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DEVELOPMENT OF IN-HOUSE COAL SEAM PERMEABILITY TESTING CAPABILITIES

Tim Cummins¹ and Luke Fredericks¹

ABSTRACT: Coal seam gas has historically been and still remains a major issue for underground Illawarra Coal’s mining operations in the Southern Coalfield. The control of seam and strata gas is essential to maintaining operational safety and mining continuity. The Resource and Exploration department surface exploration drilling program is currently investigating coal seam gas characteristics through the use of coal permeability testing (injection fall-off testing). The need for coal permeability testing is essential for assessing the reservoir gas characteristics in the seams. Coal seam structure and reservoir properties are closely related to regional and localised geological structure, which greatly influence in situ coal seam permeability and reservoir characteristics.

Testing is conducted on all seams within the mining stress relaxation envelope of the mined seam. Specialist software (PAN Systems) is used to process the data and interpretation is undertaken in conjunction with all other available data-sets.

Permeability testing is critical for understanding the gas regimes within Illawarra Coal’s four mining lease areas. Permeability data is needed for the Bulli through to the Tongarra coal seams primarily for mine gas drainage, evaluation of Coal Bed Methane production potential of deeper seams in the Illawarra Coal Measures and identification of zones of variable gas drainability and outburst potential.

INTRODUCTION

Coal seam gas has historically been and still remains a major issue for underground Illawarra Coal mining operations in the Southern Coalfield. The control of seam and strata gas is essential to maintaining operational safety and mining continuity. The Resource and Exploration department surface exploration drilling program is currently investigating coal seam gas characteristics through the use of Coal permeability testing (injection fall off testing). The need for Coal permeability testing is essential for assessing the reservoir gas characteristics in the Illawarra Coal measures.

There are a number of techniques for testing coal seams to determine its reservoir characteristics. These include, Injection Falloff, Drill Stem Test (DST) and Step Rate. To limit the standby time of the drill rig, only injection falloff tests are conducted. This involves isolating the individual coal seams and injecting fresh water at a constant rate to pressures below the predicted coal seam fracture point. The injection is then stopped and the hole sealed to allow the injected water to dissipate into the test interval. The injection phase usually takes 2 hours and the fall off 2-5 hours depending on the permeability, the lower the permeability the longer the pressure take to dissipate into the seam.

Illawarra Coal has conducts internal reporting and interpretations using the PAN System software with assistance from BHP Billiton Petroleum / Coal Bed Methane division.

REGIONAL GEOLOGY AND MINING OPERATIONS

Illawarra Coal has four operational coal mines including the Dendrobium Colliery in the south and West Cliff, Appin and Douglas Collieries in the north (Figure 1). The regional geology of the area is the Permian-Triassic sequences of the Sydney Basin. The stratigraphy of area consists of the Permian Illawarra Coal measures which are overlain by the Triassic Wianamatta and Narrabeen Groups (Figure 2).

Four major coal horizons within the Illawarra Coal measures are tested for coal seam permeability - the Bulli, Balgownie, Wongawilli and Tongarra seams. The Bulli seam is the mined seam for mines in the northern leases.

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while the Wongawilli seam is extracted by the Dendrobium mine. Longwall mining operations within each mining lease area are bounded by geological features such as faulting and intrusions. Coal permeability is used to better understand coal seam reservoir characteristics; these are directly related to geological features in the immediate area. Permeability testing is then combined with other geological data-sets for developing and planning future mine plan orientations and coal extraction zones.
COAL SEAM GAS FLOWS

Conducting permeability testing and interpretation of results is vital for understanding coal seam characteristics and gas flow regimes within Illawarra Coal Holdings. Gas flows from coal seams over and underlying the working economic seams flow into the goaf area after longwall mining. This effect increases the gas regime, and has the potential to “gas out” the mine. This significantly impacts on mining operations as mining continuity is disrupted and coal extraction cannot resume until the gas is drained to below safe working levels. Coal seams that contain high gas contents have the potential to outburst and injure workers. These zones must be drained to a suitable level before any mining can occur. Early identification of low permeability coals allows larger lead times for pre-drainage from underground or the surface if a long drainage time is required. The data obtained from permeability testing is incorporated in the planning of systematic gas drainage which can be implemented before the commencement of mining.

<table>
<thead>
<tr>
<th>AGE GROUP</th>
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<th>SUB-GRP</th>
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<td>PEBBLY BEACH FORMATION</td>
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<td>CFM</td>
<td>CLYDE COAL MEASURES</td>
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</table>

Fig. 2 - Stratigraphy of the southern coalfield

TYPES OF WELL TESTS

There are a number of techniques that can be used for testing coal seams to determine its reservoir characteristics, including, Injection / Fall off, DST and Step-Rate. DST involves promoting flow from the seam by controlled removal of the hydrostatic head by inserting an air cushion in the rods. Step-rate tests are conducted on injection wells to determine the maximum injection rate possible without fracturing the coal reservoir (Singh, and Krase, 1987). Step-rate testing consists of a series of constant rate injection periods, with rates increasing from low to high injection rates in a step wise fashion where each step period is of equal length of time.
Coal Permeability Injection / Fall Off Testing

BHP Billiton Illawarra Coal has been conducting in-house coal permeability testing since October 2004. Prior to this around 40 tests had been conducted and in the past year and a half an additional 130 tests have been done. Testing procedures have since been constantly refined, documented and updated allowing more reliable results to be produced, and less coal seams being fractured during well testing.

Injection / fall off testing involves injecting fluid into the reservoir to increase bottom hole pressure, and a subsequent shut-in period and pressure drop during the fall off period (Bourdet 2002). Permeability testing equipment lowered down the wire-line can be simply and efficiently added on to existing drilling equipment which eliminates the need for a separate testing rig. A schematic of the double inflatable packer system used in borehole testing equipment that is supplied to Illawarra Coal by AGE Developments is shown in Figure 3.

Permeability testing of Coal seams is conducted during the drilling of an exploration borehole which minimises stand by times and the duration of drilling the hole. Permeability tests are conducted on coal seams based on their potential gas content and contribution to the goaf, and reservoir thickness which is usually greater than 0.7 cm.

Fig. 3 - Equipment used for down-hole coal seam permeability testing (AGE Developments)
WELL TESTING PROCEDURES

Injection testing is conducted once the coal seam and a suitable sump (that includes at least 50 cm of the coal floor) has been drilled and recovered. The coal seam is drilled using fresh water to reduce the influence the drilling fluids, which have the potential to reduce permeability (Figure 4). The hole is first flushed with fresh water to further remove drilling fluids, particularly where mud was required to weight the hole. Drilling mud infiltrates the walls of the borehole increasing the skin effect, which will be discussed in the interpretation section. Appropriate amounts of drill rods are either added or removed so that the bottom of the packer will be set in the roof of the coal seam so that the test interval is the coal seam horizon.

Two dual recording down-hole memory gauges that record seam pressure and temperature at two second intervals are attached to the bottom of the inflatable packer. An air line that which inflates the packer system with nitrogen gas is also attached to the packer. The packer is then attached to the drill rig’s wire-line and run-in to the bottom of the hole to the bit seating sub on the diamond drill bit. The packer is then inflated at a nominal pressure 2.76 MPa (400 psi) over the hydrostatic pressure head of the borehole in order to overcome packer deflation. Hydrostatic head pressure in fresh water is determined by the following formula.

Hydrostatic Head Pressure = Depth of Coal * 1 meter of head of kilopascal (9.80)* 0.145. 0.145 is the conversion factor to pound-force/square inch (North).

Once fully inflated, the top packer seals the rods and the bottom packer which is seated below the drill bit seals on the borehole wall. The two down-hole packers are designed to seal the testing section off from the annulus. The rods are filled with fresh water removing any gas. The top of the drill rods is fully sealed at the surface with pack off seals that prevents water leakage.

A surface pump with hydraulic rate controls is used to inject water into the borehole via hose lines and flow gauges. This can inject water at a constant rate, pumping as little as 0.10 to 600 litres per hour, up to a pressure of 4.14 MPa (600 psi). The injection delivery rate from the pump is kept constant at the surface during testing once the down-hole pressure begins to rise.

Test data is recorded at the surface with a flow meter manifold that consists of a flow meter and a pressure gauge. The analogue pressure gauge displays down-hole pressure in the test interval to a maximum pressure of 4.14 MPa (600 psi) and the analogue flow meter records water volume pumped into the hole from the injection pump. A digital flow meter has recently been used to improve accuracy. The flow meter is connected via hose lines between the pump and the analogue flow meter and accurately records injection rates as small as 0.10 litres per minute to a maximum of 9.5 litres per minute and cumulative volumes injected down-hole.

Injection Phase

Testing involves isolating the individual coal seams and injecting fresh water at a constant rate to pressures below the predicted coal seam fracture point. This fracture point is calculated from the estimated Closure pressure (Pc) of the coal seam using known values of the Poisson’s ratio, overburden and pore pressures gradients in the borehole using the formula.

\[
Pc \text{ (estimate)} = \frac{v}{(1-v)} \times \text{Overburden Pressure} - \text{Pore Pressure}\]

Poisson’s Ratio = v, assuming v = 0.25 for Coal
Overburden Pressure = 2.5 SG (1.08 psi/foot)
Pore Pressure = 0.433 psi/foot.

Therefore: \(Pc = 0.33 \times (1.08 - 0.433) + 0.433Pc = 14.6 \text{ KPa/meter}\) (formula supplied by CBM group, Don McMillon pers comms).
The Injection phase is stopped before the estimated closure pressure is exceeded, or after a nominal period of 2 hours testing. As coal seam and interburden depth varies between exploration holes in the four mining areas and generally increases towards the north, values of closure pressure also increase. Values range from a minimum of 1.7 MPa (250 psi) in the Dendrobium area for the Wongawilli seam, up to a maximum of 3.3 MPa (480 psi) in the Tongarra seam in the Douglas Area. During the testing phase the injection rate is recorded. The rate may be altered due to the hole state during the test, surface gauges give an indication of bottom hole conditions.

Fall-off Phase

After injection has ceased, the fall-off period begins where pressure is allowed to dissipate into the test interval and down-hole pressure re-equilibrates to coal seam reservoir pressure. This period generally takes 2-5 hours depending on the permeability of the seam. The lower the permeability the longer the pressure takes to equilibrate to reservoir levels. The fall-off phase ends when the bottom-hole pressure increases, this increase in pressure is called the end point of the phase. The air line is bled off and the packer system is deflated and retrieved at the surface as the wire-line is wound up.

Contributing factors that were identified in well tests for early termination of the fall off phase included drill rods, packer, air line leakage and under pressured seams. Leaks in the system relating to testing equipment or coal seam properties result in pressure being dissipated back into the borehole. This pressure decrease can be accounted by leaking or loose fitting hose-line and air line connectors and/or gas leaks through the packer threads or the air line hose. In under pressurised coal reservoirs, the pressure is less than the hydrostatic head and during the fall off period, the down-hole pressure in the reservoir is reduced. This reduction causes a vacuum effect where water is drawn down from the hydrostatic head and is injected into the reservoir, thus raising the down-hole pressure and effectively ending the fall off phase.

IN-HOUSE REPORTING AND DATA COLLECTION

Illawarra Coal has identified the need to for internal interpretation and reporting of permeability test results. In-house interpretations done by Illawarra Coal allow for efficient, and cheaper modelling of data that is completed in a timely fashion as opposed to external reporting of results by outside consultancy firms. Data interpretations and modelling on a single well can be made immediately on data retrieval from the gauges.
Data Interpretation and Results

After initial collection the data from the two down-hole memory gauges are loaded into the PAN System software. Hole properties are then entered into PAN System

- Predicted seam pressures and temperature
- Hole diameter
- Test interval and wellbore storage coefficient, calculated from the volume of fluid in the test interval including the drill string.

Injection rates are assigned to the pressure time curve (Figure 5). Note the rate change at the start of the injection period.

![Injection fall off graph of raw pressure data Vs time with injection rates](image)

**Fig. 5 - Injection fall off graph of raw pressure data Vs time with the injection rates**

Both the injection and fall off periods are interpreted independently and the entire test is interpreted. The wellbore storage value is calculated from a single slope line, and the radial flow is selected using a zero slope line from a log-log graph of dimensionless time and pressure (Figure 6). These values are refined by the semi-log plot where the straight lines can be manipulated to better fit the pressure curve. Further refinement by fitting a type curve (Figure 7) which gives a variety of idealised curves with varying permeability and wellbore storage from the previously entered parameters.

The results are the run through computer generated matches, quick-match, to refine the interpretation. The final process involves a fully automatic computer generated match using the Auto-match function, Figure 7. This match involves selecting the injection and fall off data and injection rates and using the well parameters initially entered into the program to calculate values for the test. Numerous parameters are obtained from the test such as; permeability, wellbore storage, skin, temperature and the radius of the hole tested.

Complications during the interpretation result from numerous factors during the test period. Leaks in the system can occur through the rods, out of the headworks and past the packers. Leaks must be eliminated or false interpretations can result. Test induced changes to the test horizon also have a detrimental effect on the interpretation. Induced fractures during the injection period effectively restart the test period as down-hole conditions have been changed.
Fig. 6 - Log-log plot of dimensionless time and pressure

Fig. 7 - Test Result overview using quick match results
Fractures result when the critical seam fracturing pressure is exceeded during the injection phase. This pressure is estimated prior to the test, however, some seams are under-pressure, standing water level over 200 m below the potential hydrostatic head. This results in the fracture pressure being reduced by over 280psi. After observation of this phenomenon a falling head test is conducted to estimate the actual value.

PERMEABILITY MODELLING

Permeability testing is critical for understanding gas regimes for Illawarra Coal’s four mining leases. Permeability data is required for:

- Mine gas drainage planning
- Evaluation of Coal Bed Methane production potential of deeper seams in the Illawarra Coal Measures.
- Identifying tight coal zones, structures, coal fracturing
- Mine planning

Mine Gas drainage and mine planning

Permeability testing conducted on a regional scale over a mining lease area can provide a general flow regime of gas flow in the area and help manage and reduce the potential of outburst. Areas of poor drainage, and/or high CO₂ or CH₄ gas contents are identified, and drained well before coal extraction occurs. Permeability testing is used in conjunction with surface and underground geological mapping, and gas contouring for medium term mine planning.

Coal Bed Methane Production

Collection and analysis of well test data is vital in accurately estimating the in-situ natural fracture system permeability (Mavor and Saulsberry). Permeability testing can identify areas of over pressured and under saturated coal reservoirs, as well as identify areas of high potential for methane production.

Coal Permeability Modelling

Permeability measured in Millidarcy’s (md), is the ability of a fluid to pass through a porous medium (Mavor and Saulsberry). Permeability values across Illawarra Coal mining areas are highly variable due to geological conditions in the coal seam, and different structural domains between different mining lease areas. Average permeability values for coal seams across Illawarra Coal mine lease areas are shown in Table 1.

Coal Seam Permeability

Table 1- Averaged permeability results across Illawarra Coal mining leases

<table>
<thead>
<tr>
<th>Mining Lease</th>
<th>Appin</th>
<th>West Cliff</th>
<th>Douglas</th>
<th>Dendrobium</th>
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<tr>
<td>Bulli</td>
<td>3.6</td>
<td>2.0</td>
<td>1.7</td>
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<td>Balgownie</td>
<td>4.2</td>
<td>N/A</td>
<td>0.5</td>
<td>N/A</td>
</tr>
<tr>
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<td>0.3</td>
<td>2.6</td>
<td>1.6</td>
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<tr>
<td>Tongarra</td>
<td>0.5</td>
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Coal permeability is modelled by Illawarra Coal Resource & Exploration using Surfer 8 which is a gridding, contouring, and surface mapping program. Permeability values in Millidarcy’s are geo-referenced and contoured in 2D using the krigging method. Figure 9, shows a typical contour map derived from surfer. The Petroleum / Coal Bed Methane Division incorporates permeability results with other mine planning and geological data sets into Petrel software which calculates drainage rate potential throughout specific mine areas taking in consideration all geological conditions. The resulting data allow drainage plans to be created indicating what type of drilling program is required and what lead time to use. Limitations of permeability testing arise from 700 m drill hole spacing between exploration holes and potential unknown or unconfirmed minor structures such as faulting and intrusions that both act as a barrier to gas drainage and may significantly increase or decrease
Effective coal permeability. Individual test can be influenced greatly by localised geology. However the more tests conducted permit a region by region pattern to be developed.

![Fig. 8 - Simplified 2-D contouring of permeability results in the Appin area.](image)

**Coal seam geology and structural impacts on Injection well testing**

Structures play an important role in affecting local coal seam properties, coal permeability and the injection phase of well testing. Even the drilling process can affect coal seam properties with the vertical unloading of stress from retrieval of core can release stresses perpendicular to the drilling direction (North). Drill core that has been affected by faulting displays shattered coal, shear zone features, crumbling of core, as well as increased jointing and joint re-activation. Localised intrusions at coal seam level also increase jointing and fracturing within the coal seam.

Permeability testing can identify hard and soft coal zones that are not encountered with surface exploration boreholes. These zones are related to structural and intrusive features. Soft coal has a lower than expected fracture point due to the weaker structural properties of the seam. Interpretations on soft coal zones are difficult, though these zones have a good potential for gas drainability. Hard coal zones generally have lower permeability and a lower potential for lower gas drainability especially in CO$_2$ rich environments.

Cleating forms in response to local or regional folding and stress directions within the coal. Aquifers preferentially flow along the cleating and natural bedding features of the coal reservoir (Fetter 2001). Cleats within the coal can be forced open from well testing with increased down-hole fluid pressure, and flow can then be stimulated through them. Opening of cleat structures are observed in test results in a minor decrease in pressure, and a subsequent build up, skin values are negative on the Injection phase and positive on the fall off phase as they close with the decrease in down-hole pressure.

Under pressured coal seams contain less reservoir pressure than the hydrostatic pressure gradient of the borehole, hence the return flow rate to the surface is less than the rate it is injected in the hole from the delivery pump before the shut-in valve is operated. Over pressured seams contain a saturated coal matrix with a maximum amount of sobred gas under present reservoir conditions (Mavor and Saulsberry). The injection phase is generally shorter than for that of under pressured or general dual porosity reservoir systems.
CONCLUSIONS

BHP Billiton Illawarra Coal uses coal seam permeability testing for defining and assessing conditions in the coal reservoir system, and the effects of geological structure on the coal reservoir. Permeability testing is useful for defining regional gas flow regimes in order for maintaining continuity in underground mining operations, and for future mine planning purposes. The Resource & Exploration Department has developed and refined in-house procedures for permeability testing, and for interpretations on well test data using PAN system software. Interpretation of well tests using PAN software allows for a detailed and accurate analysis on coal seam reservoir properties, and responsiveness of a well to injection testing.

REFERENCES

MacMillon, D, 2005. Personal communication, 8 November.