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DEVELOPING METHODS FOR PLACING SAND-PROPPED HYDRAULIC FRACTURES FOR GAS DRAINAGE IN THE BULLI SEAM

K. Mills¹, R. Jeffrey², D. Black³, T. Meyer³, K. Carey³, S. Goddard³

ABSTRACT: BHP Billiton Illawarra Coal is seeking ways to significantly increase gas capture rates from in seam drilling programs in its underground coal mining operations. Hydraulic Fracture Technology (HFT), a joint venture between SCT Operations Pty Ltd and CSIRO Petroleum, is working with Illawarra Coal to develop the capability to enhance gas drainage rates in the Bulli Seam using sand-propped hydraulic fracturing based on HFT's experience at Dartbrook Mine where gas drainage rates were increased by 5 to 180 times.

One of the principal challenges for implementing sand-propped hydraulic fracturing in the Bulli Seam is the high vertical stresses that cause borehole breakout in horizontal holes drilled in coal. Borehole breakout effectively precludes the use of open hole straddle packers which are a convenient tool for placing multiple sand-propped hydraulic fractures in in-seam holes. Results of an initial six week trial undertaken at Douglas Project pit-bottom are described, which is aimed to developing the capability to install, grout and perforate casing so that straddle packers can be used for sand-propped hydraulic fracturing in overstressed boreholes. The primary goals of the pit-bottom trial at Douglas were to confirm that horizontal boreholes in Bulli coal at 500 m overburden depth are overstressed and unsuitable for use of open hole straddle packers, and to establish a method for installing, cementing and slotting casing so that straddle packers can be used to place hydraulic fractures. Both these goals were successfully achieved.

INTRODUCTION

Sand-propped hydraulic fracturing has been developed in the petroleum industry for stimulation of oil and gas wells, including coal seam methane wells. Several projects have been carried out in Australia and overseas with the objective of trialling stimulation of in-seam gas drainage holes by hydraulic fracturing in coal operations. A recent project conducted at Dartbrook Mine in 2002 (Jeffrey and Boucher, 2004; Jeffrey et al., 2005) demonstrated significant improvements in gas capture rates. In hard-to-drain coal the gas drainage rate was increased by up to 180 times, with the rate increasing over time.

The sand-propped hydraulic fracturing technique involves pressurising a section of borehole with water at sufficient pressure to overcome the *in situ* stresses in the ground and the tensile strength of the coal. Ideally a single vertical fracture develops and grows out from the borehole for a distance of 20-50 m in a direction parallel to the major horizontal principal stress. Sand propping involves the introduction into the fracture of specially graded sand suspended in the water flow. At the end of the treatment, the sand remains in the fracture and props the opposite sides of the fracture apart to provide a conductive drainage path back to the borehole. At Dartbrook, the *in situ* stresses were such that the horizontal boreholes remained stable enough for open hole straddle packers to be used to place the sand-propped hydraulic fractures. However, in the Southern Coalfield, the vertical stresses are typically too high for the borehole to remain stable and so the sides of horizontal boreholes drilled in coal are routinely overstressed. Failure of the coal caused by the overstressing results in borehole breakout, which enlarges the borehole in a horizontal direction. If borehole breakout is severe enough, it stops straddle packer systems from sealing and causes damage to the packers, thereby preventing their effective use, unless some sort of casing system can be developed that improves the surface against which the packers are set.

Borehole breakout is regarded as a major challenge to the effective implementation of sand-propped hydraulic fracturing in the Southern Coalfield. The work described in this paper is aimed specifically at finding suitable strategies to improve the condition of the borehole so that straddle packers can be used successfully. The concept of casing the hole is regarded as the approach most likely to be successful.

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A staged work program was developed with the intention of moving incrementally toward the ultimate goal of giving Illawarra Coal the in-house capability to place sand-propped hydraulic fractures. The stages of the work program involve:

1. Confirming the expectation that horizontal boreholes in coal are not suitable for setting straddle packers in the borehole without some sort of casing system.
2. Developing and testing suitable casing and cementing systems for deployment in overstressed boreholes.
3. Developing and testing a slotting system capable of perforating the casing to give access to the formation.
4. Testing a range of casing systems in an environment where the boreholes are subject to full overburden stress, and therefore likely to have broken out.

A trial site at Douglas Project pit-bottom was chosen as a convenient site for the casing, cementing and slotting tests. The site was located so that full overburden loading conditions were present and the trial did not cause undue disruption to the overall mining operation.

CASING SYSTEM TRIALS AT DOUGLAS PROJECT PIT-BOTTOM

The stages of the work program described in this section relate mainly to the Douglas Project pit-bottom trial, but some of the results from earlier casing trials conducted at CSIRO Petroleum in Melbourne are included where relevant.

Site Description

Figure 1 shows a plan of the Douglas Project pit-bottom trial site. The roadways in this area were developed some 25 years ago. A major geological fault structure is located immediately to the north-east of the site. The seam RL at the site is approximately 310 m below AHD. The surface is approximately 190 m AHD, so the overburden depth is nominally 500 m indicating a vertical stress of approximately 12.5 MPa. The seam thickness is nominally 2.2 m.

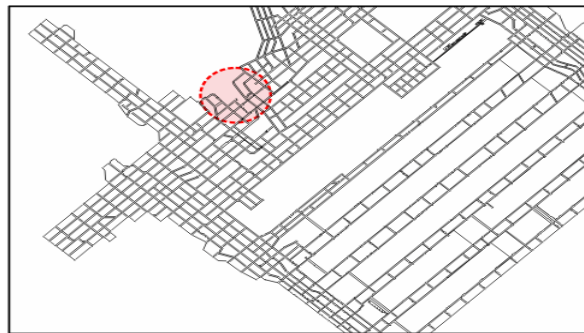


Fig 1a: General location of Douglas site.

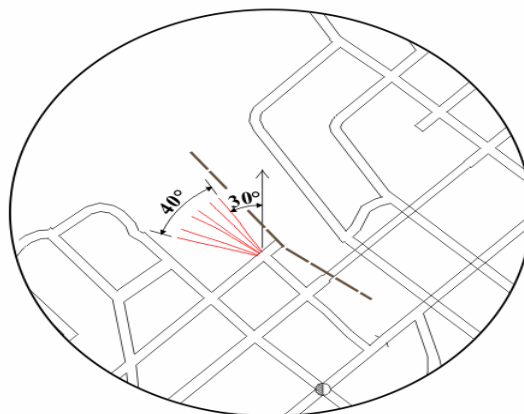


Fig 1b: Layout of boreholes at Douglas pit bottom.

Six holes were drilled using a downhole motor at a nominal diameter of 96 mm. The intention was to drill these holes so that some were dipping down, some up and others with both up-dip and down-dip sections. The alignment of the holes was surveyed using the downhole survey tool. Figure 2 shows a summary of the hole alignments in plan and long section.

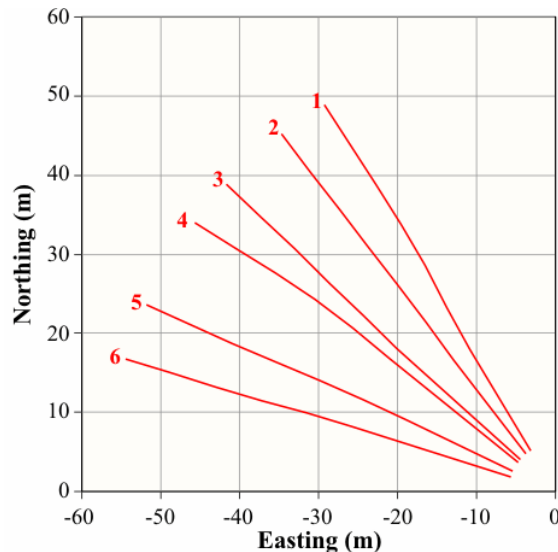


Fig 2a: Plan of borehole alignments based on downhole surveying.

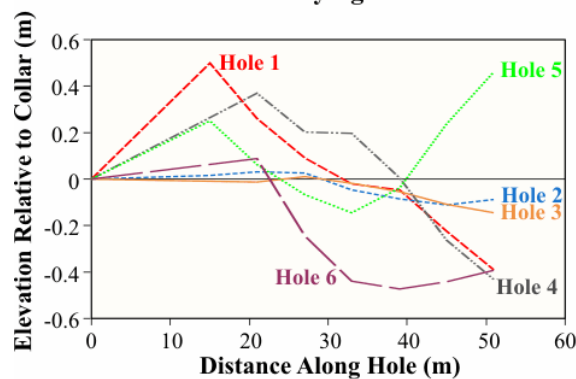


Fig 2b: Borehole alignments shown in section relative to borehole collar.

Steel standpipes were installed in all the holes by the drilling crew. The standpipes were 9 m long in Holes 1 and 2 and 12 m long in Holes 3-6. The stand pipe used was nominally 4-inch diameter and had an internal diameter of 105 mm. A 4-inch BSP coupler was attached with a short BSP to Victaulic adapter fitted to the other end of the coupler. The cement head used during the trials was attached to the Victaulic fitting using a quick-set Victaulic clamp. Figure 3 shows a photograph of the site with the holes shown painted in red on the rib and numbered from 1 to 6.

Caliper Logging

Holes 2-6 were logged using the eight arm caliper logging system developed in ACARP Project C12021 (Jeffrey et al. 2005). Two of these holes were blocked with coal debris. When Hole 1 was flushed out ahead of caliper logging, the hole was blocked a short distance beyond the end of the casing and large chips of coal were observed coming out of the hole. This hole was not logged because the risk of the caliper tool becoming jammed in the hole was considered to be too high.



Fig 3: Photograph of Douglas pit bottom site showing the location of the six 50m long boreholes used for the casing trial.

Figure 4 shows the results of caliper logging in each of the holes. The caliper was logged continuously as it was retracted along the hole, but the depth was only measured every 0.1 m. In most of the holes the instrument was able to be oriented within 15° using a downhole tilt indicator, so that the arms were oriented vertical, horizontal, 45°-225° and 135°-315°. The maximum and minimum values measured on any of the arms over each 0.1 m interval are shown as well as the average value measured on each arm.

The caliper logs show that the boreholes have a horizontal diameter greater than the as-drilled diameter over a substantial length of the hole. The horizontal diameter is generally greater than the vertical diameter and ranges up to about 180 mm in some sections. The vertical diameter is typically less than the nominal diameter of the hole. This may be a result of closure due to borehole breakout, but it may also be a function of debris in the bottom of the hole.

The key result of the caliper logs is that the boreholes are unsuitable for using open hole straddle packers for hydraulic fracturing without some sort of casing system. If straddle packers were used in these boreholes without casing, the packers would not be expected to provide an effective seal at the treatment pressures of 10-15 MPa and the packers would rupture on a regular basis.

Casing Selection

Three types of casing were selected for testing for the pit-bottom tests at Douglas Project; 76 mm outside diameter steel casing with a 3.5 mm wall thickness, 85 mm outside diameter fibreglass casing with 8 mm wall thickness and 84 mm outside diameter PVC casing with 6 mm wall thickness. Four holes were cased using steel casing, one with fibreglass and one with PVC casing. The steel casing was supplied in 3 m lengths and externally coupled. The PVC casing was supplied in 6 m lengths with upset ends. The 3 m long fibreglass casing sections had integral threads and upset ends.

The main criteria for casing selection relate to ease and robustness of handling, ability to resist external collapse pressures during grouting and hydraulic fracturing, cuttability by the longwall shearer and ease of separation from the coal product stream once it has been cut. Thin walled steel casing has advantages in all these areas except perhaps cuttability and is the preferred option for routine use.

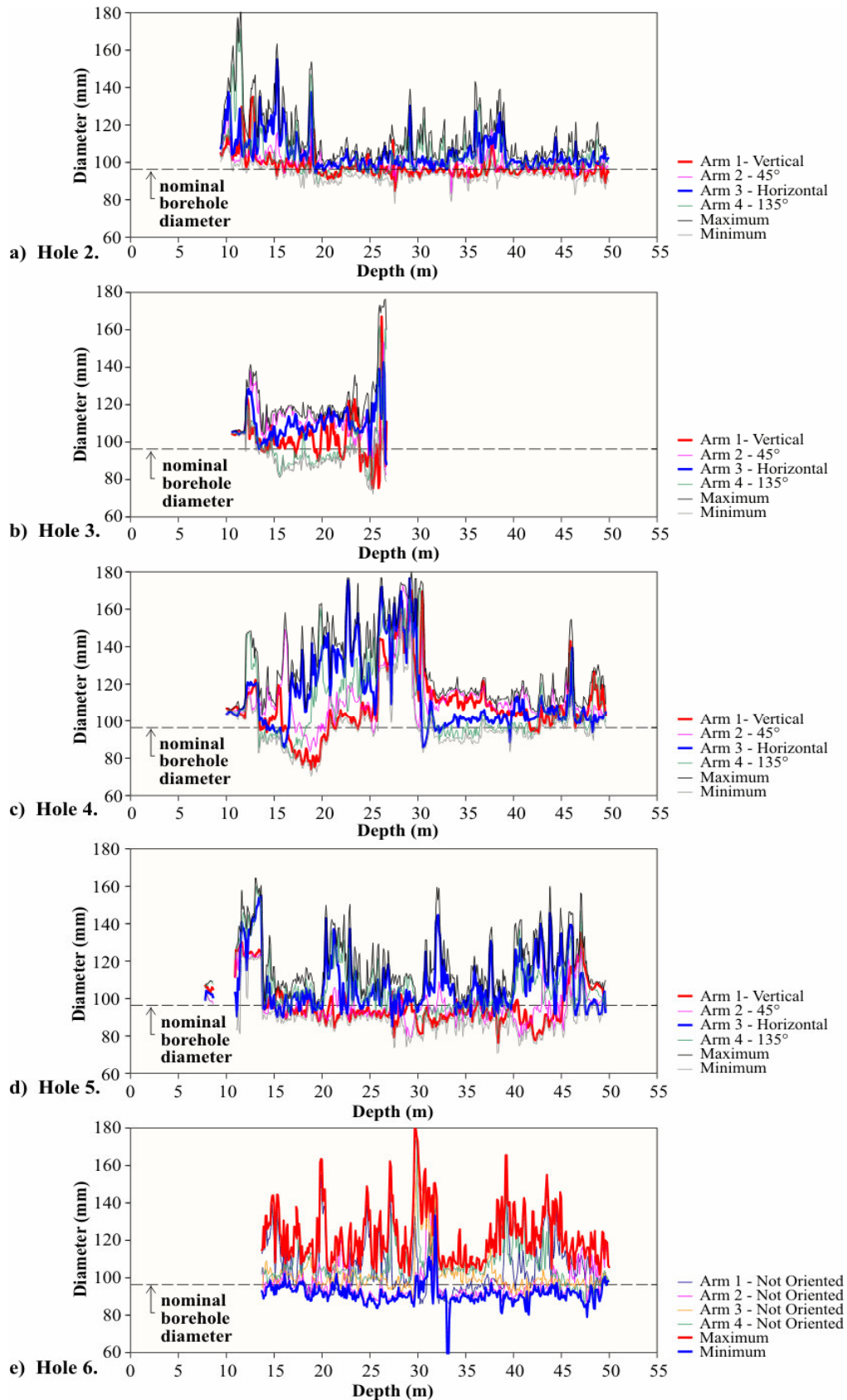


Fig 4: Caliper measurements from Holes 2-6 at Douglas.

Cement System

The cement system used in the trial was designed by Schlumberger Oilfield Services in Perth. They carried out tests to establish the optimum mixing ratios for the locally available general purpose Portland cement used in the trial. An antifoaming agent, a dispersant and a gas block agent were used in the mix. Mixing is carried out by adding the liquid additives to the mix water and stirring well. The cement is then added to the liquid as stirring continues so that no lumps form. The cement is pumped into the casing and returns up the annulus outside of the casing. When sufficient cement has been pumped to fill the annulus, a displacement plug is placed in the casing at the collar of the hole and pumped down the hole with water. The displacement plug acts as a barrier separating the cement from the water. When it reaches the end of the hole, there is no grout inside the casing, and provided there are no substantial loss zones, the grout should have returned up the outside of the casing to the collar of the hole.

Perforation System

Once the casing system has been installed, it is necessary to gain access to the coal seam from inside the casing string by perforating the casing. There are various systems available ranging from explosive perforators to mechanical cutting devices. The system that is most compatible with the equipment used for sand-propped hydraulic fracturing is an abrasive slurry system based on a sand-water system injected through a jet at high pressure onto the casing. This slurry jet cuts a slot in the casing, through the cement and into the coal within a few minutes (depending on the pressure available). By rotating the tool, a circular slot can be formed. By withdrawing the tool, a linear slot is formed.

A slotting tool was developed, tested and modified at CSIRO Petroleum in Melbourne. The tool jets were sized so that the steel casing could be cut in about 4 minutes. PVC and fibreglass casing required less time to cut than steel. Figure 5 shows a section of steel casing cut under these conditions. For this test, a short section of casing was encased in a concrete block and then cut using a sand-water slurry pumped at 120 lpm and 13.79 MPa (2000 psi) for 4 minutes. The openings shown in Figure 5 would provide more than enough access to the coal seam for carrying out hydraulic fracture stimulations. Higher cutting pressures are expected to reduce the slotting time further.



Fig 5: Slot cut into steel casing in yard test, using abrasive slurry.

Casing Installation

The Douglas pit bottom work program provided an opportunity to trial methods to place and cement casing into medium length holes, perforate the casing using an abrasive slotting tool and test the integrity of the hydraulic seal provided by the cement. The hydraulic conductivity of the coal was characterised by carrying out injection/falloff well tests. The procedure followed for each hole was generally as follows:

1. Run an HQ-size bit on the end of a drill string into the hole while rotating the bit and flushing with water. This cleaning operation ensured the hole was at least 96 mm in diameter and removed debris that may have collected in the hole since drilling.

2. Run the casing string into the hole. A casing shoe valve was installed on the first length of casing run to act as a check valve – allowing fluid to pass from the casing into the hole but not in the opposite direction. Typically the casing could be pushed in by hand for 25 m or so and then was pushed by the drill rig for the rest of the hole length (50 m).
3. Install the cement head on the stand pipe and connect the casing into the cement head so that the annulus and the inside of the casing were isolated from one another. The hole was then filled with water from the pit water supply, allowing the system to be checked for hydraulic integrity.
4. Mix and pump a volume of cement into the casing. After the first hole tested, the volume of cement mixed was standardised at 450 litres per hole. This was pumped into the casing and then the displacement plug was pumped down the casing to push the cement out into the annulus.
5. Wait 4 to 12 hours for the cement to cure. Then remove the cement head.
6. Test the cement hydraulic seal by notching the casing and then injecting fluid through the notches while monitoring for leakage along the cement filled annulus.
7. Carry out coal characterisation tests as required.

CHARACTERISATION TESTING

Two types of characterisation tests were used at Douglas.

Step-Rate Tests

The step-rate test involves injecting into the entire hole or into a single slot at a constant rate for a fixed period of time. The rate is then increased to a higher fixed rate and injection at that rate continues for the same fixed period. Typically 4 to 8 steps in rate are used for one test.

When injecting into the entire hole, the test results give an estimate of the injection pressure versus injection rate response for the hole. This test is useful in estimating what the rate of loss of a particular fluid (for example, cement or water) will be into the coal if the hole is pressurised to some fixed level. A pressurised hole will lose fluid at a decreasing rate if the pressure is held constant, but this test provides a first order estimate of the loss rate for short pressurisation intervals (such as during cementing).

As a fracturing response test, the step-rate test is used to estimate the fracture extension pressure. The fracture extension pressure is the pressure required to extend a hydraulic fracture and is an upper estimate of the minimum principal stress magnitude.

Injection/Falloff Well Test

In the injection/falloff well test, water is injected through a slot at a constant low rate such that the pressure rise does not approach the fracturing pressure. A short test involves 1 to 2 hours of injection followed by 1 to 2 hours of falloff. A more standard test in coal would require 4 to 6 hours of injection and up to 12 hours of falloff. Short tests were used at Douglas to see how these tests might be carried out in a production setting and to estimate the coal parameters.

The data from an injection/falloff well test are analysed to obtain the permeability of the coal and the initial pressure in the coal. In addition, a parameter called the skin is obtained which is an indication of the permeability damage or stimulation effect existing locally at the borehole.

RESULTS

All six holes at the Douglas pit bottom site were cased during the project although it was not possible to fully install casing in Hole 1 because of hole instability. Casing strings were installed and cemented in the other five holes.

In general, there were no difficulties installing the casing, provided the holes were flushed immediately beforehand using a 96 mm drill bit and drill rods. The casing was able to be pushed into the hole by hand to about 25 m before it was necessary to use the machine. However, without cleaning the hole first, the casing was typically not able to be run much past the end of the standpipe.

Cementing through the casing with return along the annulus proved to be more challenging, mainly because of equipment limitations. The cement system was able to be mixed without difficulty in two high-shear mixing tubs

capable of holding up to 450 litres of cement at a time. The cement was then pumped into the hole using a 2 MPa progressive cavity pump. In several of the holes, grout return was observed at the collar of the hole. But power outages, blockages and insufficient pump pressure meant that in several holes, the displacement plug was not able to be pumped to the end of the casing. Once the steady flow of grout was interrupted, it proved difficult to get it restarted again with the equipment available.

A small gap was observed to occur at the top of the cement annulus in some of the holes. While the existence of a small gap, of width less than about 1mm, is not necessarily a problem for subsequent treatments using sand propped hydraulic fracturing, it is nevertheless an inconvenience that would be best to eliminate.

If a gap is present, the casing string needs to be strong enough to withstand the external fluid pressure when injection fluid leaks through the gap along the outside of the casing. The loading on PVC, fibreglass, and steel casing required to cause collapse is about 0.3 MPa, 3.5 MPa and 13 MPa respectively. Steel casing is therefore the preferred option from the perspective of collapse pressure at treatment pressures expected to be of the order of 10 MPa. Fracturing through slots in the casing can occur even if there is some fluid loss into the gap. Once sand is started, it will bridge across and plug any small gaps.

The gap at the top of the casing is caused by various processes.

- The cement may settle slightly during curing and free water rises to the top. If this occurs, the free water leaves a small gap along the top of the hole. Careful mixing of the cement and use of dispersants limits the amount of free water in the mix.
- If the displacement fluid (typically water) bypasses the displacement plug or leaks from any of the casing couplers, it can channel back along the casing, preferentially at the top as it is of lower density, and form a gap or further enlarge any gap that may already exist.
- Fluid pressure in the seam can drive water (or gas) into the hole after cementing. This fluid will tend to separate at the top of the hole. Maintaining pressure in the cement that is above the pressure in the coal will eliminate this problem.

By pumping grout into the gap at the collar, it was found to be possible to effectively seal up any gaps that had formed, but there is clearly benefit in not having any gap form in the first place. Pumping cement into a slot placed some distance along the casing could also be used, but was not attempted during the Douglas trials.

Slotting of the casing using the abrasive jet proved to be relative easy. With the pressures available, it took several bags of sand and some 4-10 minutes of pumping to cut a circular slot in the steel casing. Higher pressures and better control of the rotation rate is expected to reduce this timeframe to just a few minutes in normal operation.

STEP-RATE TEST RESULTS

A step-rate test along the full length of the hole was carried out in Hole 6 using water. The hole was first filled with water from the pit-water supply. The step-rate test was then carried out by injecting into the casing (before it was cemented) through the cement head. The return valve on the annulus was shut during the injection so the water injected was forced into the seam. The highest rate achieved was 55 litres per minute and the pressure during this step reached 2 MPa.

The water test establishes a reference point for comparison to the step-rate test carried out in Hole 2 using cement. After starting the cementing and obtaining cement returns through the annulus at the collar to confirm that the entire hole was full of cement, the annulus return valve was closed and injection was carried out in ever-increasing rate steps. The final step was at 6 litres per minute and the pressure reached 1.8 MPa. The cement loss rate at 1.8 MPa was therefore 6 lpm. It is anticipated that this rate would decrease with time.

The fluid pressure in the seam at this site is very low because the coal contains virtually no gas and has been draining into the mine openings for about 25 years. Therefore, the 1.8 MPa is acting against essentially no hydraulic pressure in the seam and represents a pressure above the seam pressure.

In a gassy area, the seam pressure might be 3 MPa, but to force cement into the seam the pressure would have to be increased above 3 MPa and if the cement pressure were increased to 4.8 MPa the loss rate might be about 6 litres per minute per 40 m of hole (allowing for the stand pipe). The intention in gassy areas is to keep the cement

pressure just above the gas pressure in the seam so the loss of cement under these conditions would be expected to be less than 6 l pm per 40 m of hole.

A short well test was conducted through one of the slots at 25 m in Hole 4 after re-cementing of the annulus. The well tests provide an order of magnitude estimate of seam permeability and pressure at the site. Water was then injected for 1 hour at 1.47 litres per minute. The falloff in pressure after shutting in the slot (isolating the pressurised fluid in the slot and allowing it to drain away into the formation) was then recorded for 1 hour.

Figure 6 shows the analysis of the falloff data from the well test in Hole 4 at the 25 m slot. This analysis is considered to give the best estimate of reservoir pressure. Figure 7 shows a second analysis plot of the falloff data for the well test in Hole 4 at the 25 m slot which gives the best estimate of permeability.

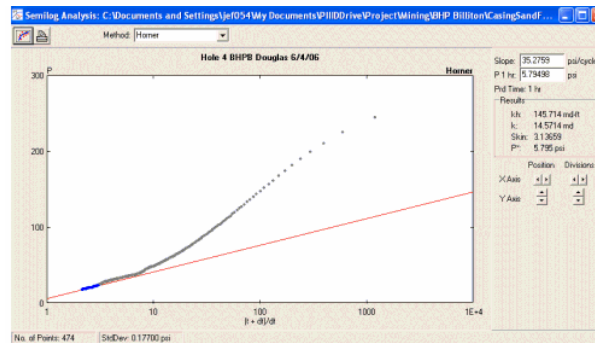


Fig 6: Analysis plot of the falloff data from the well test in Hole 4 at the 25m slot. This analysis gives the best estimate of reservoir pressure.

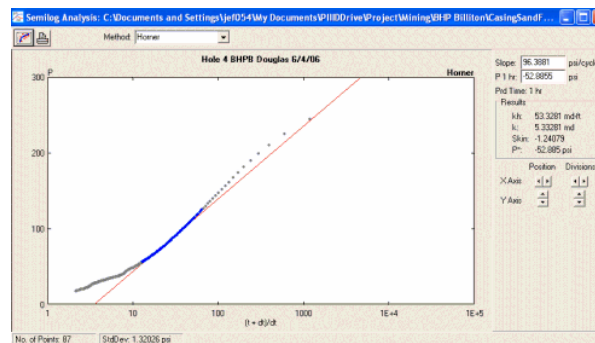


Fig 7: Second analysis plot of the falloff data for the well test in Hole 4 at the 25m slot. This analysis gives the best estimate of permeability.

The flattening of the falloff curve in the Horner plot is indicative of a test carried out by injecting water into an unsaturated seam. The early part of the curve (larger Horner time) where the slope is greater is used to obtain an estimate of the seam permeability. In later times (small Horner time) the pressure is affected by the low gas pressure in the reservoir and the slope tends to flatten and approach the reservoir pressure asymptotically. The intercept of this portion of the curve with a Horner time of 1 provides an estimate of the reservoir pressure. If more accurate estimates of permeability and reservoir pressure are required, the injection and falloff portions of the test should be extended to several hours each.

Notwithstanding the short duration of the tests, permeability of about 5md and a reservoir pressure of about 34 kPa (5 psi) seem reasonable estimates based on the site location. It should also be noted that this analysis assumes radial flow conditions exist while such a short test is expected to take place almost wholly in a spherical flow period.

CONCLUSIONS

The primary goals of the pit-bottom trial at Douglas were to:

- Confirm that horizontal boreholes in Bulli coal at 500 m overburden depth are overstressed and unsuitable for straddle packers without a casing system.
- Establish a method for installing, cementing and slotting casing so that straddle packers can be used.

Both these goals were achieved.

Caliper logging showed that horizontal gas drainage holes drilled in coal at 500m overburden depth are subject to vertical stress sufficient to cause large amounts of borehole breakout and compromise the effective use of straddle packers in open holes. The horizontal diameter was often larger than the 96 mm nominal hole size and in some sections of the holes reached 180mm indicating considerable breakout from vertical overstraining of the borehole.

Three different kinds of casing, steel, fibreglass and PVC were successfully installed, cemented and then slotted using an abrasive jet system. Of these, steel was confirmed as the most suitable for routine use because of its superior strength and collapse properties, and the ease with which it can be separated from the coal product stream using magnets.

A petroleum well cement system was used. The cement contained a gas block additive which helps resist gas from entering and channelling through the cement before it cures.

The cementing operations at Douglas Project pit-bottom have proved the concept of using a cement head and a displacement plug system to place the cement into the annulus.

Steel and fibreglass casing were notched successfully using an abrasive jet slotting method. Increased pressure during slotting is expected to reduce the time to cut slots in steel casing to just a few minutes. The sand used for slotting was carried out of the hole to the collar in the returned water and the slotting tool was easily moved further out of the hole after each slot was cut.

The PVC string was cemented in with pressure inside the casing exceeding 4MPa without bursting the casing. The casing did not collapse over the 17 m length that could be inspected from the collar. Likewise, the fibreglass casing withstood the cementing pressures without damage and packers were run to 35 m with no difficulty. However, setting packers to pressures above 20 MPa, anticipated for placing sand-propped fracture, may not be possible in these lower-strength casing materials. Steel is by far the strongest casing material used and can withstand high external and internal pressures without damage.

There does not appear to be any reason why this method of casing installation, cementing and slotting would not be effective as a practical means for allowing sand-propped hydraulic fracturing to be placed in overstressed coal holes using straddle packers.

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