

Coal properties and mine operational factors that impact gas drainage

D.J. Black^{1,2} and N.I. Aziz¹

¹ University of Wollongong, Wollongong, New South Wales, Australia

² Pacific Mining and Gas Management (**PacificMGM**), www.pacificmgm.com.au

ABSTRACT: Advances in coal production over the last 20 years have led to an increase in coal mine gas emissions. These gas emissions, if not effectively managed, may exceed the diluting capacity of the mine's ventilation system resulting in gas concentrations in excess of statutory limits and the presence of an unsafe condition within the mine. Where such conditions exist it is typical for production to be slowed or stopped until such time as the rate of gas emission is effectively controlled and managed. This paper discusses the findings of a research project based on an underground mine operating in the Bulli coal seam, located in the southern Sydney Basin of New South Wales, Australia. This mine had encountered a large area with poor drainage characteristics, which initially caused production delays and increased drilling cost, and ultimately led to a review of the mine plan and loss of some 3.0 million tonnes of coal reserves. The project involved detailed analysis of the impact on in-seam borehole gas production performance from a broad range of coal properties and operational factors. The variables included in the analysis represent coal properties such as rank, type, structure, seam gas, ash and mineralisation and operational factors such as borehole length, orientation, dip and applied suction. From the analysis a number of coal properties and mine controllable, operational factors are identified that have significant impact on gas production. Recommendations are made to optimise gas drainage productivity in light of the conditions present within the mine.

1 Introduction

Many Australian underground coal mines are progressing toward areas which require gas drainage to improve the mine environment and general safety as well as the management of greenhouse gas emissions. Coincident with increasing depth and progress into less amenable mining conditions many mines will encounter areas where the removal of seam gas, ahead of mining, is extremely difficult. Where difficult drainage areas are encountered, mines may be faced with significant production delays while intensive drilling is carried out to reduce gas concentrations to acceptable levels. To avoid costly delays, mine management may choose to avoid such areas completely, resulting in loss of reserves, loss of potential revenue and ultimately reduced mine life.

This analysis is based on data gathered from an active underground longwall mine operating in the Bulli seam, located to the south of Sydney, Australia. The seam is stratigraphically the uppermost coal seam in the Permian Illawarra Coal Measures of the southern Sydney Basin. The depth of cover, in the area of study is 450 to 500 m with a regional dip of 1.5°, toward the west. Figure 1 shows the gas composition in the mining domain, ranging from almost pure CH₄ in the east to almost pure CO₂ in the west.

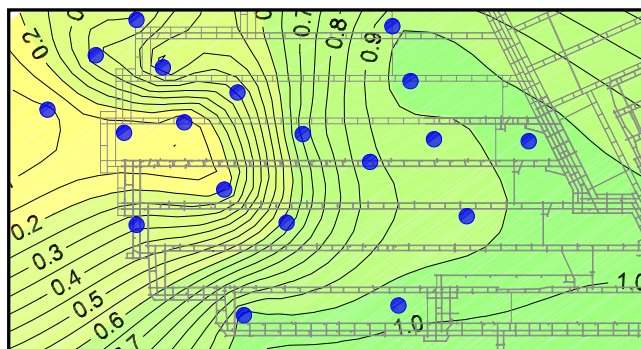


Figure 1 Coal seam gas composition relative to current and future mine workings.

2 Minesite Gas Production

Mines operating in the Bulli seam have, since 1980, employed in-seam gas drainage drilling as an integral part of the gas and outburst management effort. These mines regularly drill more than 100,000 m of underground to in-seam (UIS) boreholes for gas drainage annually. Figure 2 shows the intensity of UIS gas drainage drilling relative to the mine workings.

The boreholes were regularly inspected and production data gathered. The availability of extensive gas production data underpinned this analysis enabling the impact of a variety of coal seam properties and borehole specific factors on individual borehole productivity to be assessed. Production data from 279 in-seam gas drainage boreholes

was collated covering an area of approximately 7.2 km², representing five longwall panels.

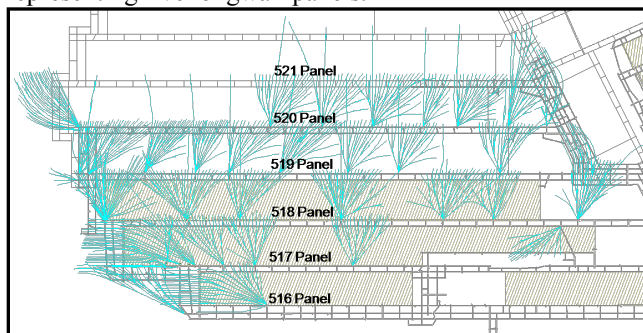


Figure 2 Location of in-seam boreholes included in analysis.

In addition to the volume and rate of gas production from each borehole the following data was also measured:

- Total length, inclusive of major branches;
- Average orientation relative to both identified primary cleat and principal horizontal stress directions; and
- Average apparent dip relative to strike and dip of the coal seam.

Figure 3 shows the combined total gas production of boreholes drilled from each of the 34 separate drill sites relative to the position of the stub along the length of each longwall panel. There was a consistent reduction in gas production along the length of each panel, from east to west. Further analysis of individual borehole production data identified that several boreholes produced greater than 500,000 m³ however almost half produced less than 100,000 m³.

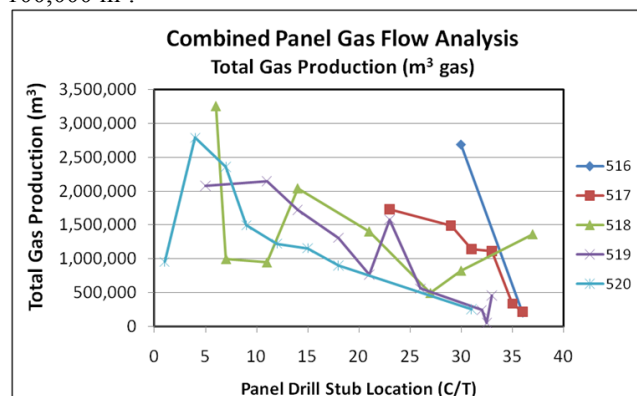


Figure 3 Total drill stub gas production relative to panel and drill stub location.

Figure 4(A) shows the distribution of total gas production volume from each of the 279 boreholes relative to the location of the borehole along the length of the panels. Zero cut-through (c/t) is the eastern, outbye end of the panels and 40 c/t is the western, inbye end of the panels. Figure 4(B) shows the cumulative volume of gas produced within the first 50 days of production (D50) relative to borehole location. The results indicate a significant reduction in gas production along the length of the panels.

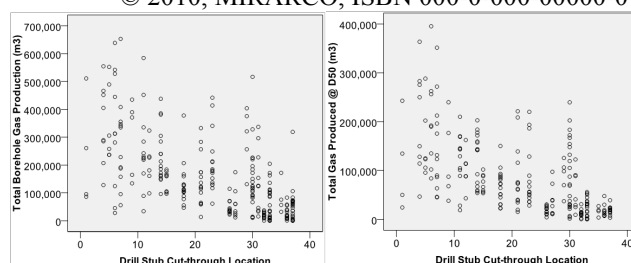


Figure 4 (A) Total gas production relative to location; (B) Day50 gas production relative to location.

Prior to undertaking this study the general consensus of mine personnel was that the decrease in borehole gas production was due to increasing CO₂ composition and the generally low permeability throughout the mining area. Given the relatively large proportion of CO₂ rich coal within the planned future mining area the operation was faced with the potential for further loss of reserves due to continued inability to remove gas ahead of mining. Support was provided to investigate and confirm the reason(s) for the drop in gas production and to identify actions to improve gas drainage performance, thereby avoiding future mining delays and loss of reserves.

3 Operational Factors

Table 1 lists the operational factors considered. These factors are considered to be operational as they are within the control of the mine operator, through the design of drilling patterns and management of the gas drainage and reticulation system. However the layout of the mine workings and the UIS drilling method employed ultimately limit the degree to which these factors are able to be varied.

Table 1 Operational factors considered in analysis

Borehole length	Orientation to stress
Borehole diameter	Apparent dip
Drilling density	Drainage time
Orientation to cleat	Applied suction pressure

3.1 Borehole Length

Figure 5(A) shows the average length of the boreholes was 836 m, with the range extending from 53 to 1,180 m. The majority of boreholes are between 500 and 1,000 m in length.

Figure 5(B) shows total gas production relative to borehole length and there is some evidence of increasing production with increasing length.

Although the relationship between gas production and length is not strong it can be seen that maximum gas production was achieved from boreholes between 600 and 1,500 metres in length.

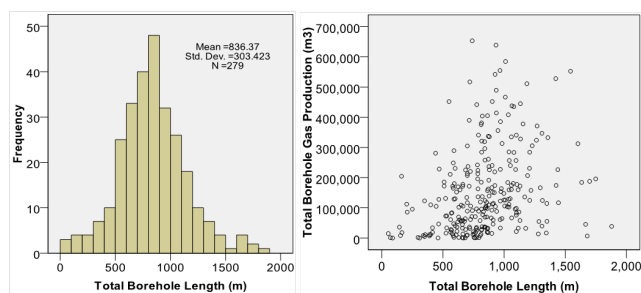


Figure 5 (A) Histogram showing distribution of borehole length; (B) Total gas production relative to total borehole length.

3.2 Borehole Diameter

In this study the drilled diameter of the boreholes was a standard 96 mm. This diameter is typical among UIS gas drainage drilling throughout Australia.

Sections of boreholes were measured and found to have diameters well in excess of design. The failure, referred to as borehole break-out, occurs due to the impact of high vertical stress on weak coal (Mills *et al.*, 2006).

3.3 Drilling Density

The spacing between UIS boreholes is typically a function of the drainage time available and the extent to which the *in situ* gas content must be reduced prior to mining. Figure 6 illustrates the change in drilling density at this mine. In the more easily drainable zones, at the commencement of the panels, where CH₄ was the predominant seam gas, spacing varied between 20 and 25 m. In the inbye zones, which are slower to drain and the seam gas was predominantly CO₂, the spacing was less than 12 m.

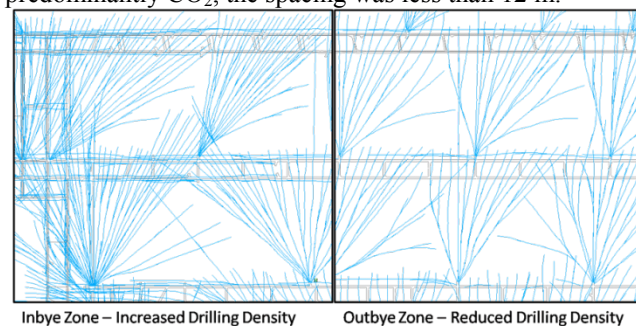


Figure 6 Drilling density relative to panel location.

To evaluate the impact of drilling density on gas production the total coal volume within the extremities of each of the 34 drilling sites was divided by the total length of UIS boreholes present (m³/m). Gas production was found to be greater in the less densely drilled, outbye zones.

Further analysis of the data within 1,000 m intervals along the panels indicated that drilling density does not have a significant impact on gas production.

3.4 Borehole Orientation

The average orientation of each borehole was determined based on measurements made at 100 m intervals along the full length, including significant branches.

3.4.1 Orientation relative to cleat

The orientation of the borehole relative to the dominant cleat direction was determined by reference to geological mapping data conducted along the length of two accessible longwall gateroads within the mining area (Newland, 2007). Two cleats were identified, oriented 100/280° and 10/190° respectively. Newland reported a change in the major, or dominant, cleat, within certain zones along the length of the gateroads, however the 100/280° cleat was dominant in the majority of cases. The 100/280° cleat was therefore considered dominant and representative of the mining area in this study.

The angle of the borehole relative to the 100/280° cleat was calculated and used to evaluate the impact of orientation relative to cleat on gas production.

Borehole orientation relative to cleat was found to be quite evenly distributed, spanning the full range from 0 to 90°. The average orientation relative to cleat was 49°.

Figure 7(A) and 7(B) show the distribution of total gas production and D50 gas production relative to borehole orientation to cleat.

The data indicates that maximum gas production is not achieved from boreholes oriented perpendicular or parallel to the two measured cleat orientations and that borehole orientation, relative to cleat, does not have a significant impact on gas production.

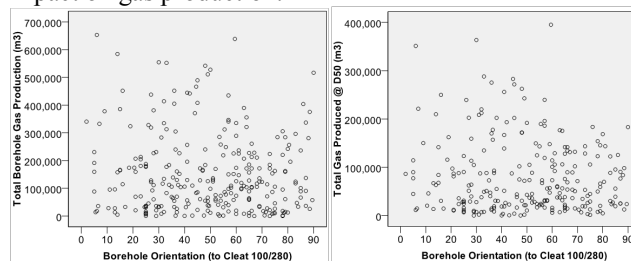


Figure 7 (A) Total gas production relative to borehole orientation to cleat; (B) D50 gas production relative to hole orientation to cleat.

The data indicates above average gas production from boreholes orientated between 5 and 60° degrees to the 100/280° cleat. Therefore neither cleat is considered to be a dominant path for gas flow and boreholes that cut across both cleats have improved exposure to the gas flows paths within the coal seam.

3.4.2 Orientation relative to stress

The orientation of maximum horizontal stress was determined by measurement of borehole breakout during logging of surface exploration boreholes and found to be 075/255°.

The borehole orientation relative to the maximum horizontal stress was calculated and used to evaluate the impact on gas production.

The results show that the difference in orientation ranged from 0 to 90°, with an average of 38° degrees.

Figure 8(A) and 8(B) show the distribution of total gas production and D50 gas production relative to borehole orientation to stress.

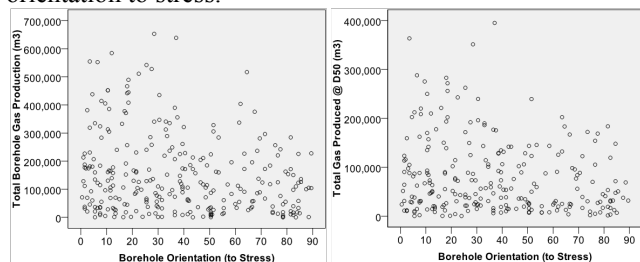


Figure 8 (A) Total gas production relative to borehole orientation to stress; (B) D50 gas production relative to borehole orientation to stress.

The data indicates that above average production is achieved from boreholes that are oriented more parallel than normal to the maximum horizontal stress.

3.5 Apparent Dip

The Bulli seam across the mining area generally dips toward the west at a rate of 1 in 39 (1.5°), falling approximately 95 m along the 3700 m length of the panels.

The apparent dip of the boreholes was determined through assessment of the average orientation of each borehole relative to the local strike and dip of the seam, based on 2 m contour intervals generated from coal roof data acquired during surface to seam exploration.

Detailed information relating to the vertical fluctuation of the borehole during drilling ('porpoising') was not available and therefore not accounted for in this analysis. The average apparent dip of all boreholes within the dataset is +1.28°, with the range extending from approximately -2.0 to +4.0°.

Figure 9(A) and 9(B) show the distribution of total gas production and D50 gas production relative to the apparent dip of each borehole.

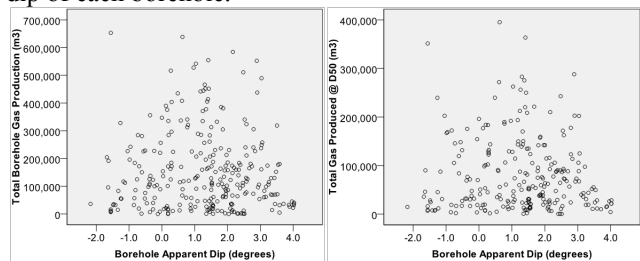


Figure 9 (A) Total gas production relative to apparent dip; (B) D50 gas production relative to apparent dip.

The data indicates that apparent dip has some impact on gas production, with greater maximum gas production being achieved from boreholes having positive apparent dip. These boreholes are favourably oriented to support self-draining of produced water, without the need for pumping, which may otherwise impede gas production.

3.6 Drainage Time

Drainage time is a measure of the productive life of the borehole which ends once the borehole is abandoned or intersected by mining and/or associated UIS drilling.

The drainage time provided to the boreholes within this mining area, shown in Figure 10(A), ranged from as little as one week through to one year, with an average of 157 days. It is also worth noting that 25% of the boreholes drilled have an effective life of less than 100 days.

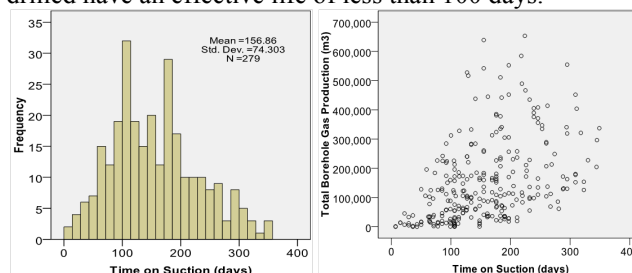


Figure 10 (A) Histogram showing distribution of drainage time; (B) Total gas production relative to drainage time.

Figure 10(B) shows the relationship between total gas production and drainage time. Gas production increases in response to increasing drainage time and at least 100 days should be provided in order to achieve reasonable gas production. In the case of the slower draining coal, located inbye of 30 c/t, a significantly longer period is required.

3.7 Applied Suction

Suction is applied to the collar of each borehole once connected to the underground gas drainage reticulation network. The size of the pipes within the network varies, depending upon expected volumetric flow requirement, ranging from 75 mm diameter flexible hose connections through to 610 mm diameter steel trunk lines. A dedicated borehole is used to connect the underground reticulation network to a surface drainage plant which houses five liquid ring compressors.

Measurement of applied suction pressure was recorded periodically at each borehole location. Given the variable of suction pressure, the median value was calculated for each borehole and used as the basis for evaluating the impact of applied suction pressure on gas production.

The suction pressure applied to the boreholes was found to range from 1.0 to 31.0 kPa, with an average of 13.5 kPa, as shown in Figure 11(A). Suction pressure decreased along the length of the panels which may be the result of increasing resistance within the gas reticulation pipe network. Figure 11(B) shows total gas production relative to median applied suction pressure.

The upper bound of the dataset suggests gas production increases in response to increasing applied suction pressure. Considering 1,000 m sections along the length of the panels there was little evidence to support such a relationship. The applied suction pressure and high production rate is a mere coincidence as the outbye zone is easily drainable.

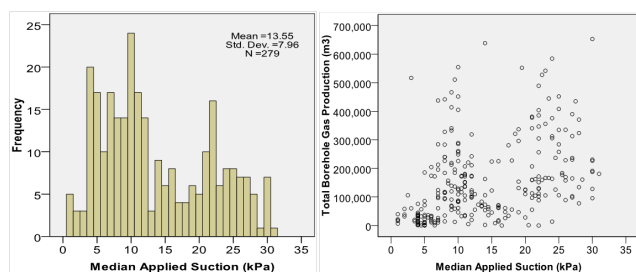


Figure 11 (A) Histogram showing distribution of median applied suction pressure; (B) D50 gas production relative to applied suction.

Therefore, although suction should be applied to each borehole to limit the risk of gas leakage into the underground environment, there is no evidence to suggest that increasing applied suction pressure achieves increased gas production.

4 Coal Properties

Table 2 lists the coal seam properties considered. Data was obtained from various sources including the results of testing and analysis conducted by internal and external laboratories and consultancies along with the results of testing and analysis undertaken at the University of Wollongong's Mining Gas Research laboratory.

Table 2 Coal seam properties considered in analysis

Carbon content	Inherent moisture content
Volatile matter	Seam thickness
Vitrinite reflectance	Gas content
Inertinite/Vitrinite content	Gas composition
Mineral matter	Total gas in place
Seam/Coal ash content	Degree of saturation

4.1 Coal Rank

The rank of the coal within this study area is classified as medium volatile bituminous with values of carbon content, volatile matter and vitrinite reflectance ranging from 67.3 to 70.8% (69.0% average), 20.1 to 23.5% (21.7% average), and 1.26 to 1.32% (1.29% average) respectively.

Gas production was found to increase with increasing coal rank, however the higher rank coal happened to be located at the outbye, most productive area of the mine. Further analysis of the data within the four 1,000 m zones along the length of the panels confirmed a relationship, albeit weak, between gas production and coal rank. Figure 12(A) and 12(B) show total gas production relative to carbon content for the complete data set and the samples within each of the four 1,000 m zones along the length of the panels.

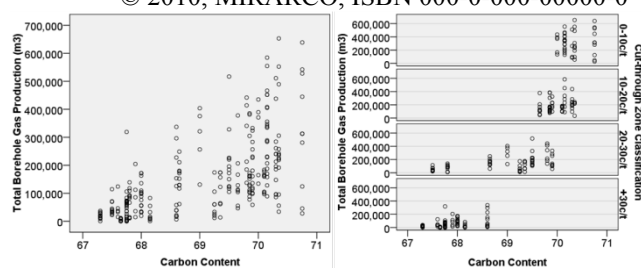


Figure 12 (A) Total gas production relative to carbon content; (B) Total gas production relative to carbon content within four 1,000 m zones.

4.2 Coal Type

Petrographic analysis of 90 coal samples was used to determine the distribution of maceral type. The average inertinite content was found to be 55.4%, with a range of 47.0 to 61.5%. The inertinite component percentage increased along the length of the panels, from outbye to inbye.

Figure 13(A) indicates some reduction of total gas production in response to increasing inertinite content. Figure 13(B) shows the relationship between total gas production and inertinite content within the four cut-through zones along the panels. Assessing the gas production relative to inertinite content, within the cut-through zones, suggests that coal type has little impact on gas production.

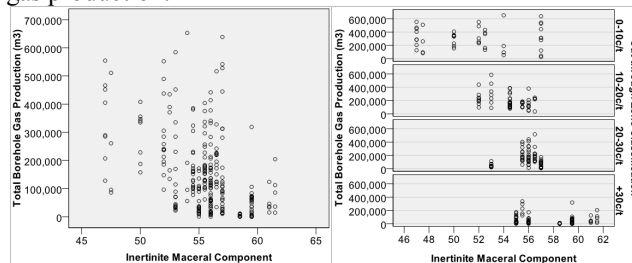


Figure 13 (A) Total gas production relative to inertinite content; (B) Total gas production relative to inertinite content within four 1,000 m zones.

Petrographic analysis also provided data relating to the mineral matter content of the coal samples. The average mineral matter content was found to be 3.3%, ranging from 2.4 to 4.6%. No relationship was found between total gas production and mineral matter content.

4.3 Ash Content

Analysis of 94 coal samples was conducted at an independent laboratory to determine raw ash, through density separation, and coal ash, through proximate analysis.

The raw ash, also known as seam ash, ranged from 10.5 to 14.0%, with an average of 12.2%. And the coal ash content ranged from 8.3 to 10.7%, with an average of 9.7%. In both cases there was some evidence of decreasing total gas production in response to increasing ash content.

Figure 14(A) shows the relationship between total gas production and coal ash content and Figure 14(B) shows

the relationship between total gas production and coal ash content within the four cut-through zones along the panels.

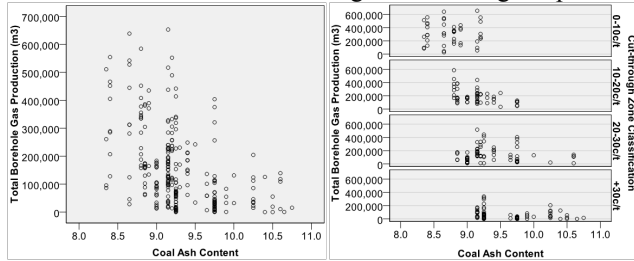


Figure 14 (A) Total gas production relative to coal ash content; (B) Total gas production relative to coal ash content within four 1,000 m zones.

4.4 Inherent Moisture Content

Inherent moisture content data was available from proximate analysis testing on 91 coal samples. The average moisture content was 0.9%, with a range of 0.8 to 1.0%.

Over such a narrow range no relationship was found to exist between total gas production and inherent moisture content.

4.5 Seam Thickness

The average thickness of the Bulli seam was found to be 2.6 m, with a range of 2.3 to 2.9 m.

Figure 15(A) indicates increasing gas production associated with increasing coal seam thickness. However the thicker coal is located at the outbye part of the mining area which has a higher gas production rate than the inbye area. Figure 15(B) also gives some indication of increasing gas production in response to increasing seam thickness within each of the four cut-through zones.

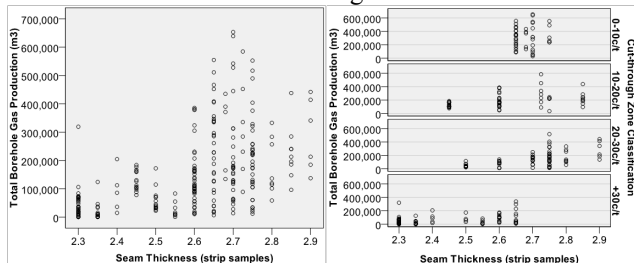


Figure 15 (A) Total gas production relative to seam thickness; (B) Total gas production relative to seam thickness within four 1,000 m zones.

Therefore it is considered that seam thickness may have some impact on gas production although it is not a dominant factor.

4.6 Seam Gas

Within the study area the gas composition ($\text{CH}_4:\text{CO}_2$ ratio) spans a broad range, from a low of 13% to a high of 98%, whilst the gas content span a much smaller range, from a low of 7.5 m^3/t to a high of 15.5 m^3/t . The relationship between gas composition and gas content, Figures 16(A) and 16(B), shows little variation in gas content across a wide gas composition range in the inbye zones, whereas in

the outbye zones both the gas content and gas composition are greater.

Figure 17(A) indicates increasing gas production in response to increased gas content. However, as shown in Figure 17(B), the relationship between gas production and gas content, within the four cut-through zones, is not strong suggesting other factors may be impacting gas production.

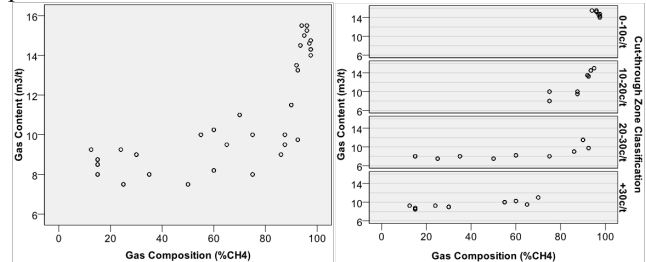


Figure 16 (A) Gas content relative to gas composition; (B) Gas content relative to gas composition within four 1,000 m zones.

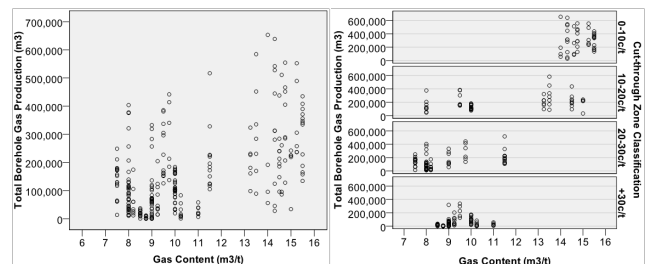


Figure 17 (A) Total gas production relative to gas content; (B) Total gas production relative to gas content within four 1,000 m zones.

Figure 18(A) shows that as methane gas composition decreases so to does average gas production, with an increase in the proportion of boreholes that achieve very low total gas production.

Figure 18(B) shows gas production relative to the composition of the coal seam gas within the four cut-through zones. The data suggest a relationship exists, independent of location. Further assessment of the data, divided into three groups on the basis of gas composition, found that gas production was again positively impacted by time on suction and less impacted by gas content. Therefore it is concluded that the seam gas composition does have an impact on gas production.

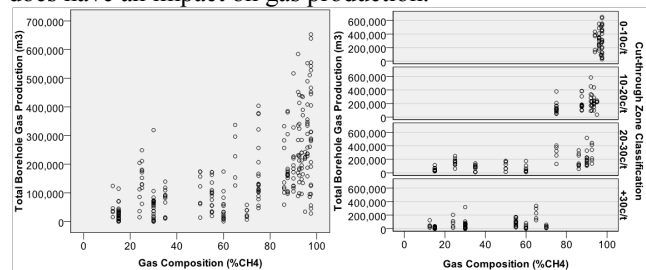


Figure 18 (A) Total gas production relative to gas composition; (B) Total gas production relative to gas composition within four 1,000 m zones.

Consideration was also given to the impact on gas production of total gas in place (GIP), which is the product of gas content, seam thickness, coal density ($\rho=1.34$) and area drilled. Figure 19(A) shows the relationship between total gas production and total GIP for each of the 34 drill sites. The results show on average 32% of the total GIP is produced and this relationship is quite strong ($R^2 = 60\%$).

Figure 19(B) shows the distribution of gas production relative to GIP within each of the four cut-through zones. The positive relationship between total production and GIP is maintained in each zone along with evidence of the consistent decrease in total gas production with distance into the panels.

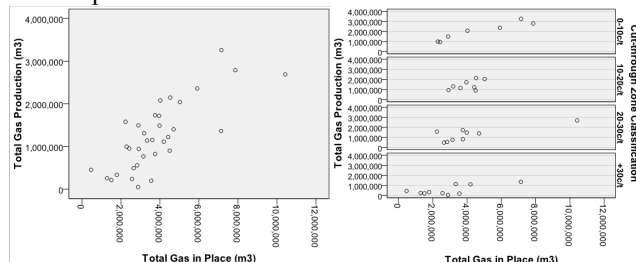


Figure 19 (A) Total gas production relative to total gas in place; (B) Total gas production relative to total gas in place within four 1,000 m zones.

4.7 Degree of Saturation

Given the relatively low gas content, particularly in the more CO₂ rich zones, an assessment of the relative impact on gas production from effects of gas saturation was undertaken. Piezometers installed into the Bulli seam, provided data relating to hydrostatic pressure change due to mining and gas drainage. A pressure of 2.5 MPa was found to be representative of the *in situ* seam gas pressure condition at the commencement of gas production activity. Comparing the gas content, at virgin condition, to the theoretical saturated gas content, based on isotherm data, the degree of saturation within each of the 34 drill sites was determined.

The relationship between degree of saturation and each of gas content and gas composition is shown in Figure 20(A) and Figure 20(B) respectively. Of particular significance is the low saturation in the areas where gas composition is less than 60% CH₄.

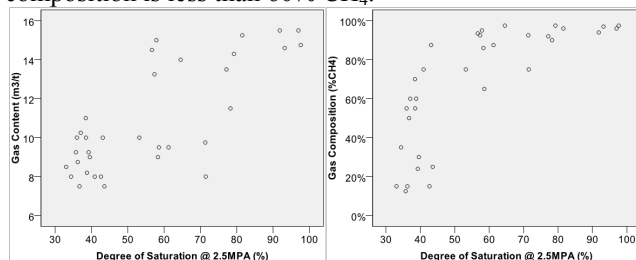


Figure 20 (A) Gas content relative to degree of saturation; (B) Gas composition relative to degree of saturation.

Where deep undersaturation exists potentially significant time is required to depressurise the coal seam

from the initial *in situ* gas condition to the pressure at which reasonable gas production can be expected, which is known as the critical desorption point. Figure 21 shows the additional pressure reduction required when the undersaturated *in situ* gas condition is CO₂ rich.

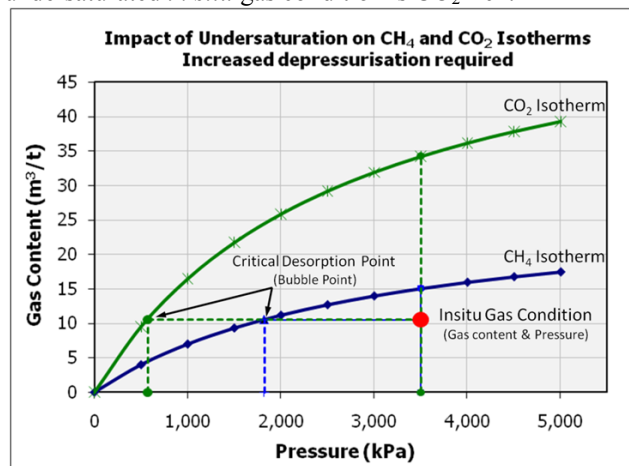


Figure 21 Impact of degree of saturation and pressure reduction required to achieve notable gas production for an *in situ* gas condition in CO₂ and CH₄.

Figure 22(A) shows the total gas production from boreholes within each of the 34 drill sites relative to the degree of saturation. Given the variability in the number of boreholes drilled from each drill site the total gas production was divided by the total number of boreholes to produce a unit gas production rate (m³/borehole). Figure 22(B) shows the results of average total gas production per borehole relative to degree of saturation.

Degree of saturation is considered to have a significant impact on gas production.

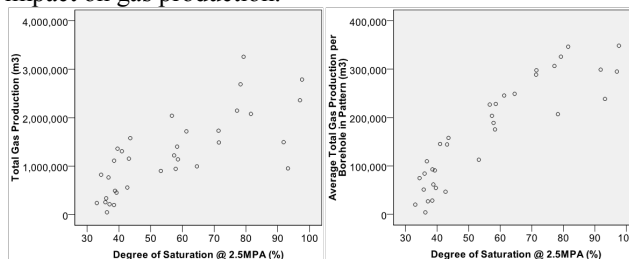


Figure 22 (A) Total gas production relative to degree of saturation; (B) Average total gas production per borehole relative to degree of saturation.

5 Gas Drainage System Management

An investigation into gas drainage system performance at Bulli seam collieries (Black, 2007) found sections of the gas drainage pipe network were adversely impacted by accumulations of water and coal fines. Such accumulations increased system resistance thereby reducing both total production capacity and effective suction pressure inbye of such restrictions.

UIS drilling was found to be a significant source of water and coal fines. Although water and fines management was available at the collar of the borehole

drilled it was found that, due to the design of the drilling pattern, some interaction existed between boreholes, particularly within the initial ten metres. This interaction allowed drill fluid and coal fines to flow into adjacent boreholes and should these boreholes be connected to the gas drainage system the water/fines would flow directly into the gas reticulation pipe network.

Although necessary to maintain effective water drop-out systems throughout the gas reticulation pipe network every effort should be directed toward preventing water/fines entering the network. It is recommended that a water and fines separation unit, similar to the design shown in Figure 23, be maintained at every active drilling site as an additional control to reduce the risk of unwanted material entering and fouling the gas drainage system.

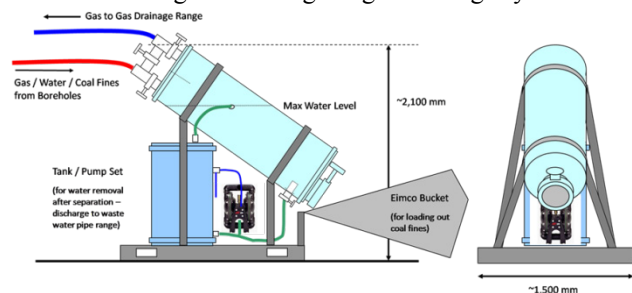


Figure 23 Example water / coal fines separator to prevent unwanted material entering the gas reticulation system during UIS drilling.

6 Conclusions and Recommendations

This detailed analysis of the relationship between total gas production and a variety of geological properties and operational factors has provided insight into the complex interactions that exist within this mining area.

Gas production was found to have positive correlation with coal properties such as rank, ash content and total gas in place. Among the properties considered, degree of saturation was found to have the closest and most significant relationship to gas production. This explains the generally poor gas production achieved from the inbye, deeply undersaturated parts of the mine.

Analysis of the factors able to be controlled by the mine operator, such as borehole orientation, drainage time and applied suction confirmed generally less impact on total gas production. However the results suggest that increased production may be achieved through maintaining UIS borehole design within certain trajectory limits. Increased gas production was achieved from boreholes oriented between 5 and 60° to the dominant cleat, 0 and 40° to the principal horizontal stress and drilled up-dip with an apparent dip between 0 and +3.0°. Within this assumed optimum range 107 boreholes achieved an average total gas production of 198,600 m³, 63% greater than the average of the boreholes outside of this range. The average D50 total gas production was found to be 69% greater than the average of the boreholes outside of this range.

Analysis of applied suction pressure highlighted the variability in suction pressure applied to the boreholes throughout the course of their productive life. There was evidence of a reduction in applied suction pressure with distance into the panels suggestive of increasing resistance. Separate studies support the increase in resistance resulting from accumulations of water and coal fines within the gas reticulation network. In order to maintain the efficiency and overall production capacity of the gas drainage system management effort should support effective design and ongoing maintenance.

Of all the operating factors considered time on suction was shown to have the most significant impact on total gas production. The drainage time ranged from one week to one year with almost 25% of the 279 boreholes analysed having a drainage time of less than 100 days. It has been shown that potentially significant drainage time is required in order for the seam pressure to be reduced to the critical desorption point, particularly in the deeply undersaturated, CO₂ rich zones. The nature of UIS drilling requires it to be in close proximity to mining activity which allows only a short effective drainage window. Where the degree of saturation is less than 50% the drainage time required far exceeds the window available through the use of UIS drilling. In such areas supplementary surface-based gas drainage methods should be used and provided upward of five years drainage time rather than five months.

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