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CYCLIC INERT GAS INJECTION – AN ALTERNATIVE APPROACH TO STIMULATE GAS DRAINAGE FROM TIGHT COAL ZONES

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ABSTRACT: Traditional methods of coal seam gas drainage depend on reducing the reservoir pressure to enable gas desorption from the coal matrix. Studies in coal mine gas drainage, particularly in coal seams that are deeply undersaturated and have low permeability, found the rate of reservoir pressure reduction was prohibitively slow. In such conditions, lengthy production delays were experienced while additional gas drainage drilling was undertaken in an attempt to reduce seam gas content below specified threshold limits. Such additional drilling represents a high additional operating cost and typically yields low total gas production whilst adversely impacting the mine's gas drainage drilling schedule and potentially leading to coal production delays. A novel method to enhance gas drainage from tight coal zones, known as cyclic inert gas injection, which does not rely on reservoir pressure reduction to stimulate gas flow, is proposed.

INTRODUCTION

Gas drainage is an integral part of many underground coal mines, with efficient and effective gas management required to support safe and productive mine operations. In gassy mines, such as those operating in the Bulli seam, located in the Southern Sydney Basin, Australia, there has been a reliance on Underground to Inseam (UIS) drilling to pre-drain the working seam to reduce the gas content below prescribed threshold limits ahead of mine development. In rural areas, such as Central Queensland, Surface to Inseam (SIS) methods, in particular Medium Radius Drilling (MRD) has become an effective drilling method to access and extract coal seam gas. Figure 1 illustrates a variety of UIS and SIS drilling methods that are available for use in coal seam gas drainage.

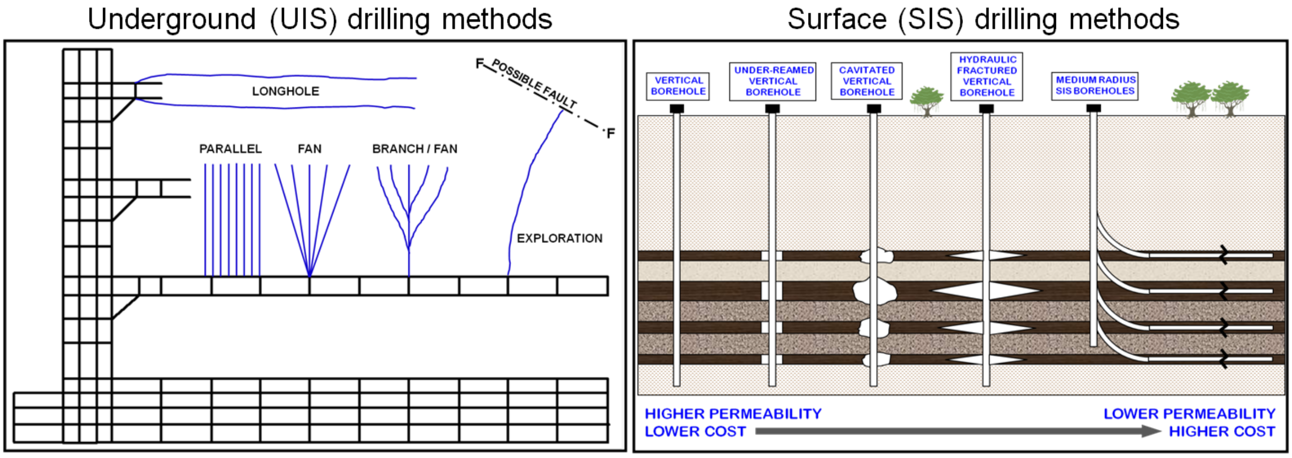

Figure 1: Underground and Surface based drilling methods / patterns available for use in coal seam gas drainage.

Due to the many restrictions associated with access and operations within an underground coal mine, UIS drill rigs are much smaller than surface drill rigs and therefore are limited to drilling shorter, smaller diameter boreholes. In order to achieve the required gas content reduction prior to mining, UIS drainage relies on drilling a larger number of closely spaced boreholes to drain the coal seam in a relatively short period. The drainage time available for UIS is typically less than 12 months. In comparison, SIS drainage typically involves drilling a small number of long MRD boreholes, in excess of 1,500 metres, that flank the planned future gateroad driveage. Given the high cost of SIS gas drainage the MRD boreholes should be installed such that they are afforded a lengthy drainage window, which should be at least three years ahead of planned mining in the area.

Conventional UIS and SIS gas drainage methods are dependent upon reducing the reservoir pressure within the particular coal seam from the *in situ* condition to the Critical Desorption Pressure (CDP) corresponding to the sorption isotherm for the given coal / gas mix (Durucan and Shi, 2009). Such methods, although relatively simple, are not particularly efficient as the reduction in reservoir pressure also corresponds to a reduction in the rate of gas production from the borehole (Puri and Stein, 1989).

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In deeply undersaturated conditions a significant pressure reduction may be required to reach the CDP, as illustrated in the case of CO_2 rich coal seam gas conditions in Figure 2, which requires a pressure reduction of approximately 3,000 kPa to reach the CDP.

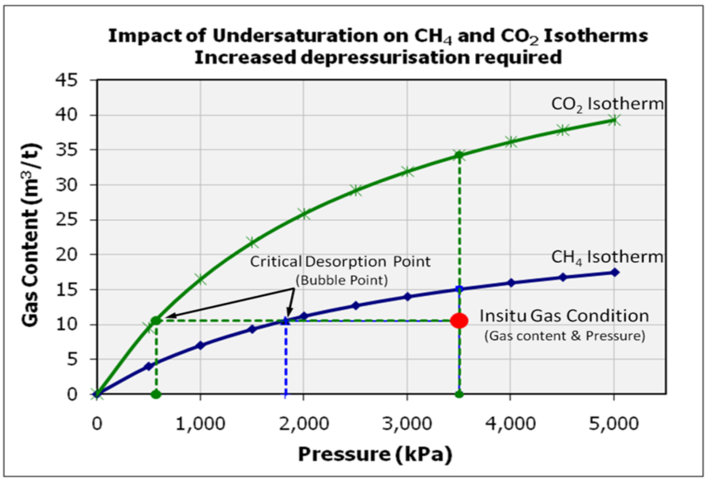

Figure 2: Typical Bulli seam gas content and reservoir pressure condition relative to CH_4 and CO_2 isotherms.

Figure 3 presents data that highlights the relationship between gas production from conventional UIS boreholes and Degree of Saturation (DoS) of the coal seam. In such conditions, where the permeability of the coal seam is also low, the time period required to achieve even a small pressure reduction may be prohibitively long resulting in negligible gas content reduction within the available drainage window. Where such conditions exist it is recommended that the coal seam in the tight coal zone be treated with an additional gas drainage enhancement technique to enhance the permeability of the coal and increase the rate of gas flow from the coal.

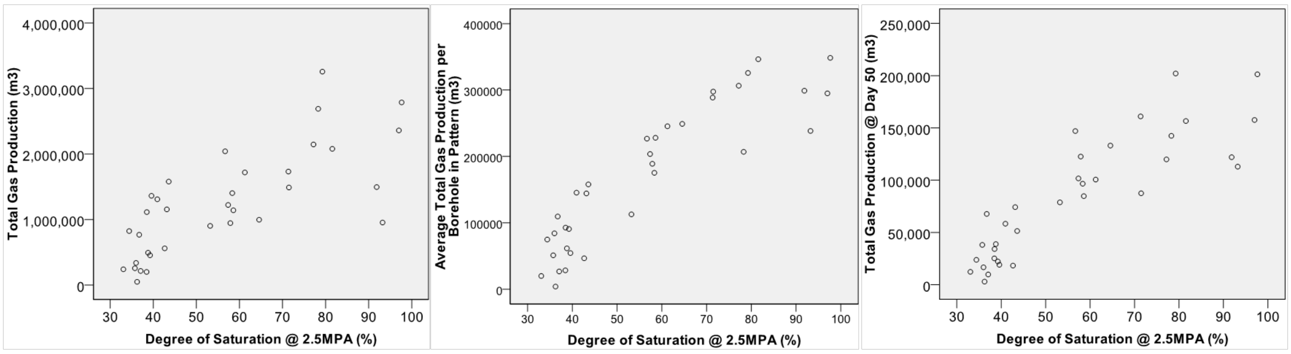

Figure 3: Data indicating relationship between UIS gas production and Degree of Saturation.

DEGREE OF SATURATION

Coal that contains the maximum amount of gas at reservoir pressure and temperature conditions is said to be 'saturated', whereas coal that contains less than the theoretical maximum is referred to as 'undersaturated'. Gas is most easily drained from coal seams that are fully saturated (Lamarre, 2007). Slightly undersaturated coals behave similarly to saturated coals with only a short delay prior to first gas production followed by a steady, strong, rising gas production rate. 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.

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 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 (Standards Australia, 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.

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

where:

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

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

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.

$$P_d = P_L \cdot \frac{V_{meas}}{V_L - V_{meas}} \quad \text{.......(3)}$$

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)

Data collected from 18 piezometers installed into the Bulli seam were used to monitor changes in seam pressure in response to advancing mine working and gas drainage. Figure 4 shows the advance of UIS gas drainage drilling and mine development, along with the change in recorded average monthly seam pressure, over an eight month period.

Of particular significance in this example is the fact that in the inbye part of the gateroad development that had historically been very slow and difficult to drain, the hydrostatic pressure within the coal seam just prior to roadway development is quite high, approximately 1,000 kPa, and the rate of pressure reduction appears slower than the more easily drained outbye areas. Referring to the sorption isotherm curve for this CO_2 rich area, shown in Figure 2, where the *in situ* gas content is 10.5 m^3/t, it can been seen that the corresponding critical desorption point is 570 kPa. In this case, where the reservoir pressure remains above the critical desorption pressure, the slow rate of gas production from the inbye part of the mining area is largely attributable to the deep undersaturation in the area and highlights the need for significantly increased drainage time, or the use of a drainage enhancement technique to stimulate gas flow from such deeply undersaturated areas.

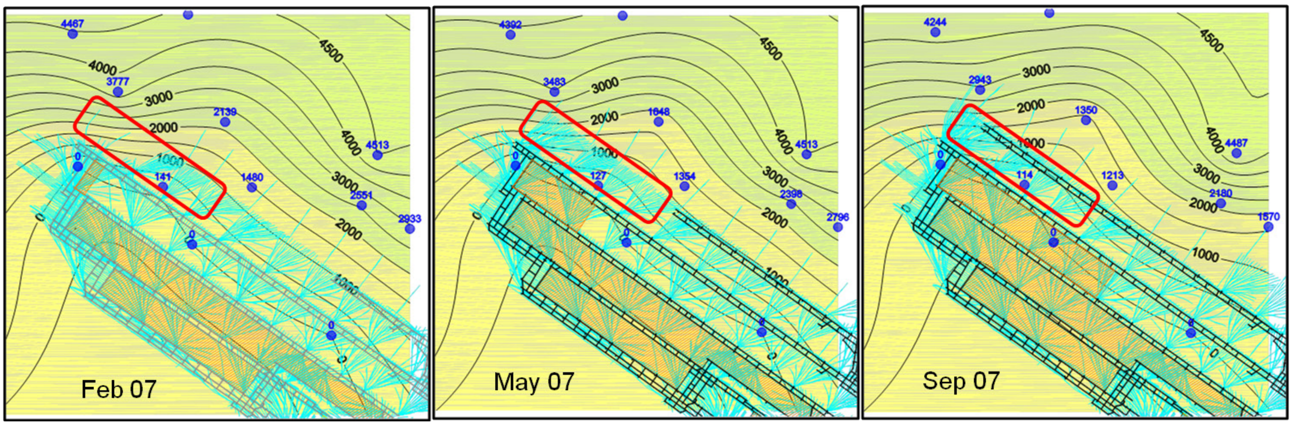

Figure 4: Impact of gas drainage and mine development on measured hydrostatic pressure in the Bulli seam.

ENHANCED COALBED METHANE DRAINAGE

Enhanced Coalbed Methane (ECBM) is a technique used to increase the rate of coal seam methane gas production that involves the injection of an inert gas, typically CO_2 and/or N_2, into a coal seam to stimulate gas desorption and increase total coal seam gas production (Stevenson, *et al*., 1993 and Durucan and Shi, 2009). A cross-section view of a surface based ECBM process is illustrated in Figure 5. A similar method was proposed by Battino and Hargraves (1982) to stimulate gas production from UIS boreholes which involved injecting compressed air into CO_2 rich coal and N_2 into CH_4 rich coal through a central borehole to accelerate gas production from adjacent producer boreholes.

The injection of CO_2 or N_2 into the coal seam, referred to as inert gas stripping, reduces the partial pressure of CH_4 in the free gas phase to stimulate the desorption of CH_4 from the coal matrix (Brown, *et al*., 1996, Durucan and Shi, 2009 and

Mazumder and Wolf, 2008). The movement of the inert gas through the coal seam 'sweeps' the desorbed seam gas toward the production borehole(s).

The use of ECBM to enhance coal seam gas production was first trialled in 1993 in a small scale N_2-ECBM pilot project in the Fruitland formation, San Juan Basin and CO_2-ECBM pilot project in the Manville formation, Alberta (Ham and Kantzas, 2008 and Saghafi, 2009). A typical ECBM drilling pattern consists of a central gas injection borehole surrounded by a number of dedicated gas production boreholes, used to extract the seam gas / injected gas mixture from the coal seam.

The process of CO_2 adsorption does however induce swelling of the coal matrix which can reduce permeability and have a detrimental impact on the ability to inject additional gas into the coal seam. During CO_2-ECBM at the Allison Unit pilot project in the San Juan Basin a reduction in permeability of more than two orders of magnitude was experienced as a result of sorption induced swelling (Durucan and Shi, 2009).

N_2 is considered a superior gas for use in ECBM injection for methane production as it achieves a greater sweep efficiency and is less likely to induce sorption related permeability reduction (Oudinot, *et al*., 2007 and Durucan and Shi, 2009). Injection of N_2 following CO_2 at the Tiffany ECBM pilot in the San Juan basin not only reversed the permeability reduction caused by the previous CO_2 injection but enhanced the rate of N_2 injection into the coal seam (Oudinot, *et al*., 2007 and Durucan and Shi, 2009).

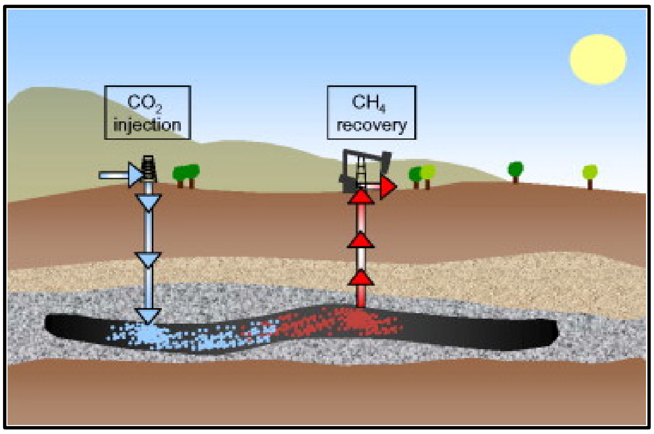

Figure 5: Illustration of the CO_2-ECBM technique to stimulate coal seam methane gas production.

The effectiveness of ECBM is highly dependent on prevailing geological conditions, the properties of the coal seam gas reservoir, the layout of the injection and production boreholes, and the design of the injection program. To be effective, the injected inert gas must be in contact with the coal matrix for sufficient time to stimulate desorption and sweep seam gas from a large area of the coal seam. In cases where the face cleat and geological structures align sub-parallel to the path between the injection and production boreholes the injected gas is more likely to take a direct path toward the production borehole resulting in low sweep efficiency and reduced effectiveness of the ECBM method. The adverse effect of a geological structure on ECBM in a UIS application that allows the injected gas to flow directly to the adjacent producers boreholes is illustrated in Figure 6; pattern A illustrates the desired migration of injected inert gas and pattern B illustrates the effect of the injected inert gas flowing directly to the producer boreholes along the structures present in the coal seam.

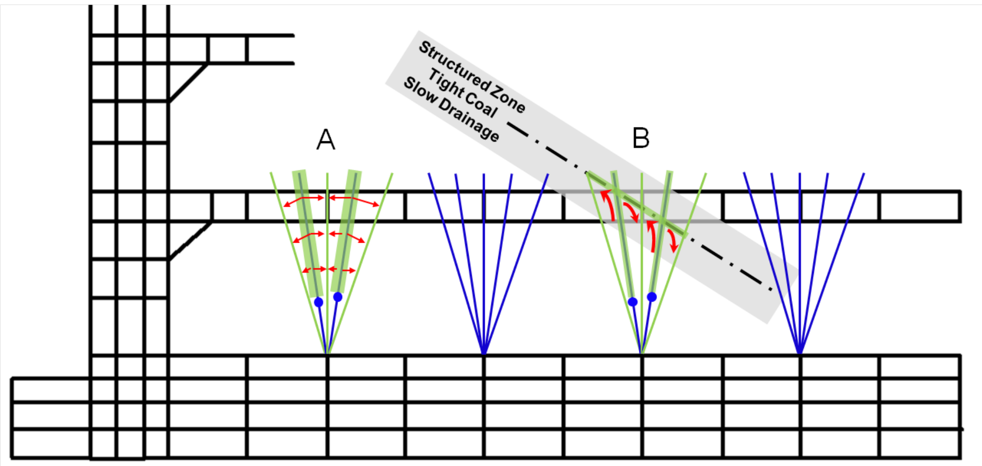

Figure 6: Illustration of the adverse effects of geological structures on the effectiveness of ECBM.

Given the fact that many coal seams are highly structured and likely to feature multiple potential paths that may render a conventional ECBM treatment through SIS or UIS boreholes ineffective, it is necessary to develop a new enhancement technique that is better suited for use in, and able to stimulate gas production from, such disturbed zones. Such a technique is referred to as Cyclic Inert Gas Injection (CIGI) (Black, 2011 and Black, *et al.*, 2011).

CYCLIC INERT GAS INJECTION

Unlike conventional ECBM, CIGI does not rely on the broad sweeping effect of inert gas flow through the coal seam between the injection and production boreholes and is well suited to areas where geological structures may be present.

CIGI involves injecting a heated inert gas, such as N_2, into a coal seam through a dual purpose injection-production borehole, at a pressure greater than reservoir pressure and less than fracture initiation pressure, to penetrate the cleat and flood the coal structure surrounding the injection borehole. Upon completion of the injection phase, the borehole is shut-in for a period to encourage desorption of CH_4 from the coal matrix. After sufficient hold time the borehole is opened to produce a mixture of desorbed CH_4 and inert gas. The cycle of inject-hold-produce is repeated multiple times and the intent is to grow the size of the treated coal zone with each stimulation treatment cycle. Figure 7 illustrates the major components of a CIGI project and the progressive increase in the size of the treated coal zone during a five cycle coal seam stimulation treatment through a single vertical borehole.

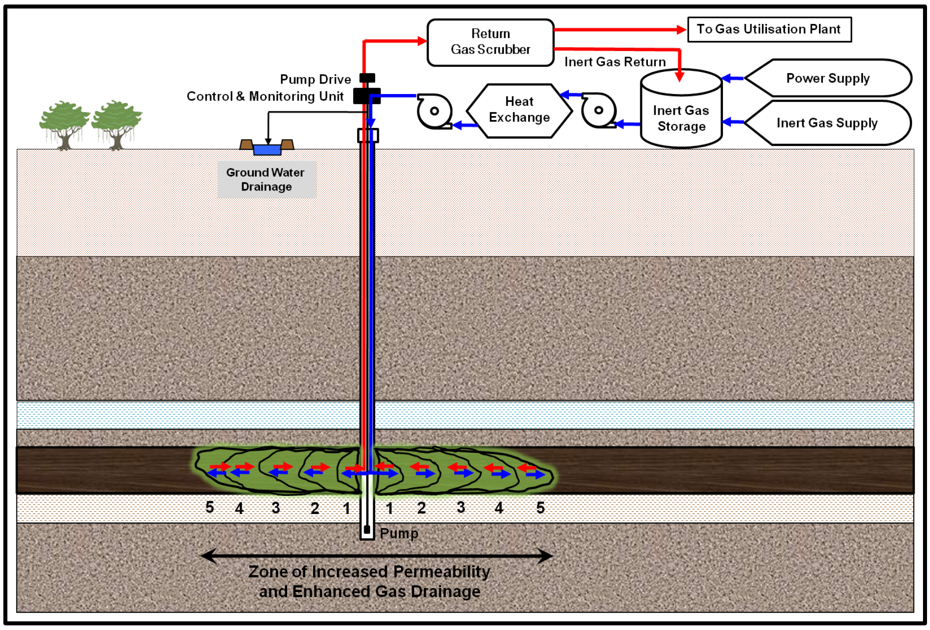

Figure 7 – Illustration of a five (5) cycle CIGI treatment to increase coal seam permeability coal production

The technical advantages of the CIGI treatment over conventional gas drainage and ECBM to enhance coal seam gas production are able to be realised through combining the following key characteristics of coal seam gas reservoirs:

- When inert gas is injected into a coal seam at a pressure greater than reservoir pressure and less than fracture initiation pressure the pores expand as the inert gas permeates through the coal seam, opening the cleat and penetrating deep into the formation;
- The presence of fractures and geological discontinuities are not detrimental to the process as they provide additional pathways that facilitate inert gas penetration into the coal seam thereby increasing the size of the treated zone;
- Due to the non-elastic nature of coal many of the flow paths that open during the gas injection stage will, to varying degrees, remain open when the gas pressure is released, thus increasing the number and size of potential gas flow paths within the coal seam (Harpalani and Zhao, 1989);
- At the conclusion of each inert gas injection cycle the injection borehole should be sealed shut for a specified time period to encourage the diffusion of seam gas from the coal matrix. The reduced partial pressure of the inert gas within the cleat and fracture network of the coal promotes CH_4 desorption from the coal matrix;
- The temperature of the inert gas should be increased prior to injection into the coal seam. The process of heat transfer from the injected gas increases the temperature of the coal seam thus energising the CH_4 gas molecules and increasing the rate of movement out of the coal matrix;
- Increasing the temperature of the coal also has a positive effect of reducing the gas sorption capacity of coal which in turn increases the relative degree of saturation of the CH_4 / inert gas mix;
- Given the mixed gas sorption isotherm of a CH_4/N_2 gas mix is lower than for pure CH_4, the process of injecting N_2 into a coal seam to form a mixed seam gas will serve to reduce the effective gas sorption capacity of the coal within the treatment zone thereby creating a localised increase in the relative degree of saturation, as illustrated in Figure 8; and

- During the gas production phase a reduction in pressure within the cleat and fracture network, and the change in effective stress, will cause the coal matrix to swell which may lead to a reduction in permeability. However this effect will be counteracted by the process of matrix shrinkage which occurs as CH_4 is desorbed. After having been subjected to multiple inject-hold-produce cycles the CH_4 content of the coal is expected to be substantially less than the pre-treatment state resulting in a net increase in effective permeability of the coal seam within the treatment zone.

Laboratory studies undertaken at the University of Wollongong (UoW) examined the effect of displacing adsorbed gases in coal using N_2 injection (Florentin, *et al*., 2010). The work involved injection of N_2 into coal samples saturated with binary CO_2/CH_4 gas in a high pressure triaxial gas chamber to a pressure of 3.0 MPa. Results indicate the injection of N_2 caused both gases to be displaced from coal delivering a 20% increase in CH_4 production from the coal samples. The study also recorded strain changes both perpendicular and parallel to coal layering/bedding, indicating an increase in coal permeability.

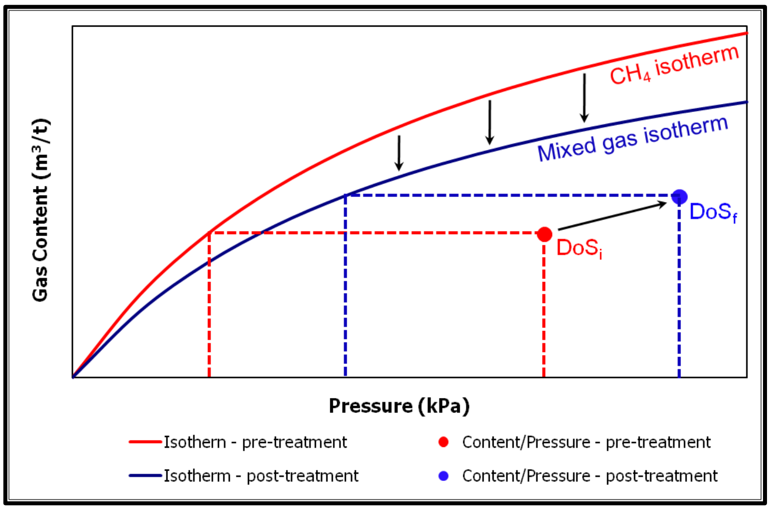

Figure 8 – Localised increase in degree of saturation (DoS) resulting from the proposed CIGI treatment

Figure 9 provides an example of a UIS drilling pattern to illustrate the effect of the CIGI treatment to enhance gas production from a tight coal zone that would otherwise be extremely difficult to drain using conventional drainage methods. If not effectively treated to stimulate gas production and reduce the gas content of the seam prior to scheduled development of the gateroads through the effected zone, production delays are likely. In this example a packer assembly would be securely installed within the borehole, nominally at least 25 metres from the borehole collar, prior to the commencement of the various branches that have been drilled into and through the tight coal zone. Multiple cycles of inert gas injection would then be applied to the boreholes through the packer assembly to allow inert gas to penetrate into the tight coal zone, as illustrated.

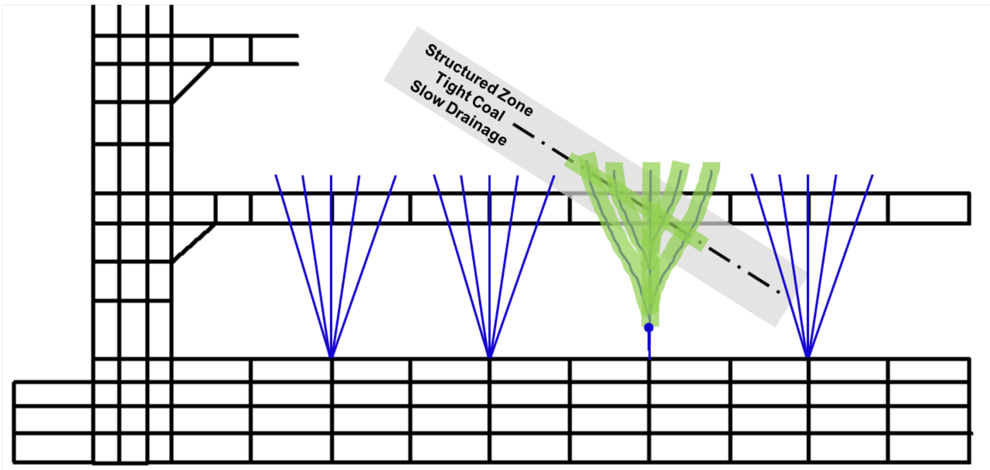

Figure 9 – Illustration of a CIGI treatment in a UIS drilling pattern to treat a tight coal zone ahead of gateroad development

Upon completion of the hold stage of each inert gas injection cycle, when the borehole is opened to release the gas, it is expected that the composition of the produced gas will be a combination of both seam gas and the injected inert gas. In the majority of coal mine gas drainage operations the production of a mixed gas, particularly if only utilising CIGI to enhance gas production from isolated tight gas zones, will not have an adverse effect on typical site based gas utilisation processes such as flaring and reciprocating gas engine electricity generators. Should the gas be produced for sale into the commercial natural gas market it can be expected that the gas will require additional processing to remove the inert gas from the drained gas mixture prior to sale and utilisation.

CONCLUSIONS AND RECOMMENDATIONS

A new technique to enhance coal seam gas production is proposed which involves the cyclic injection of an inert gas into the coal seam through a common injection/production borehole. The use of a single dual-purpose (injection/production) well eliminates the risk of bypass and low sweep efficiency that exists with conventional ECBM methods. The proposed cyclic inert gas injection technique utilises a combination of four independently proven processes (i) matrix swelling and shrinkage in response to gas adsorption/desorption, (ii) gas diffusion from the coal matrix in response to gas concentration gradient, (iii) reduced sorption capacity of coal at elevated temperature, and (iv) gas flow from the treated coal seam to the injection/production well due to pressure gradient upon completion of each inject-hold-release cycle. By cyclic inert gas injection it is proposed to increase the *in situ* gas condition, raising the mixed gas content and gas pressure, thereby raising the energy state of the seam gas surrounding the injection borehole to promote enhanced gas drainage performance from the coal seam. Through injection of inert gas, such as N_2, the isotherm of the mixed gas would be reduced relative to a localised increase in the mixed gas content of the coal seam, thereby increasing the degree of saturation and reducing the reservoir pressure reduction required to reach the critical desorption point on the isotherm.

The development of the cyclic inert gas injection method offers potentially significant benefits to coal mine operators in being able to improve coal seam gas drainage performance, particularly from tight coal zones that may be extremely difficult to drain using conventional methods.

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