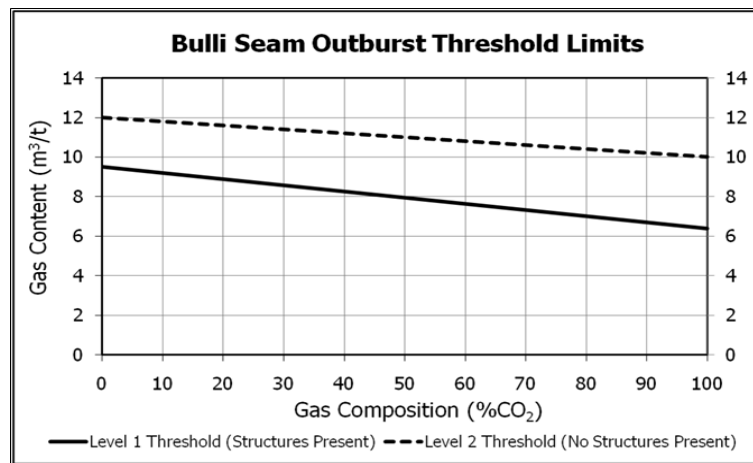


Figure 7: Lama's recommended Bulli seam Outburst Threshold Limits (Lama, 1995)

The gas content TLV prescribed by the DMR (Figure 5), which are lower than the TLVs proposed by Lama (Table 4 and Figure 7), indicates an additional level of conservatism and increased 'factor of safety' was applied by the DMR. Although the prescribed TLV was conservative (Black *et al.*, 2009), the lower gas content threshold did achieve the objective of the DMR, which was to eliminate fatal outburst incidents in the Bulli seam. The removal of gas by gas drainage and the reduction of gas content to safe levels were uncritically accepted by the mining industry (Lama, 1995). Favourable conditions present in the mines at that time enabled the seam gas content to be reduced below TLV relatively easily and without delay to mine operations and coal production.

IMPACT OF SEAM GAS COMPOSITION ON OUTBURST RISK

The outburst TLVs adopted in Australian mines reflect the view that mining in coal with high concentrations of CO₂ represents a significantly greater risk of outburst in comparison to mining in coal with high concentration of CH₄.

Commonly reported views of researchers suggest (a) CO₂ is more outburst prone than CH₄ (Lama, 1995 and Williams, 2000), (b) CO₂ outbursts are more violent than CH₄ outbursts (Hargraves, 1980, Hanes, 2001, Lama and Saghafi, 2002), and (c) CO₂ reduces the strength of coal (Wu, *et al.*, 2010).

Wynne (2002) questioned the difference in threshold limit for CO₂ and CH₄, posing the question "*is an outburst more likely in a CO₂-rich seam than in a CH₄-rich seam?*".

Results of gas content and gas composition data collected from core samples near recorded outburst events in Australian underground coal seams, presented in Figure 8, highlight the absence of outburst events below approximately 9.0 m³/t, specifically in conditions where CO₂ is the dominant seam gas.

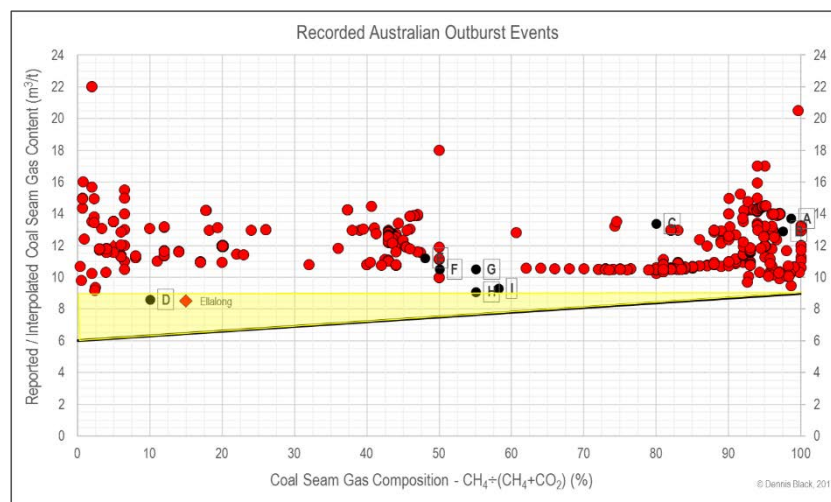


Figure 8: Gas content and composition measurement near recorded Australian outburst events

The basis for the commonly held view that outbursts associated with carbon dioxide are more violent, more difficult to control and more dangerous appears to be due to the greater sorption capacity of coal for carbon dioxide (Hargraves, 1980, Hanes, 2001, Lama and Saghafi, 2002). Laboratory based experimentation of outburst propensity using briquettes formed from pulverised coal in small-scale outburst simulation apparatus, such as those described by Skoczylas (2012), Wang *et al.* (2015) and Zhao *et al.* (2016), do not discuss the fact that when comparing the burst response of coal samples saturated with CO₂ and CH₄ at the same pressure, the effective gas content of the CO₂ test sample will be approximately twice that of the CH₄ test sample, due to the inherent sorption characteristics of coal. Consequently, for a given coal seam

gas pressure, coal samples will contain a larger volumes of carbon dioxide and emission problems therefore appear more acute (Beamish and O'Donnell, 1992).

The sorption capacity of Bulli seam coal for both CO₂ and CH₄, as reported by Black (2011) and presented in Figure 9, highlight the increased sorption capacity of CO₂ in comparison to CH₄. With reference to the isotherms for CO₂ and CH₄ presented in Figure 9, and considering the measurement of gas content is the principal measure of outburst risk; for a given gas content value the isotherms indicate the gas pressure of the CH₄ rich sample will be substantially greater than the CO₂ rich sample and therefore CH₄ rich coal potentially contains gas at higher pressure than the CO₂ rich coal and therefore potentially represents a greater outburst risk.

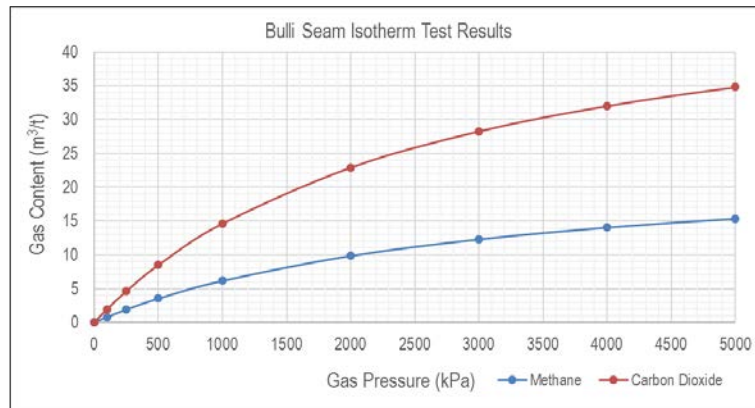


Figure 9: Example Bulli seam isotherm curves for methane and carbon dioxide sorption (after Black, 2011)

With respect to the impact of CO₂ on coal strength, the effects of sorption induced swelling and potential weakening of coal samples observed in laboratory testing does not typically relate to *in situ* conditions experienced in Australian coal seams containing CO₂. Australian coal seams containing high concentrations of CO₂, such as the Hoskissons seam mined at Narrabri, the Greta seam mined at Austar and the Bulli seam mined at Metropolitan, Tahmoor and Appin do not routinely experience weakened coal conditions.

OUTBURST THRESHOLD LIMITS APPLICABLE TO NON-BULLI SEAM MINES

Outburst thresholds in non-Bulli seam mines are established based on the GeoGAS Desorption Rate Index (DRI) and acceptance of the outburst mechanism where the desorption rate of gas is directly used as an indicator of outburst proneness (GeoGAS, 2007). The background and relevance of using DRI as the basis for determining outburst TLV has been reviewed and discussed in Black (2018).

In the DRI approach, outburst proneness is regarded by GeoGAS as being directly related to the desorption rate of the coal. Bowen Basin coals (Goonyella Middle and German Creek seams) have higher DRI compared to the Bulli seam and, accordingly, the gas content thresholds are lower. For CH₄, the Bulli seam gas content threshold is 9.5 m³/t at a DRI of 900. For the same DRI, the Goonyella Middle seam has a gas content of 7.0 m³/t and the German Creek seam (Middlemount/Tieri) a gas content of 7.7 m³/t (GeoGAS, 2007).

The DRI900 method was proposed, based on a review of the Bulli seam threshold for 'normal mining', which is effectively equivalent to a TLV for structured coal, and no work was done to establish a method to determine TLV for non-structured coal.

Kidybinski (1980) in Lama (1995) recognised that factors other than gas pressure and gas content play an important role in promoting instantaneous outbursts of coal and gas in coal seams. Outbursts often occur in coal weakened by local geological distortion. Strength variations within the coal, due to tectonic and sedimentary conditions are often greater than strength variations due to variations in gas pressure and desorption phenomena. Kidybinski further suggested that coal strength, coal weakness, may have a greater effect on local outburst hazard than gas pressure and desorption characteristics. These additional, and potentially more significant outburst risk factors are not considered in the GeoGAS DRI900 approach to determination of outburst TLVs in Australian coal seams.

MINING EXPERIENCE ABOVE NORMAL OUTBURST GAS CONTENT THRESHOLD LIMITS

In the years following the 1994 introduction of the Bulli seam TLVs there has been significant advances in directional drilling technology and the standard of management plans used at most mines to identify, assess and control outburst risk. Also, many mines have progressively moved into areas of increased gas content and reduced permeability, where it is becoming increasingly difficult to drain gas below the 'normal mining' TLV and mine operators are questioning the appropriateness of the outburst TLVs (Black and Aziz, 2008 and Black *et al.*, 2009).

Several Australian underground coal mines have completed formal reviews of their outburst management plans which led to increasing TLV supported by additional management controls, such as increased drilling density and increased gas content testing. Increased TLV, presented in Figure 10, were approved for Tahmoor colliery in 2003 and West Cliff colliery in 2005. In the years following the changes to the TLV, both collieries operated without an outburst incident. Metropolitan colliery has also reviewed and introduced additional TLVs to allow controlled mining in areas where gas content remains above the 1994 'normal mining' TLV.

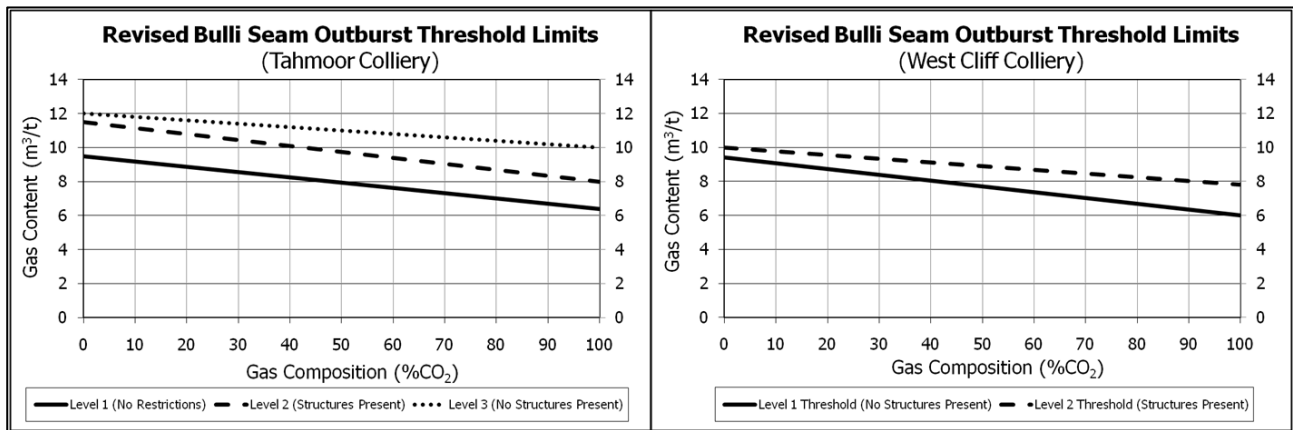


Figure 10: Revised outburst TLVs at Tahmoor and West Cliff colliery (Black, 2011)

At Tahmoor colliery, in addition to the Level 1 TLV, below which no restrictions are placed on mining, introduced two additional TLV levels. The Level 2 TLV applies to structured coal and where the measured gas content is greater than Level 1 and less than Level 2, in addition to more intensive drilling and coring, the rate of development advance is restricted to 12 m/day. The Level 3 TLV applies to coal free of geological structures. Where the measured gas content is greater than Level 1 and less than Level 3, in addition to increased drilling and gas content testing, the rate of development advance is restricted to 25 m/day in each heading and cut-through to a maximum of 75 m in any 24 hour period. In areas where gas content remains above the defined TLV, normal mining is prohibited and grunching is the only approved development mining method.

At West Cliff colliery, in addition to the Level 1 TLV, one additional TLV was introduced. While no restrictions were placed on the rate of development advance, where the measured gas content was between the Level 1 and Level 2 TLV increased drilling, structure identification and gas content testing was required. Where the gas content remained above the Level 2 TLV, normal mining was prohibited and an alternative mining method, such as remote control or grunching, was required.

Figure 11 shows gas test results from areas of the Bulli seam where gas content was above the 'normal mining' outburst threshold limit that were mined by non-standard methods without inducing an outburst. The figure shows gas data from areas mined by (a) fully remote controlled continuous miner operation, (b) grunching using conventional shotfiring, and (c) limited rate mining where limits are placed on the maximum hourly and daily rate of advance of conventional continuous mine development operations. In the 15 year period that Tahmoor colliery has employed limited rate mining through structured and non-structured coal, with gas content up to 12.0 m³/t (CH₄) and 10.0 m³/t (CO₂), an outburst has not occurred (Borg, 2014). Tahmoor has also mined over 3,000 metres of roadways, by grunching due to inability of conventional pre-drainage to reduce gas content of the coal seam below the original TLV, without inducing an outburst in 'tight' coal with gas content up to 14 m³/t (Wynne, 1999, 2000, 2011).

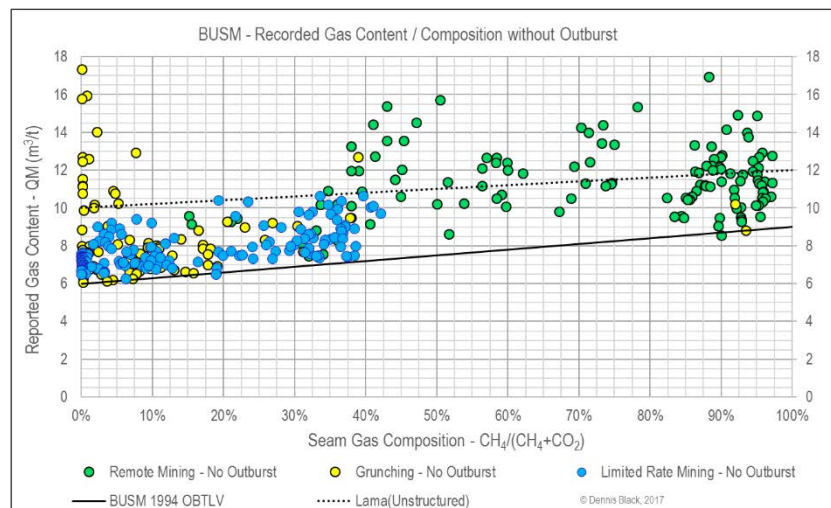


Figure 11: Summary of grunching, remote and reduced rate mining experience in Bulli seam mines post 1994

Blanch (2017) raised concerns in relation to the use of limited rate mining, suggesting there was increased risk of an outburst event occurring if mining were to be undertaken in areas where the gas content remained above the 1994 'normal mining' TLV. Tahmoor's 15 years' experience mining through such areas, along with similar experience at West Cliff, Metropolitan and other Australian collieries, does suggest (a) the use of limited rate mining is an effective control to mine in areas of increased gas content, or (b) the 1994 TLV are very conservative and the gas content levels in those areas did not present an increased outburst risk, particularly in areas where no geological structures are present. Further

investigations are planned to assess seam gas pressure in advance of development working faces and the impact of mining rate on the seam gas pressure profile.

Figure 12 presents gas test results from locations where outburst have occurred in areas of the known outburst risk in the Bulli seam that were mined using remotely operated continuous miner and grunching methods. Like the historical outburst events data presented in Figure 8, the recently acquired outburst data presented in Figure 12 highlights the absence of outburst events below approximately 9.0 m³/t, and does not support the view that coal rich in CO₂ is at greater risk of outburst. Further investigations into the impact of gas composition on outburst risk are planned.

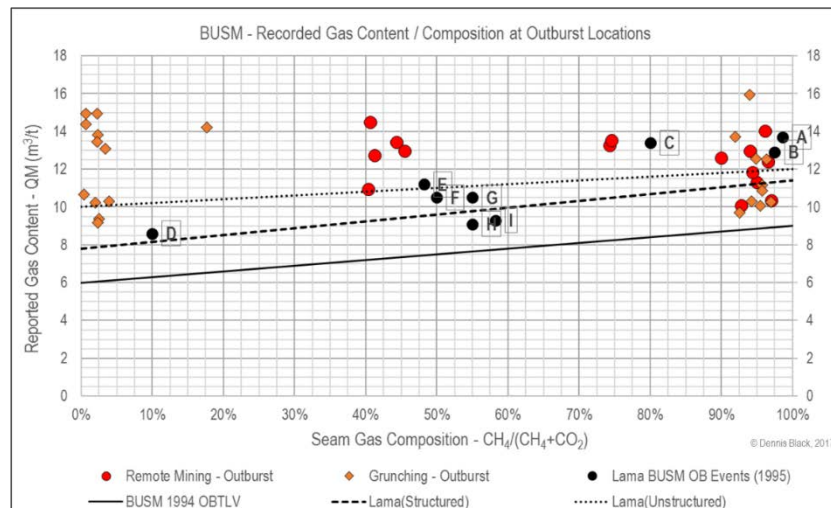


Figure 12: Bulli seam gas content and composition where outburst occurred when mining in known high risk zones

CONCLUSIONS

Outbursts represent a major safety hazard to personnel working near the coal face in areas of increased outburst risk. The current approach to TLV have been effective in preventing injury from outburst however increasing evidence, based on operational experience, suggest the current method is overly conservative in some conditions, to the point of adversely impacting mine productivity without delivering significant incremental increase in safety.

While abnormal geological conditions have been linked to all fatal outburst incidents and at least 98% of the non-fatal outburst incidents recorded in Australia, the presence or absence of geological structure is typically not reflected in outburst TLVs in Australian mines. Gas content is recognised as having the most significant impact on outburst risk and gas drainage to reduce gas content to safe levels plays a significant role in control and reduction of outburst risk in Australian underground coal mines.

Investigations into Australian outburst history and mining experience in areas where gas content was above the 1994 Bulli seam outburst threshold limits has provided no evidence that outburst had occurred at gas content levels below approximately 9.0 m³/t, independent of gas composition and geological conditions. Using limited rate mining methods, mining has been carried out, without outbursts, in areas where gas content TLV has been equivalent to 12.0 m³/t (CH₄) and 10.0 m³/t (CO₂).

While China, Russia and other European countries assess outburst risk through measurement of gas emission rate from fresh cut coal samples, using outburst indices such as ΔP , ΔP_{0-60} , ΔP Express and K_T Index, Australia is the only country that uses a measure of gas emission from crushed coal during the Q3 gas content testing as the basis for establishing outburst TLVs.

Coal mining practice in Australia requires rapid mining rates to sustain high productivity retreating longwalls which in turn rely on effective systems to identify areas of increased outburst risk and effective treatments to reduce the outburst risk in advance of mining operations.

Control and management of outburst risk, including measures to predict and reduce outburst risk in advance of planned mining, must be effective and continue to support the high safety and production targets of the Australian underground coal mines.

Further work will continue in association with the University of Wollongong to (a) investigate the impact of gas composition, coal toughness and gas pressure on outburst risk, and (b) develop a multi-factor Outburst Risk Index appropriate for assessing outburst risk in Australian mining conditions.

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REFERENCES

- Beamish B., O'Donnell G., 1992. Microbalance applications to sorption testing of coal, Symposium on Coalbed Methane Research and Development in Australia. Coalseam Gas Research Institute – James Cook University, Townsville, 19-21 November, Vol. 4, p. 31-41.
- Black, D J and Aziz, N I, 2008. Improving UIS gas drainage in underground coal mines, in *Proceedings of the 8th Underground Coal Operator's Conference COAL2008*, University of Wollongong, (eds: N I Aziz and J A Nemcik), Wollongong, 14-15 February, pp 186-196
- Black, D J and Aziz, N I, 2009. Reducing coal mine GHG emissions through effective gas drainage and utilisation, In *Proceedings of the 2009 International Coalbed & Shale Gas Symposium*, University of Alabama, Tuscaloosa, 18-22 May, Paper No. 0912.
- Black, D J, Aziz, N I, Jurak, M J and Florentin, R M, 2009. Outburst threshold limits – are they appropriate?, in *Proceedings of the 9th Underground Coal Operator's Conference COAL2009*, University of Wollongong, (eds: N I Aziz and J A Nemcik), Wollongong, 12-13 February, pp 185-192
- Black, D J and Aziz, N I, 2010. Outburst threshold limits – current research outcomes, in *Proceedings of the 10th Underground Coal Operator's Conference COAL2010*, University of Wollongong, (eds: N I Aziz and J A Nemcik), Wollongong, 11-12 February, pp 203-209.
- Black, D J, 2011. Factors affecting the drainage of gas from coal and methods to improve drainage effectiveness, PhD Thesis Report, School of Civil, Mining and Environmental Engineering, University of Wollongong, ACARP Project Report No. C18004.
- Black, D J, 2018. Analysis of Bulli Seam Benchmark and DRI to determine outburst threshold limits, in *Proceedings of the 2018 Coal Operator's Conference*, University of Wollongong, (eds: N I Aziz and R J Kininmonth), Wollongong, 7-9 February
- Blanch, M, 2017. Outburst thresholds – misconceptions, criticisms and context, in *Proceedings of the Coal Operator's Conference*, University of Wollongong, Wollongong
- Borg, J, 2014. Grunching Through Potential Outburst Zones – Tahmoor underground colliery, presentation at the ACARP Gas and Outburst Seminar, November 2014.
- Chatterjee, P K, 1982. Coal mining disasters in New South Wales and Queensland between 1920-1979 – a technical appraisal, in *Proceedings of the Australasian Institute of Mining and Metallurgy*, No.281 March, pp. 37-45.
- Clarke, M, 1994. Notice pursuant to Section 63 Coal Mines Regulation Act 1982, New South Wales Department of Mineral Resources – Coal Mining Inspectorate and Engineering Branch, 11 May.
- Eade, P, 2002. Case study outburst and gas management, in *Proceedings of the 2002 Coal Operators' Conference*, Wollongong, 6-8 February, pp 105-113.
- GeoGas, 2007. Outburst threshold determination – Wongawilli seam, August, p.2.
- Gray, I and Wood, J, 2013. Outburst in underground coal mines – a coherent approach for improved management, Presentation at the ACARP Coal and Gas Outburst Workshop, June 2013, [online]. Available from: <http://outburst.miningst.com/wp-content/uploads/2015/04/Ian-Gray-Jeff-Wood-Final.pdf> [Accessed: September 2017].
- Gray, I, Shelukhina J and Wood, J, 2016. A practical approach to the determination of outburst threshold, in *Proceedings of the 2016 Coal Operator's Conference*, University of Wollongong, (eds: N Aziz and B Kininmonth), Wollongong, 10-12 February, pp 330-346
- Hanes, J, 1979. A geological assessment of the major coal burst in A North Intakes – 01 December 1978, Dampier Mining Company, p.44.
- Hanes, J, 1986. The effects of mining on the geological equilibrium at Leichhardt Colliery, Blackwater, Queensland, Symposium on Ground Movement and Control related to Coal Mining, AusIMM Illawarra Branch, Wollongong. [online]. Available from: http://www.undergroundcoal.com.au/outburst/presentations_publications/ausimm_1986/Hanes.pdf [Accessed: September 2017].
- Hanes, J, 1995. Outbursts in Leichhardt Colliery: Lessons learnt, International Symposium on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines, (ed: R D Lama), Wollongong, 20-24 March, pp 445-449.
- Hanes, J, 2001. Outbursts management and control, Coal Operators' Geotechnical Colloquium – Tribute to Dr Alan J Hargraves, AusIMM Illawarra Branch, 15 February, pp 13-21.
- Hanes, J, 2006. Leichhardt Colliery Outbursts and Signs. [online]. Available from: [http://www.mineaccidents.com.au/uploads/leichhardt-colliery-outbursts-and-signs806\(1\).pdf](http://www.mineaccidents.com.au/uploads/leichhardt-colliery-outbursts-and-signs806(1).pdf) [Accessed: September 2017].
- Harvey, C R, 1994. Outbursts in the Bulli coal seam, UN-ECE Symposium on Rock Bursts and Sudden Outbursts: Theory Forecasting Prevention and Protection of Miners, St Petersburg, 5-7 June, 46p.

- Harvey, C R, 2002. Thresholds and compliance issues, in *Proceedings of the 2002 Coal Operators' Conference*, (ed: N I Aziz), University of Wollongong, Wollongong, 6-8 February, pp 234-236.
- Hargraves, A J, 1980. Keynote address – a review of instantaneous outburst data, *The Occurrence. Prediction and Control of Outbursts in Coal Mines Symposium*, AusIMM Southern Queensland Branch, September. pp. 1-18.
- Hyslop, A, 2017. Case study of the outburst incident on the longwall face at Metropolitan colliery, ACARP Gas and Outburst Committee Half Day Seminar, Wollongong, 28 June.
- Lama, R D, 1991. Control of outbursts in the Bulli seam, Confidential Report, Kembla Coal & Coke Pty Ltd.
- Lama, R.D. (1995) Safe gas content threshold value for safety against outbursts in the mining of the Bulli seam, Int. Symp. cum Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines, Lama, R. D. (ed.), Wollongong, Australia, pp. 175–189
- Lama, R D and Bodziony, J, 1996. Outbursts of gas, coal and rock in underground coal mines, R. D. Lama and Associates, Wollongong.
- Lama, R. D. and Bodziony, J. (1998) Management of outburst in underground coal mines, *International Journal of Coal Geology*, Vol. 35, pp. 83–115
- Lama, R D and Saghafi, A, 2002. Overview of gas outbursts and unusual emissions, in *Proceedings of the 2002 Coal Operators' Conference*, (ed: N I Aziz), University of Wollongong, Wollongong, 6-8 February, pp 74-88.
- Marshall, P, Griffiths, L and Lama, R D, 1980. Occurrence of outbursts at West Cliff Colliery, *The Occurrence. Prediction and Control of Outbursts in Coal Mines Symposium*, AusIMM Southern Queensland Branch, September. pp. 19-39.
- Moore, R D and Hanes, J, 1980. Bursts in coal at Leichardt Colliery, Central Queensland and the apparent benefits of mining by shotfiring, in *Proceedings of the Symposium on the Occurrence, Prediction and Control of Outbursts in Coal Mines*, Australasian Institute of Mining and Metallurgy – Southern Queensland Branch, pp 71-83.
- New South Wales Department of Mineral Resources (NSWDMR), 1992. Annual Report 1991-1992, Department of Mineral Resources New South Wales.
- New South Wales Department of Mineral Resources (NSWDMR), 1995. Outburst Mining Guideline MDG No.1004, Coal Mining Inspectorate and Engineering Branch, Department of Mineral Resources New South Wales.
- Newman, B, 2005. Handling gas problems at Tahmoor Colliery, Presentation at the ACARP Coal and Gas Outburst Workshop, September 2005 [online]. Available from:
http://miningst.com/Outburst/presentations_publications/outburst_2005/pdf/Bob%20Newman%20Sept%202005.pdf [Accessed: September 2017].
- Piper C, 1998. Overview of West Cliff longwall outburst; Half day Seminar, Gas and Coal Outburst Committee, Wollongong, 24 June 1998.
- Skoczylas, N, 2012. Laboratory study of the phenomenon of methane and coal outburst *International Journal of Rock Mechanics & Mining Sciences* Volume 55, pp.102-107.
- Stone, I, 1991. Outbursts at Tahmoor, in *Proceedings of Workshop on Detection of Outburst Prone Structures in the Bulli Seam*, Technical Group of the Bulli Seam Outburst Investigation Committee, 5 December.
- Truong, D, Gray, I and Hebblewhite, B, 1983. Prediction, Prevention and/or control of Outbursts, End of Grant NERDDP Report No. 234, Dept. of Resources and Energy, Canberra.
- Walsh R, (1999) West Cliff Longwall Outburst – update; Half day Seminar, Gas and Coal Outburst Committee, Wollongong, 23 June 1999.
- Wang, S, Elsworth, D and Liu, J, 2015. Rapid decompression and desorption induced energetic failure in coal, *Journal of Rock Mechanics and Geotechnical Engineering*, Volume 7, pp.345-350.
- Ward, H, 1980. Outburst occurrences at Metropolitan Colliery, in *Proceedings of the Symposium on the Occurrence, Prediction and Control of Outbursts in Coal Mines*, Australasian Institute of Mining and Metallurgy – Southern Queensland Branch, pp 63-68.
- Williams, R.J. (2002) Gas content testing for outburst management compliance, 3rd Australasian Coal Operator's Conference, Wollongong 6-8 February 2002, pp. 47-52
- Wu, D, Zhao, Y, Cheng, Y, and An, F, 2010. ΔP index with different gas compositions for instantaneous outburst prediction in coal mines, *International Journal of Mining Science and Technology*, Volume 20 (2010) 0723–0726
- Wynne, P, 1999. Tahmoor poor drainage problem, Gas and Coal Outburst Committee Half Day Seminar, Wollongong, 23 June 1999.
- Wynne, P, 2000. Grunching to advance through above-threshold coal at Tahmoor Colliery, in *Proceedings of Gas and Coal Outburst Committee – Half Day Seminar*, Wollongong, 21 June.
- Wynne, P, 2002. Case Study Management of Outburst Risk at Tahmoor Colliery, in *Proceedings of the 2002 Coal Operators' Conference*, (ed: N I Aziz), University of Wollongong, Wollongong, 6-8 February, pp.98-104.

- Wynne, P, 2011. Raising the outburst threshold at Tahmoor colliery, Presentation at the ACARP Coal and Gas Outburst Workshop, Wollongong, June 2011, [online]. Available from:
http://miningst.com/Outburst/presentations_publications/outburst_2011_jun/Raising%20The%20Outburst%20Threshold%20-%20Peter%20Wynn.pdf [Accessed: September 2017].
- Wynne, P and Case, R, 1995. Outburst remote control mining at Tahmoor Colliery. International Symposium on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines, (ed: R D Lama), Wollongong, 20-24 March, pp 503-507.
- Zhao, W, Cheng, Y, Jiang, H, Jin, K, Wang, H, Wang, L, 2016. Role of the rapid gas desorption of coal powders in the development stage of outbursts, *Journal of Natural Gas Science and Engineering*, Volume 28, pp. 491-501.