ASSESSMENT OF FACTORS IMPACTING COAL SEAM GAS PRODUCTION

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ABSTRACT

Much research has been undertaken to better understand the impact of a variety of factors on coal seam gas production. The bulk of this research has been undertaken in laboratories using small samples of coal recovered from exploration drilling or operating mines. Given the structural change and potential degradation of coal samples during extraction, transport, storage and preparation for testing, the results of laboratory testing potentially lack transferability and may not be representative of the behaviour of gas flow and emission from intact coal seams.

The results of a mine based investigation undertaken at an operating coal mine working the gassy Bulli seam of Australia's Illawarra coal measures is discussed. Gas production data from 279 inseam gas drainage boreholes was gathered and used to evaluate the impact of a variety of geological properties and mine operational factors on subsequent gas production performance. While the total production life of the borehole was found to directly relate to total production it was the geological properties of the coal seam that had most impact on gas production. Properties such as coal rank and type, ash content, gas content, seam thickness and gas composition were all found to impact gas production, however these properties were all found to coincide directly with the total gas in place and degree of saturation. From this analysis the degree of saturation is considered to have the most significant impact on coal seam gas production performance.

INTRODUCTION

Many Australian underground coal mines have experienced, or are working toward, areas of increased gas content which are difficult to drain. Such conditions are common in the Bulli seam, located in the southern Sydney Basin of NSW, Australia, and the impact on mine operations include increased gas drainage drilling expenditure and coal production delays, and in the extreme cases, loss of coal reserves.

Intensive coal seam gas drainage is used in the gassy Bulli seam mines to reduce gas content below prescribed threshold limit values ahead of mining. Figure 1(A) shows the typical layout of underground to inseam (UIS) boreholes relative to mine workings, drilled in a fan pattern from developed roadways. Gas production data was regularly collected from the producing UIS boreholes. Of the many hundred UIS boreholes drilled throughout the mine 279 were deemed appropriate for inclusion in this study. Boreholes that had obvious interaction with adjacent boreholes were excluded from the dataset along with boreholes reported to have experienced problems, such as borehole

[1] *Pacific Mining and Gas Management (PacificMGM)*, www.pacificmgm.com.au

collapse, and those regularly reported to be full of water. The 279 boreholes included in this analysis were drilled from 34 separate drill stubs.

Gas production experience at the mine indicated increased difficulty in draining gas from the inbye ends of the panels, shown as the left side of the figure. The mine's response to the poor drainage performance was to increase the drilling density, reducing the spacing between boreholes from approximately 25 m, at the start of the panels, to less than 12 m in the inbye zones.

It was generally accepted at the mine that poor gas drainage was due to the presence of CO_2 in the seam gas. Figure 1(B) shows the change in gas composition from CH_4 rich at the panel entry to CO_2 rich at the inbye end of the panels.

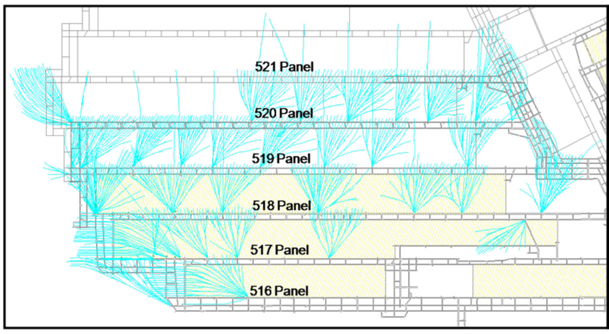

Figure 1(A) – Location of boreholes and drill sites relative to existing and future planned mine workings

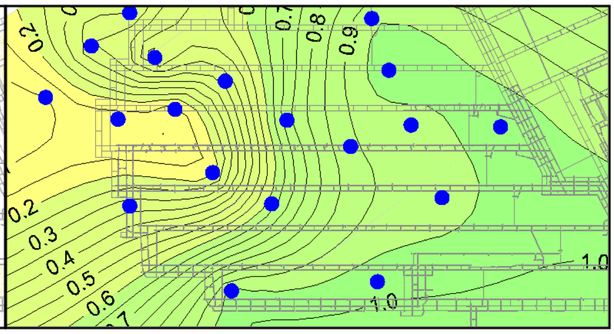

Figure 1(B) – Contour plot showing change in seam gas composition – CH_4 to CO_2 ratio

A comprehensive set of data relating to a variety of operational factors and coal properties was compiled for use in analysing the relative impact of each on UIS gas production performance. Table 1 lists the various operational factors and coal properties for which data was available. The variables were divided into two groups based on the mine operator's ability to influence and control each to improve gas production performance. It was considered that mine operator has the ability to influence operational factors whereas the coal properties are, for the most part, the result of coalification and subsequent geological changes and therefore not able to be altered by the mine operator.

Table 1 – Operational factors and coal properties included in the gas production analysis

OPERATIONAL FACTORS		COAL PROPERTIES		
Borehole length Borehole diameter Drilling density Orientation to cleat	Orientation to stress Apparent dip Drainage time Suction pressure	Carbon content Volatile matter Vitrinite reflectance Inertinite/Vitrinite content	Mineral matter Seam/Coal ash content Inherent moisture content Seam thickness	Gas content Gas composition Total gas in place Degree of saturation

ASSESSMENT OF UIS BOREHOLE GAS PRODUCTION

Analysis of gas production found a steady decrease in the total volume and rate of gas production with distance into the panels. Figure 2 show the average total gas production (m^3) from boreholes drilled from each of the 34 drill stubs relative to the position of the stubs along the length of each panel while Figure 3 show the high degree of variability in gas production from each of the 279 boreholes. The results highlight the significant number of boreholes that achieved low production, with nearly 50% producing less than 100 000 m^3.

Review of borehole production records provided insight into factors contributing to the low production from many boreholes. Regular problems with UIS boreholes were reported which included; 'borehole blocked', 'borehole full of water' and 'no suction'. Separate 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 lead to blockages and generally increase system resistance, thereby reducing production capacity.

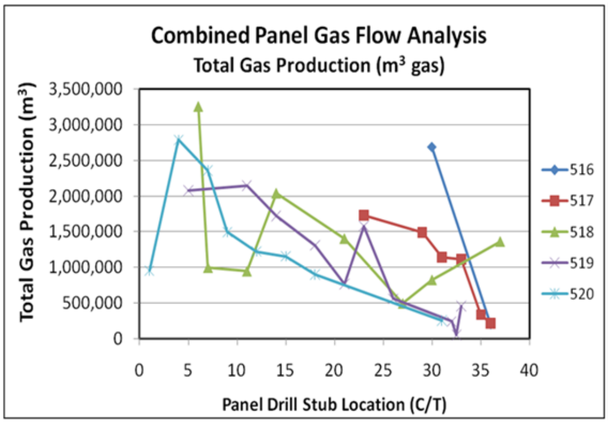

Figure 2 – Total drill stub gas production relative to drill stub location in each panel

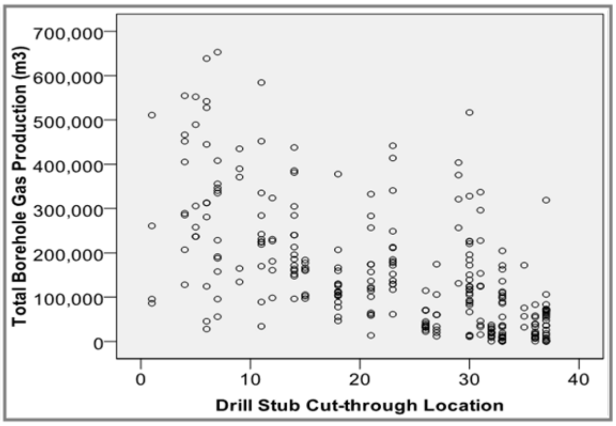

Figure 3 – Total borehole gas production relative to borehole location along panel

UIS drilling was found to be a significant source of water and coal fines. Although water and fines management was present at the collar of the borehole during drilling, it was found that the fan pattern resulted in very close spacing between boreholes immediately beyond the cased standpipe section. This interaction allowed drill fluid, along with coal fines, to flow into adjacent boreholes. When connected to the gas drainage system, water/fines flowed directly into the gas reticulation pipes.

Although necessary to maintain effective water drop-out systems throughout the gas reticulation pipe network, every effort should be directed toward maintaining boreholes free from accumulations and preventing water/fines entering the network. Where system health is regularly monitored and maintained it was considered reasonable to expect many, if not all, boreholes to achieved greater than 100 000 m^3 total gas production.

At an estimated average installed cost of $20 000 for each UIS borehole there is a potentially significant financial incentive to increase gas production from every gas drainage borehole metre drilled. Improving drainage effectiveness, gas volume produced per dollar spent (m^3/$), also aids in avoiding potentially significant financial penalty associated with unnecessary drilling expense, production delays and potential loss of reserves, as well as greenhouse gas emission costs.

ASSESSMENT OF OPERATIONAL FACTORS

Of the operational factors considered, borehole length, diameter, drilling density and applied suction pressure were found to have little impact on gas production.

The impact of borehole trajectory on gas production did not initially indicate a relationship between gas production and each of borehole orientation relative to cleat, stress and seam dip, as shown in Figures 4(A), 4(B) and 4(C) respectively. Zones of increased maximum gas production were identified for each factor, as indicated in Figure 4, where boreholes are oriented between 5 and 60^{O} to the dominant cleat ($100/280^{O}$), 0 and 40^{O} to the principal horizontal stress ($075/255^{O}$), and an apparent dip between 0 to $+3.0^{O}$. Considering the potential benefit of maintaining borehole trajectory within the recommended limits the average total gas production increased 31%, from 151 500 m^3 (n=279) to 198 600 m^3 (n=107). This was 63% greater than the average 122 100 m^3 production of the boreholes outside this range (n=172). Also, considering the potential added benefits associated with borehole and system maintenance, the average total gas production could be further increased. Excluding the sub-100 000 m^3 boreholes the average total gas production of the boreholes falling within the recommended trajectory range increased by a further 54%, to 280 000 m^3 (n=71).

Time on suction was found to have the greatest impact on total gas production. The drainage time provided, shown in Figure 5(A), ranged from as little as one week through to one year, with an average of 157 days. Approximately 25% of the boreholes had an effective drainage life of less than 100 days. Figure 5(B) shows the relationship between total gas production and drainage time which indicates increasing gas production in response to increased drainage time. Further assessment of this relationship, considering the boreholes located within each of four 1 000 m zones along the length of the panels, shown in Figure 5(C), supports the relationship. It should also be noted that the boreholes located inbye of 30 c/t achieved low production where drainage time was less than 300 days.

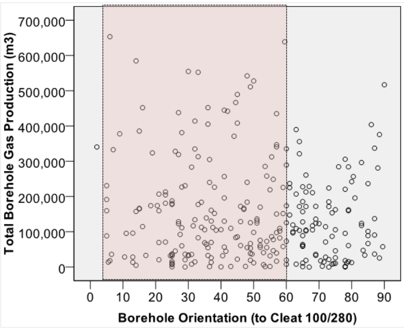

Figure 4(A) – Total gas production relative to borehole orientation to cleat (100/280°)

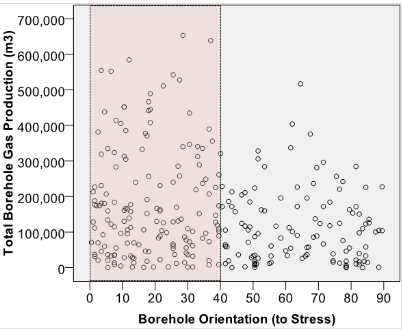

Figure 4(B) – Total gas production relative to borehole orientation to stress (075/255°)

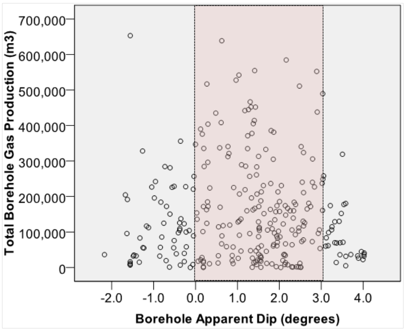

Figure 4(C) – Total gas production relative to borehole apparent dip

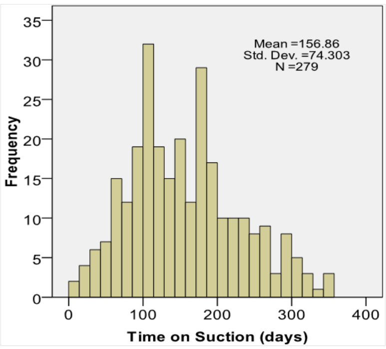

Figure 5(A) – Histogram showing distribution of drainage time

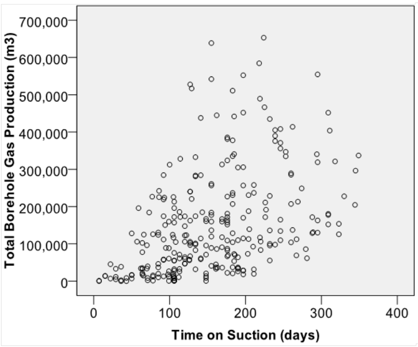

Figure 5(B) – Total gas production relative to drainage time

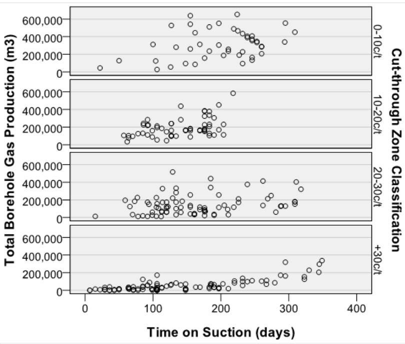

Figure 5(C) – Total gas production relative to drainage time grouped based on drill site location

In general gas production increased 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, significantly longer drainage time is required.

Therefore in addition to regular monitoring and maintenance of the gas drainage boreholes and the overall gas drainage system, the mine operator has the ability to improve the effectiveness of the gas drainage program, thereby producing more gas per drilled metre, through controlling borehole trajectory to remain within the identified limits and increasing drainage time, particularly in the case of the slower drainage boreholes located inbye of 30 c/t.

ASSESSMENT OF COAL PROPERTIES

The rank of the coal within the study area was medium volatile bituminous, with the indicators, carbon content, volatile matter and vitrinite reflectance, ranging in value 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.

Figure 6(A) shows increasing gas production corresponding to increasing coal rank. The higher rank coal was 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, shown in Figure 6(B), added support to a relationship, albeit weak, between gas production and coal rank.

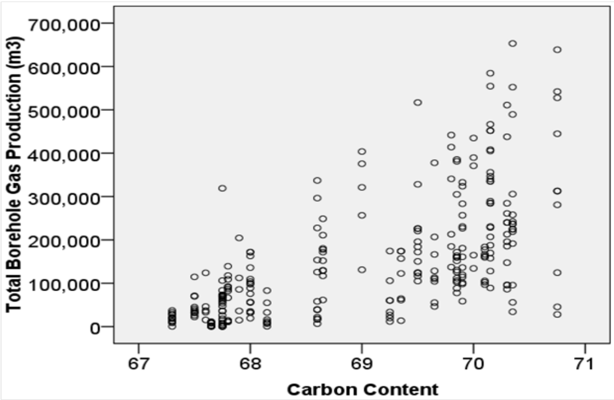

Figure 6(A) – Total gas production relative to carbon content

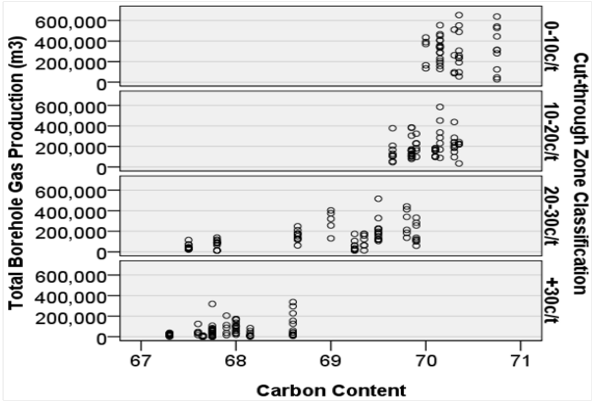

Figure 6(B) – Total gas production relative to carbon content grouped based on drill site location

Petrographic analysis was used to determine the distribution of maceral type and mineral matter for 90 coal samples. The average inertinite content was found to be 55.4%, ranging from a low of 47.0%, at the panel entry, to a high of 61.5% at the inbye end of the panel. Mineral matter content was found to be variable with an average of 3.3%, ranging between 2.4 to 4.6%. Analysis of coal type relative to gas production indicated no notable relationship.

Ash analysis of 94 coal samples determined values of raw ash, through density separation, and coal ash, through proximate analysis. The raw ash, referred to as seam ash, ranged from 10.5 to 14.0%, with an average of 12.2%. The coal ash content ranged between 8.3 and 10.7%, with an average of 9.7%. In both cases there was evidence of decreasing total gas production in response to increasing ash content. Figure 7(A) shows the relationship between total gas production and coal ash content of the complete data set. Figure 7(B) shows the relationship between total gas production and coal ash content within each of the four cut-through zones along the panels.

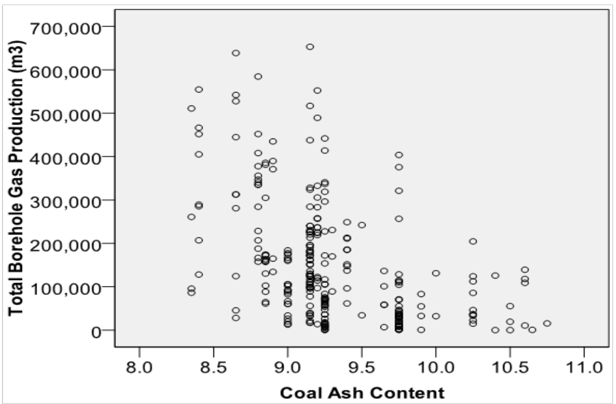

Figure 7(A) – Total gas production relative to coal ash content

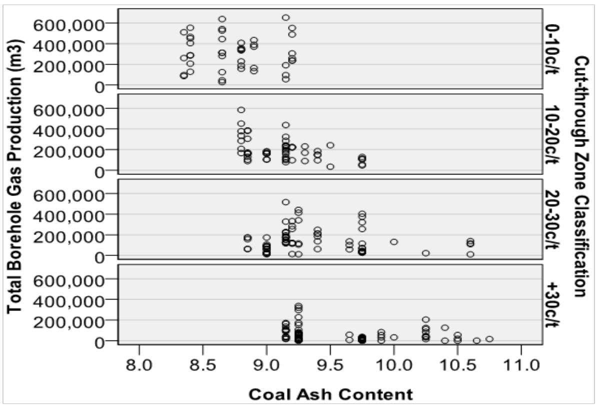

Figure 7(B) – Total gas production relative to coal ash content grouped based on drill site location

Inherent moisture content data was available from proximate analysis testing of 91 coal samples. The average inherent moisture content was 0.9%, ranging from 0.8 to 1.0%. No relationship was found to exist between total gas production and inherent moisture content.

The average thickness of the Bulli seam was found to be 2.6 m, ranging from 2.3 m to 2.9 m. Figure 8(A) indicates increasing gas production associated with increasing coal seam thickness. However the thicker coal was located at the outbye, more productive, area of the mine. Figure 8(B), shows gas production relative to seam thickness within each of the four cut-through zones, which support a relationship between gas production and coal seam thickness.

Gas composition (CH_4:CO_2 ratio) was found to range from a low of 13% to a high of 98% whilst the gas content spanned a much narrower 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 9(A) and 9(B), show the panel entry was CH_4 rich with relatively high gas content, decreasing in both gas content and CH_4 composition with distance into the panels.

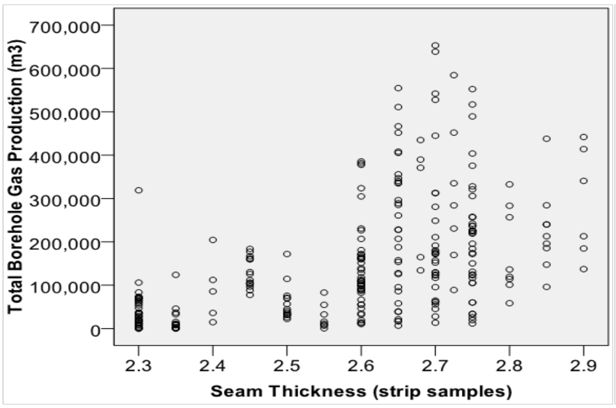

Figure 8(A) – Total gas production relative to coal seam thickness

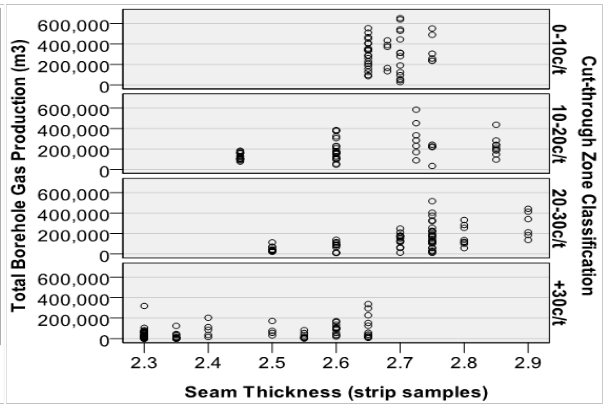

Figure 8(B) – Total gas production relative to coal seam thickness grouped based on drill site location

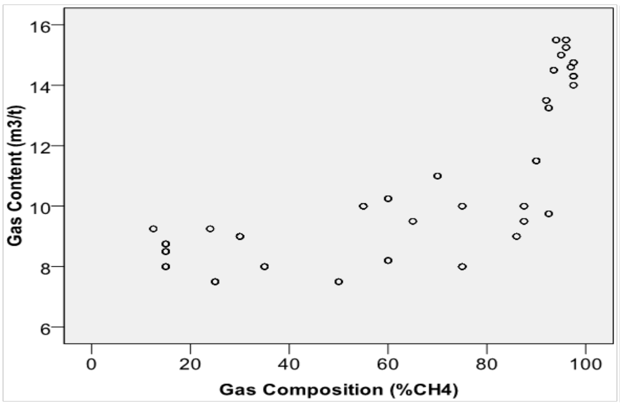

Figure 9(A) – Gas content relative to gas composition

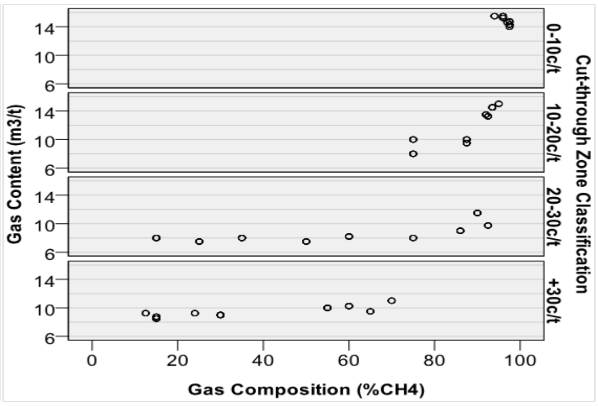

Figure 9(B) – Gas content relative to gas composition grouped based on drill site location

Figure 10(A) indicates increasing gas production in response to increased gas content. However, as shown in Figure 10(B), the relationship between gas production and gas content, within each of the four cut-through zones, is not particularly strong suggesting other factors may be impacting gas production.

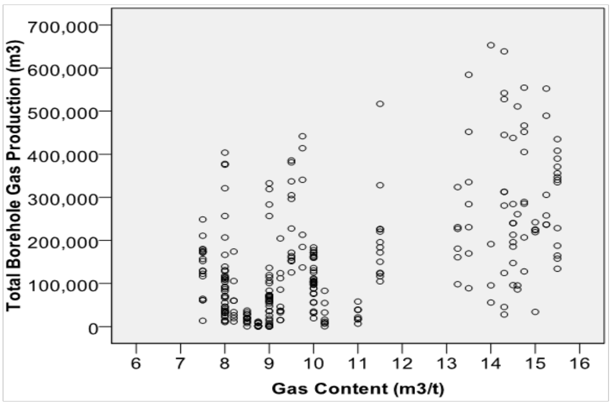

Figure 10(A) – Total gas production relative to gas content

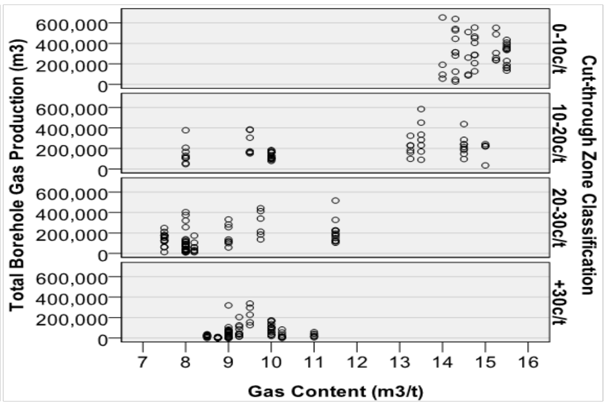

Figure 10(B) – Total gas production relative to gas content grouped based on drill site location

Figure 11(A) show an increase in gas production from boreholes located in CH_4 rich areas. Figure 11(B) shows gas production relative to gas composition within each of the four cut-through zones. The data suggest a relationship between the two variables, independent of location.

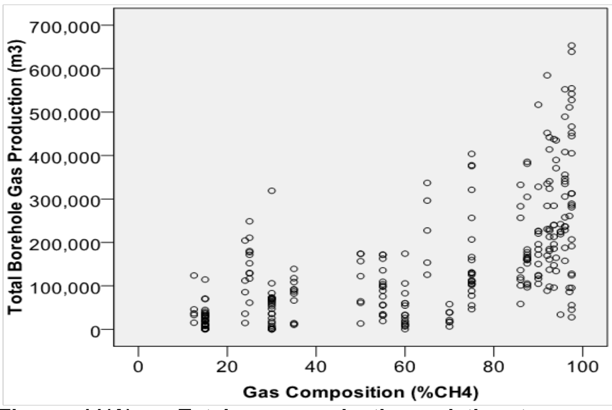

Figure 11(A) – Total gas production relative to gas composition

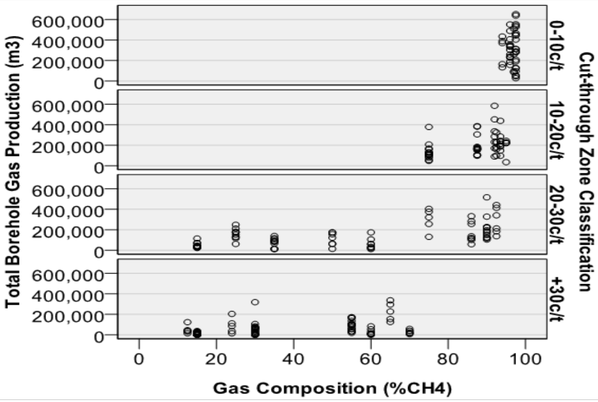

Figure 11(B) – Total gas production relative to gas composition grouped based on drill site location

The impact on gas production from total gas in place (GIP), which is the product of gas content, seam thickness, coal density (ρ=1.34) and area drilled, for each of the 34 drill patterns, was also considered. Figure 12(A) highlights a strong relationship between total gas production and total GIP for each of the 34 drill sites. It has found that an average 32% of the total GIP was removed from the coal through gas drainage. Figure 12(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 was maintained in each zone along with evidence of the consistent decrease in total gas production with distance into the panels. Figure 12(C) shows the relationship between total production and GIP, grouped on the basis of gas composition. From the data presented, not only can it be seen that gas production increases in response to increasing GIP, the more productive CH_4 rich zones have greater total GIP than the CO_2 rich zones.

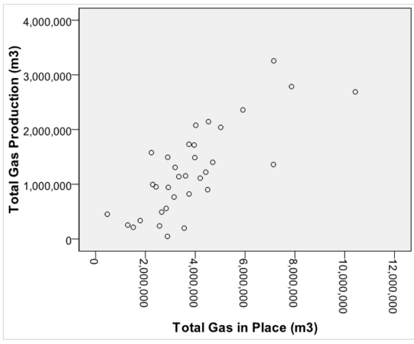

Figure 12(A) – Total gas production relative to GIP

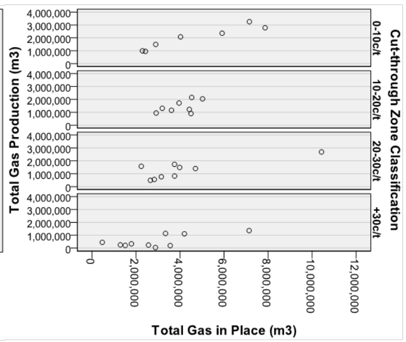

Figure 12(B) – Total gas production relative to GIP grouped based on drill site location

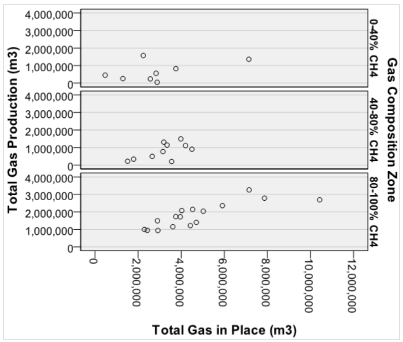

Figure 12(C) – Total gas production relative to GIP grouped based on seam gas composition

ASSESSMENT OF DEGREE OF SATURATION

A coal holding the maximum possible amount of gas at current reservoir pressure and temperature conditions is said to be 'saturated', whereas a coal holding less than the theoretical maximum is referred to as 'undersaturated'. The most successful coalbed methane production occurs in fields that are close to fully saturated (Lamarre, 2007). Slightly undersaturated coals behave similar to saturated coals with only a short delay prior to first gas production followed by a steady, strong, rising gas production rate. Deeply undersaturated coals behave quite differently and require extensive dewatering prior to initiation of gas production. In deeply undersaturated coal the critical desorption pressure, which is the pressure at which consistent gas production can be expected, is significantly less than the initial reservoir pressure and requires extensive dewatering prior to initiation of gas production. The result of the long dewatering (depressurising) period is that the peak gas production rate can be significantly less than that of an equivalent saturated coal.

Figure 13 shows a typical Bulli seam *in situ* gas condition and the relative saturation and difference in pressure reduction required to reach the respective critical desorption pressure for both CO_2 and CH_4 rich seam gas areas.

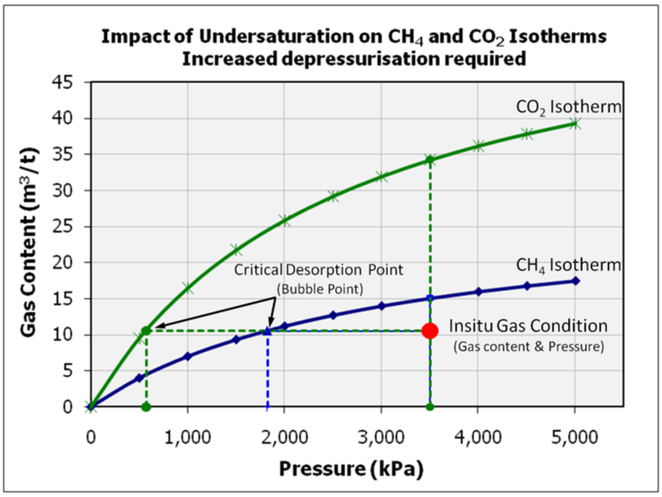

Figure 13 – Difference in saturation and pressure reduction required to reach the critical desorption point for a typical Bulli seam in situ gas condition in CO_2 and CH_4 rich areas

In a study of the economic impact of gas saturation on coals in the United States (Seidle and O'Connor, 2007) determined that as coal became less saturated, the gas production profile weakened exhibiting a longer dewatering time and lower peak production rate. Compared to a fully saturated coal, a coal that was 60% undersaturated required five times as long to reach the peak gas production rate and the magnitude was one sixth that of the saturated coal. Gas saturation is therefore an important coal property and its impact on gas production must be considered.

The degree of saturation (DoS) used in this analysis represents the ratio of measured to saturated gas content (Equation 1). The measured gas content (V_{meas}) is determined using the method described in Australian Standard AS3980:1999. The saturated gas content (V_{sat}) is calculated using the modified Langmuir equation (Equation 2), which requires prior knowledge of the Langmuir constants of volume (V_L) and pressure (P_L), determined during gas adsorption testing, and the initial reservoir pressure (P_i), determined through the use of pressure measuring devices, such as piezometers.

$$DoS = \frac{V_{meas}}{V_{sat}} \cdot 100 \qquad (1)$$

Where: DoS = degree of saturation (%)
V_{meas} = measured gas content (m^3/t)
V_{sat} = saturated gas content (m^3/t)

$$V_{sat} = V_L \cdot \frac{P_i}{P_i + P_L} \qquad (2)$$

Where: V_{sat} = saturated gas content (m^3/t)
V_L = Langmuir volume constant (m^3/t)
P_i = initial reservoir pressure (kPa)
P_L = Langmuir pressure constant (kPa)

The Langmuir equation can also be used to determine the critical desorption pressure (P_d) corresponding to a given measured gas content (Equation 3) and therefore the reservoir pressure reduction (P_i – P_d) required to reach the critical desorption point.

$$P_d = P_L \cdot \frac{V_{meas}}{V_L - V_{meas}} \tag{3}$$

Where: P_d = critical desorption pressure (kPa)
P_L = Langmuir pressure constant (kPa)
V_L = Langmuir volume constant (m^3/t)
V_{meas} = measured gas content (m^3/t)

Piezometers installed into the Bulli seam were used to record seam pressure changes in response to advancing mine working and gas drainage. Data was collected from 18 piezometers over an 11 month period, between December 2006 and October 2007, from which a monthly average pressure response was calculated for each piezometer location. A contour plot was prepared to show the pressure distribution for each of the 11 months which provided valuable insight into hydrostatic pressure change and impact of both mine workings and gas drainage drilling. Figure 14(A) and 14(B) show the change in hydrostatic pressure over the seven month period, between February 2007 and September 2007, respectively.

Of particular significance is the fact that the hydrostatic pressure within the coal seam at the time of roadway development is approximately 1 000 kPa and appears to reduce at a slower rate from the inbye parts of the mine. Using the previous example of CO_2 rich coal with an *in situ* gas content of 10.5 m^3/t the critical desorption point occurs at a pressure of 570 kPa. In this example, where the hydrostatic pressure does not fall below 1 000 kPa during the life of the gas drainage program the reservoir pressure is at least 430 kPa above the critical desorption pressure which impedes gas desorption. The fact that the reservoir pressure exceeds the critical desorption pressure partly explains the low gas production from the inbye parts of the mining area and highlights the need for significantly increased drainage time in these deeply undersaturated areas.

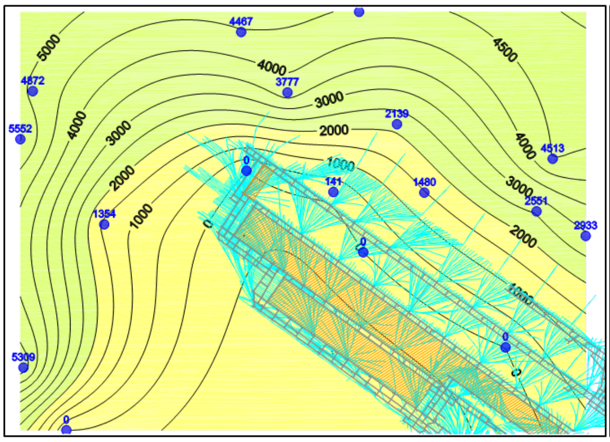

Figure 14(A) – Seam pressure gradient (kPa) relative to advancing mine workings and gas drainage – Feb. 2007

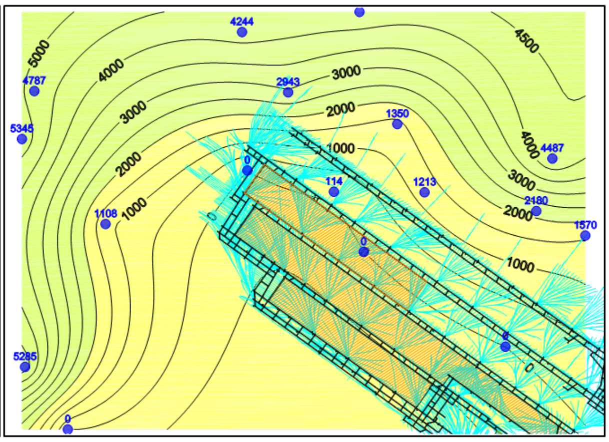

Figure 14(B) – Seam pressure gradient (kPa) relative to advancing mine workings and gas drainage – Sep. 2007

From the hydrostatic pressure contours shown above, it can also be seen that within the range of the UIS gas drainage boreholes the pressure typically does not exceed 2 500 kPa at the time of drilling. This result is consistent with the findings of Marshall *et al.* (1982), who recorded a maximum gas pressure of 2 670kPa at a distance of 40 m in a UIS borehole drilled in the Bulli seam. The gas content measured prior to, or during UIS drilling, within each of three zones along the length of the panels, plotted at an initial reservoir pressure of 2 500 kPa, are shown in Figures 15(A), 15(B) and 15(C). The figures show the decrease in DoS with distance into the panels, from the slightly undersaturated, CH_4 rich, outbye zone, through to the deeply undersaturated, CO_2 rich, inbye zone.

The relationship between DoS and total gas production from all UIS boreholes in each of the 34 drill sites is shown in Figure 16(A) which indicates a positive relationship. However, given the variable number of UIS boreholes drilled from each drill site, the relationship between total gas production and the unit gas production rate (m^3/m), shown in Figure 16(B), was also considered. The results indicate a strong relationship between gas production and DoS.

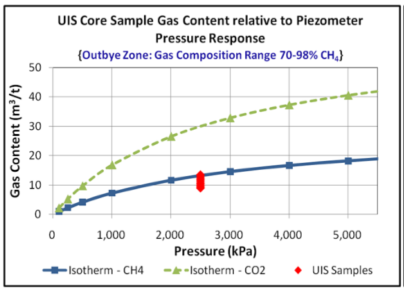

Figure 15(A) – In situ gas condition in slightly undersaturated, CH_4 rich outbye zone

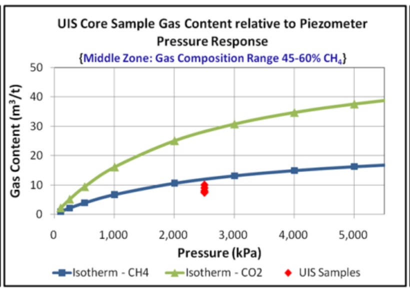

Figure 15(B) – In situ gas condition in moderately undersaturated, mixed gas (CH_4/CO_2) middle zone

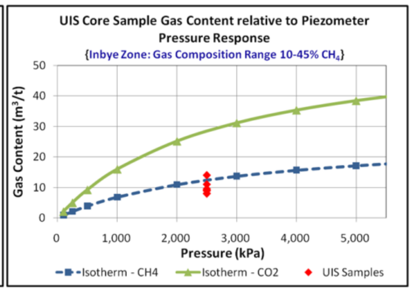

Figure 15(C) – In situ gas condition in deeply undersaturated, CO_2 rich inbye zone

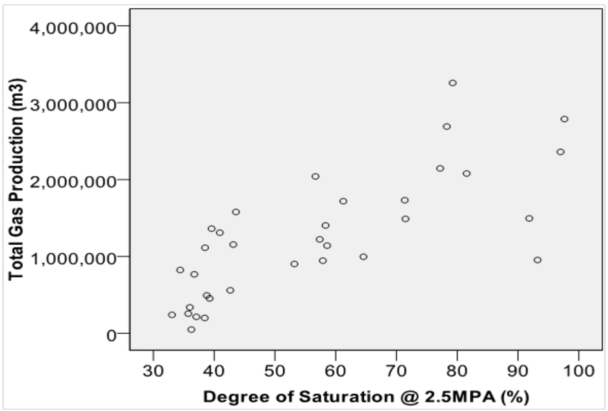

Figure 16(A) – Total drill site gas production relative to DoS @ 2.5 MPa initial *in situ* reservoir pressure

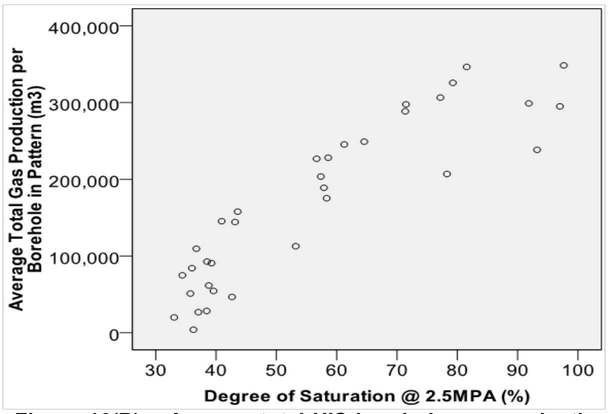

Figure 16(B) – Average total UIS borehole gas production relative to DoS @ 2.5 MPa initial *in situ* reservoir pressure

CONCLUSIONS AND RECOMMENDATIONS

This analysis has provided insight into the impact on gas production from a variety of operational factor and geological properties, within this mining area.

It was found that a significant portion of the UIS drilling effort yields little benefit. Of the 279 boreholes analysed, 124 (45%) achieved less than 100 000 m^3 total gas production. A typical operational response to such low production was to drill additional boreholes, many of which were afforded very short drainage time and delivered little benefit.

Gas production was found to positively correlate with coal properties such as rank, ash content and total gas in place, which represents the combination of gas content and volume of coal being drained. However, degree of saturation was found to have the closest and most significant relationship to gas production.

Of all the operating factors considered time on suction was shown to have the most significant impact on total gas production. Drainage time ranged from one week to one year with almost 25% of the 279 boreholes having a drainage time of less than 100 days. It was shown that potentially significant drainage time was required to reduce the seam pressure to the critical desorption point, particularly in the deeply undersaturated, CO_2 rich zones. Where degree of saturation was less than 50% the drainage time required far exceeded the drainage window available through the use of UIS drilling. In such areas the use of supplementary surface-based gas drainage methods are required.

Analysis of the factors able to be controlled by the mine operator demonstrated generally low impact on total gas production. However the results suggest that increased production may be achieved through maintaining UIS borehole orientation within an identified 'optimum' range. Increased gas production was achieved from boreholes oriented between 5 and 60^O to the dominant cleat, 0 and 40^O to the principal horizontal stress, and drilled up-dip at an apparent dip between 0.0 and $+3.0^O$. The 107 boreholes within the assumed optimum range achieved 198 600 m^3 average total gas production, 63% greater than the average production of the boreholes outside this range, and 31% greater than the average production of the total dataset.

Analysis of applied suction pressure highlighted variability in suction pressure applied to the boreholes throughout their productive life. There was evidence of reduced suction pressure with distance into the panel suggestive of increasing resistance. Separate studies attributed the increase in resistance to accumulations of water and coal fines within the boreholes and gas reticulation network. Although not analysed in this study, it was accepted that maintaining system health has a potentially significant impact on gas production capability through avoiding conditions such as, 'borehole blocked', 'borehole full of water' and 'no suction'.

Through taking action to eliminate the poor producing boreholes, by way of increased drainage time and maintaining the health of the UIS boreholes and broader gas drainage system, significant gas production improvement can be expected. In this case, the average total gas production of the 155 boreholes whose gas production exceeded 100 000 m^3 was 59% greater than the average production of the total dataset.

Combining optimum borehole trajectory and increased drainage time with regular monitoring and ongoing maintenance of the UIS boreholes and gas reticulation system would further increase the expected gas production. From the boreholes analysed in this study, 71 lie within the optimum trajectory range and achieved above 100 000 m^3. The average total gas production achieved by these boreholes was 280 000 m^3, 85% greater than the average production of the total dataset.

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