2004

Sand Propped Hydraulic Fracture Stimulation of Horizontal In-seam Gas Drainage Holes at Dartbrook Coal Mine

R. Jeffrey
CSIRO Petroleum

C. Boucher
Dartbrook Coal

SAND PROPPED HYDRAULIC FRACTURE STIMULATION OF HORIZONTAL IN-SEAM GAS DRAINAGE HOLES AT DARTBROOK COAL MINE

Rob Jeffrey [1], Christian Boucher [2],

ABSTRACT: Longwalls 107, 108 and 109 at Dartbrook Coal Mine contained coal with a high gas content and low permeability. Horizontal in-seam drain holes were found to have low gas production rates compared with drainage rates in previous panels. Hydraulic fracture stimulations, using water and sand, were therefore carried out in three boreholes in Longwalls 109 and 108 at Dartbrook to assess the effectiveness of sand propped fractures in stimulating gas drainage from in-seam boreholes.

Boreholes 108-10-10 and 108-7-1 were stimulated with 20 and 10 fractures respectively and, on average, 100 kg of sand was placed into each fracture. The fractures placed into LW 109 were to be mined and mapped, but operational constraints precluded mapping of these fractures.

The stimulations produced a significant increase in gas drainage rates from the two boreholes. Hole 108-10-10, which ran perpendicular to the major joint system in the seam, increased its early gas rate by a factor of about 180 while hole 108-7-1, which was drilled parallel to the joint set, increased its rate by about 22 compared to pre-stimulation rates. The stimulated gas rates continuously increased for several weeks and the higher rates were sustained for the entire period the holes were monitored.

Based on the higher stimulation effect achieved in hole 108-10-10 (drilled perpendicular to the jointing) compared with hole 108-7-1 (drilled parallel to the jointing), target drainage holes drilled perpendicular (north-south) to the jointing are better stimulation candidates.

Fracture modeling suggests the sand proppant bank may extend to 15m from the borehole. The unpropped portion of the fracture may extend to more than 40m. A purpose-built fracturing system was developed and used at Dartbrook to stimulate holes that covered most of LW109. This full-scale enhancement of gas drainage was successful and allowed efficient mining of that panel.

INTRODUCTION

Hydraulic fracturing is applied routinely in the petroleum industry to stimulate oil and gas wells. Typically, a stimulation treatment consists of a clear pad fluid injected at rates and pressures sufficient to initiate and extend a hydraulic fracture. Once a fracture of sufficient size and width has formed, proppant is added to the fluid and pumped into the fracture as slurry. The proppant is carried into the fracture and, after the injection stops, serves to prop the fracture open to form a permeable channel in the reservoir through which the hydrocarbons can be produced. As the well is produced, the propped hydraulic fracture connects the wellbore to a large surface area of the reservoir and provides a conductive pathway to carry the oil or gas back to the well. Such treatments are commonly done to stimulate coal seams to accelerate production rates from coalbed or coal seam methane wells. Both vertical and horizontal oil and gas wells are also candidates for fracture stimulation.

Proppants are selected based on the requirements that they are permeable and strong enough to prop the fracture open without crushing. Round, spherical and sieved sand is the lowest cost proppant material commonly used and is able to withstand fracture closure stresses of up to about 35 MPa. In higher stress environments, more costly but stronger resin-coated or ceramic proppants are used.

[1] CSIRO Petroleum
[2] Dartbrook Coal

Previous experience at other sites

Several projects to investigate propped fracture stimulation of drain holes have been carried out in Australia and overseas. The earliest work that we are aware of was carried out in Queensland by the Department of Mines. In late 1979 and early 1980 the Department conducted a four month long research project to investigate hydraulic fracture stimulation of horizontal drain holes (Croft, 1980). The project's intent was to design and test a system for pumping fluid and sand into horizontal holes at pressures and rates sufficient to induce hydraulic fracturing. The plan required the pump and other equipment to be located underground next to the coal rib. A number of equipment developmental problems were encountered and no fracture treatments were successfully performed. However, the concept of stimulating horizontal holes drilled into the seam from underground is, essentially, the same as have recently been undertaken in the trial at Dartbrook.

Fracture stimulation work is now done in horizontal wells in the petroleum industry on a fairly frequent basis (Walker, Ehrl, and Arasteh, 1993; Weijers, et al., 1992). Such wells are drilled into conventional reservoir materials (sandstones or limestones) and are stimulated by fracturing for the purpose of establishing a better connection with the reservoir. Multiple fractures can be formed during injections into long sections of open horizontal wells in a single treatment and most of the fractures formed tend to be located over the first third of the horizontal section of wellbore (Grieser, Wiemers, and Hill, 1999).

When a long section of a borehole is treated without attempting to isolate a small zone, the hydraulic fracture will initiate and grow from the point or points where pre-existing weaknesses in the borehole exist. Once a fracture starts growing, it typically will continue to extend at a lower pressure than required to initiate other fractures along the borehole. Therefore, trying to treat a long section of hole in one injection may, in the worst case, only produce one major hydraulic fracture in the entire open section of the hole.

To partially overcome this problem, diverting agents, which are materials added to the fluid that act to block the entry to the fractures, are sometimes pumped at various times during these treatments in order to divert the fluid and proppant from an established fracture into a new area of the wellbore. Control over the number and position of fractures formed in open-hole treatments like this is limited and the diverting agents have the potential to damage the permeability around the wellbore. Initiating multiple fractures or extending and propping too few fractures, are problems that can be avoided by limiting the length of the interval being treated, usually by casing the well and then selectively perforating a small zone for each treatment. Treating a long open hole section of a horizontal well does have the significant advantage of not requiring packers to be set at a number of positions along the wellbore.

In 1993, a project was undertaken to perform several hydraulic fracture stimulations in horizontal drain holes at the Soldier Canyon Coal Mine, in Utah (Kravits, 1993). Five propped fractures were placed along a 2505 foot-long horizontal borehole. Gas production from the hole increased by 46 percent and then, over a period of about 4 weeks, declined back to pre-stimulation rates. Stress conditions at this site in Utah are suspected to have allowed the hydraulic fractures to grow vertically into overlying and underlying rock, resulting in poor stimulation of the coal seam. Use of plastic beads rather than conventional sand proppant also caused problems in mixing, pumping, and placement of proppant.

ACARP project C4033 was undertaken to trial propped fractures for stimulation of horizontal in-seam boreholes (Jeffrey, 1999). In June 1996, field tests were carried out at Central Colliery near Middlemount, Queensland. Pumping and mixing equipment was located on the surface and the fluid and sand were pumped down an HQ borehole to a cut-through in the 306 maingate at Central. From the cut-through, the fluids were carried into a horizontal borehole drilled into the 307 panel. A straddle packer system was deployed in the horizontal drain hole. Water and sand bypassed the packers at injection pressures well below fracture initiation pressure.

The bypass is thought to have occurred via fractures or structures in the coal that ran along the length of the packers at the test site. Axial fractures along the packers may have formed because stress conditions, in combination with pressure exerted on the borehole by the inflated packers, were sufficient to split the borehole. Seam conditions at this site were difficult and several attempts were made to drill other holes without success. These results illustrate that some seams may not be suitable candidates for fracture stimulation by running packers in open hole sections and may require significant modifications to the hole completion or fracturing procedure.

IN-SEAM DRAINAGE AT DARTBROOK

At Dartbrook coal mine, the Wynn upper seam is extracted by longwall mining methods. The longwall operations extract 4m of the 28m thick mega seam, leaving a coal floor and roof. Figure 1 contains a plan showing Longwalls 8 and 9. The fan-array holes shown, that are drilled essentially across the panels, are the standard in-seam drainage holes used at Dartbrook. The holes drilled for the sand propped hydraulic fracturing work are shown with thicker lines and are aligned mostly along the panel length. Fractures placed in these holes would then extend east-west across the hole and parallel to the panel width.

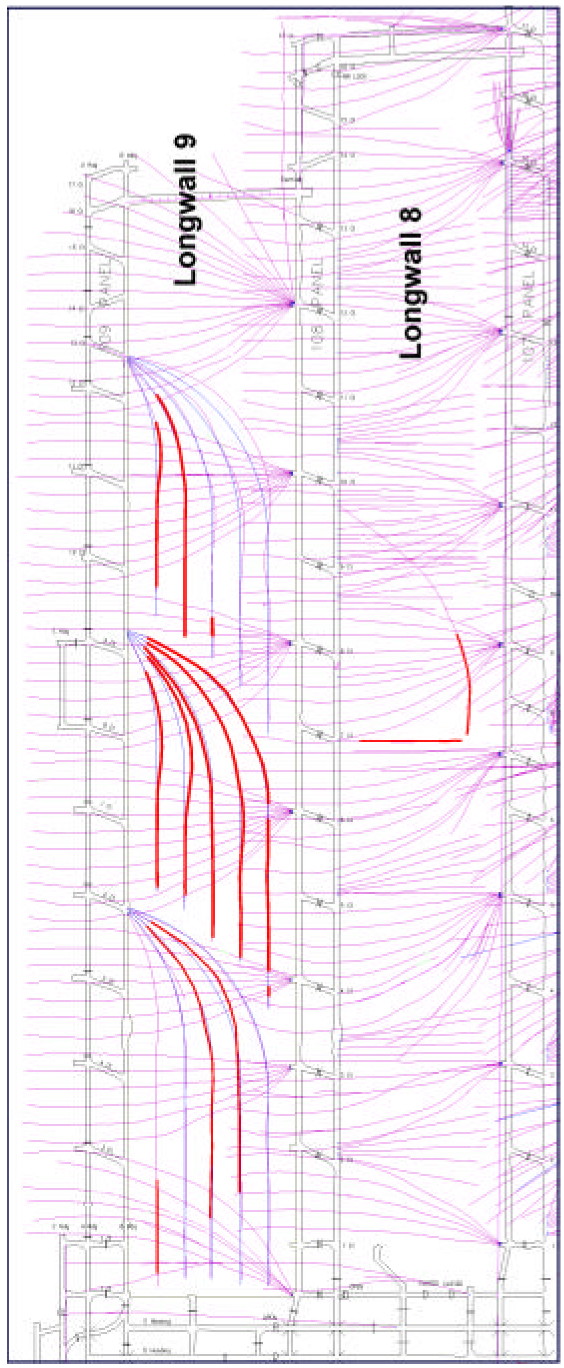

Fig 1 - Longwall 9 with hydraulic fractured holes indicated.

In-seam holes in panels mined before LW7 typically produced gas ranging in rate from 1 to 4 litres per minute per metre of hole. However, in LW7, 8 and 9 this rate was reduced, because of low permeability coal, to 0.1 to 0.3 litres per minute per metre of hole. Coal permeability was estimated to be about 0.02 to 0.03 md while gas content in these three panels was 8 to 9 cubic metres per tonne, composed of 90 percent carbon dioxide and 10 percent methane. This drainage rate was too low to effectively reduce the gas content to a content of 5 cubic metres per tonne, which is known to be low enough to avoid gas delays during longwall mining.

HYDRAULIC FRACTURE STIMULATION OF DRAINAGE HOLES

A measure of the effect of fracture stimulation on gas drainage can be obtained by comparing the productivity index, J_0, for the unstimulated hole to the productivity index, J, for the stimulated hole. The productivity index is defined as:

$$J = \frac{q_g}{(\bar{p} - p_{wf})}$$

where q_g is the gas rate, $\bar{p}$ is the average reservoir pressure, and p_{wf} is the borehole flowing pressure(Lee, 1989). This expression for J is only correct for produced fluids that are of small compressibility (such as oil or water) but is applied to gas production to give order-of-magnitude estimates. The effect of stimulation is usually illustrated by plotting the ratio J/J_0, which is called the stimulation ratio, as a function of another parameter such as time. Figure 2 contains a plot of J/J_0 against time constructed for a set of reservoir and fracture parameters and is presented to qualitatively illustrate the magnitude of fracture stimulation on gas production. For low-permeability reservoirs, the stimulation ratio during unsteady state flow (which can last for long periods of time) can easily exceed 10 or even 100 in value.

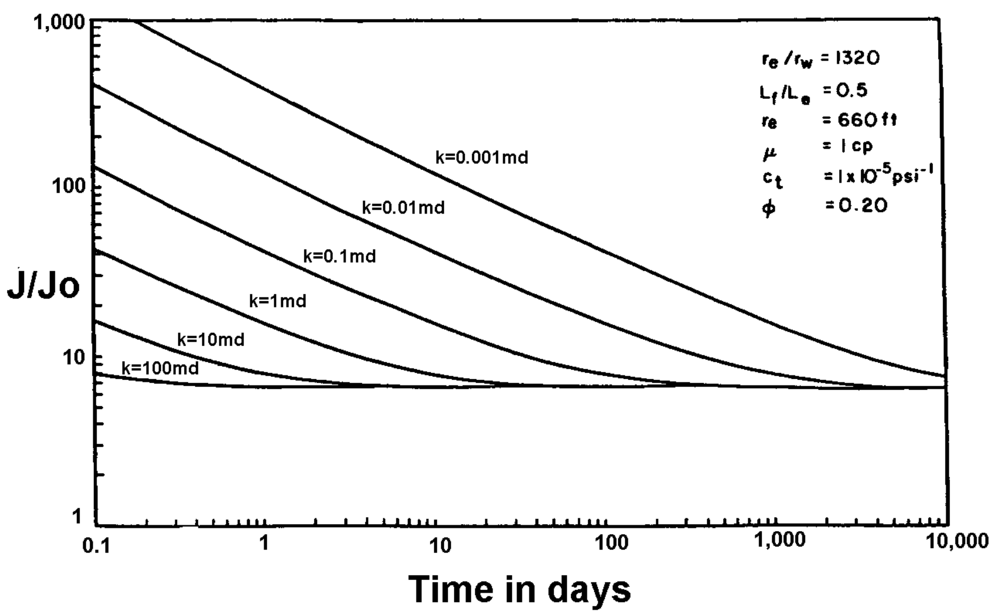

Fig 2 - Productivity ratio with time for different reservoir permeabilities (after Lee, 1989)

Water Only Fractures

In late 2001, a program of hydraulic fracture stimulation of horizontal drain holes was started at Dartbrook. The initial program used small water-only treatments placed at 3m intervals along several boreholes in Longwall 107[1]. Typical treatments consisted of 5 minutes of injection at 160 to 170 litres per minute (800 to 900 litres total volume). The gas rate per metre of borehole was increase by these treatments by a factor ranging from 2 to 3. However, this stimulated gas rate was too low for the coal to be drained in time available and the stimulated gas rate dropped off too quickly after the drainage started (Gray, 2002).

A trial using hydraulic fractures that included placing a sand proppant into the fractures was therefore undertaken to determine if the additional fracture conductivity produced by propped fractures would provide the additional degree of stimulation needed. At the same time, the trial allowed an assessment to be made of the equipment needed to carry out such treatments from underground.

STIMULATION TRIAL IN LW108

A system of equipment to undertake the sand-propped fracture trial, from the maingate side of LW8, was assembled from existing CSIRO Petroleum equipment and mobilized for use underground at Dartbrook.

The major joint system in the coal at Dartbrook is subvertical and strikes at about 110 degrees. However, this joint system strikes at about 90 degrees in LW8 and 9[1]. This joint system typically runs parallel to the maximum horizontal principal stress in the seam, which is also the direction that hydraulic fractures grow. The hydraulic fractures were, therefore, expected to be subvertical, growing along this joint direction. The borehole drilled at cut-through 10 was designed to run perpendicular to the expected fracture direction over its last 100m of length while the hole drilled from cut-through 7 was drilled more parallel to the expected fracture direction (see Figure 1). Fracture stimulating these two holes was designed to provide a comparison of the stimulation effect as a function of borehole orientation. Purpose-drilled boreholes targeted for this type treatment would best be drilled so the fractures form across the borehole axis, but extensive pre-existing drainage holes exist in the seam. A comparison of these two boreholes with different orientations was useful in determining if the existing drainage holes could be successfully stimulated or if new boreholes with the preferred orientation should be drilled to optimize the stimulation process and effect.

The hole at 10 cut-through was fracture stimulated with 20 fractures over its last 62m of extent (dark portion in Figure 1) with twenty fractures placed along this hole at 3 m. In contrast, the fractures placed in the hole at 7 cut-through should have been more aligned with the hole. A total of 10 fractures were placed over 88 m of this hole. In both cases, about 100 kg of 30/60 mesh sand proppant was pumped into each fracture formed.

Hydraulic Fracture Growth and Proppant Distribution

A numerical hydraulic fracture model has been used to approximately match the pressure measured during the fracture treatment at 327.7 m in the borehole at cut-through 10. The injection rate used in the treatment was 250 litres per minute. Coal and site properties used for this match consisted of a Young's modulus of 3500 MPa, Poisson's ratio of 0.34, minimum horizontal stress of 5.4 MPa, and coal permeability of 0.03 md. Figure 3 contains a plot of the pressure match obtained and Figure 4 shows the model-predicted fracture growth with time. Figure 5 shows the model-predicted proppant distribution. The propped fracture is predicted to have a conductivity of 10 md-m with this conductivity extending out to 15 m each side of the borehole.

Most of the proppant, as indicated in Figure 5, lies within 15 m of the borehole, but the fracture conductivity is enhanced out to 50 m. The model predicts the fractures grow vertically to about 7m in height.

Gas rates from each hole were monitored on a regular basis from the time they were drilled. The results of this trial were striking. Gas rate from both holes increased dramatically, with the hole drilled from 10 cut-through showing the largest increase. Figure 6 shows the specific gas rate history for the holes, expressed as gas rate per metre of hole. Not only did the gas rate increase significantly, but the increased rate was maintained for months. The curves shown are for gas rate per metre based on the entire hole length and for the length of the holes

[1] Byrnes, R .Private communications, April 2002

actually stimulated. The rate in the later case increased by a factor of 180 for hole 108-7-IF1 and by a factor of 22 for hole 108-10-10L. A stimulation ratio, J/J_0, may be somewhat larger than the factors given based on the raw gas rates. The producing pressure of the flowing holes is maintained constant by the vacuum applied to the system while the mean reservoir pressure decreases slowly as gas is extracted, resulting in an increase in J compared to the raw gas rate. Results of this trial justified a drilling and sand-propped fracture stimulation campaign for LW9.

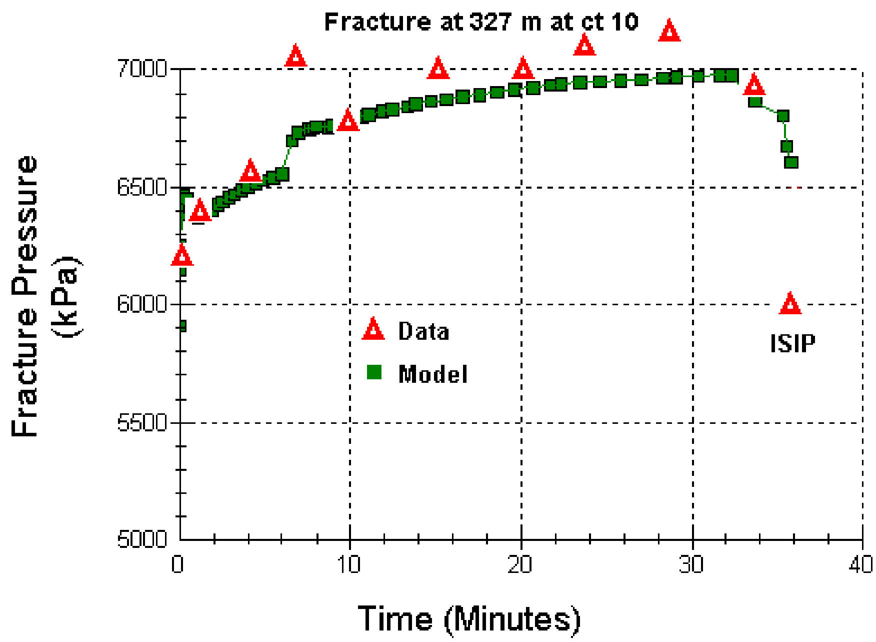

Fig 3 - Fracturing pressure versus time for the treatment at 327m at cut-through 10. The red squares are measured pressure.

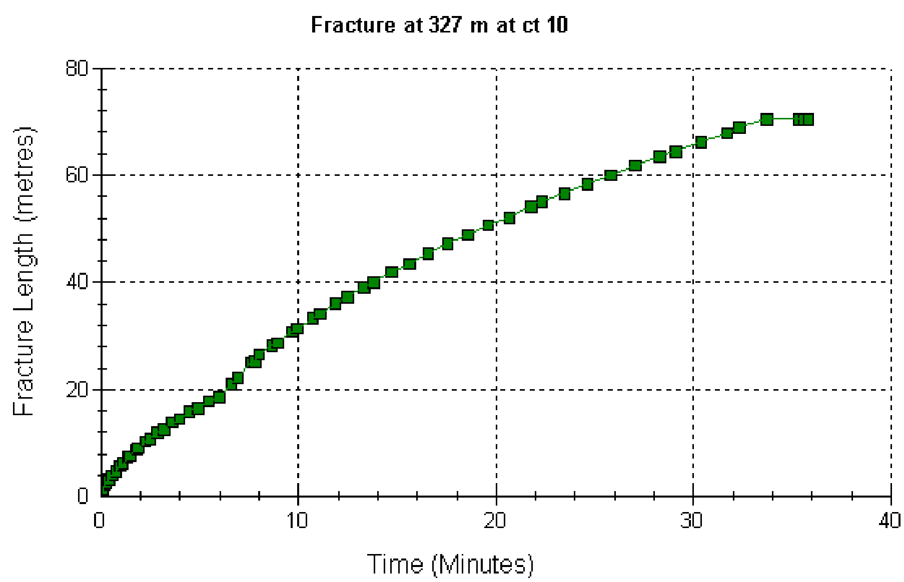

Fig 4 - The growth of the fracture with time for the treatment at 327 m at cut-through 10. The fracture grows to 32 m size in 10 minutes which is approximately the growth rate indicated by the observations of water at the rib during the last treatment at 7 cut-through.

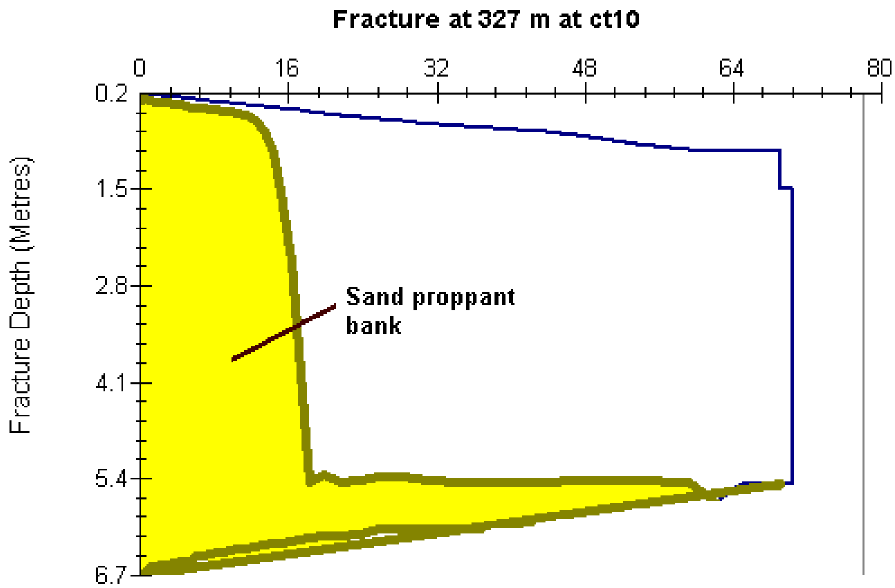

Fig 5 - The model-predicted proppant bank for the treatment at 327 m at cut-through 10. 160 kg of sand was placed in this treatment.

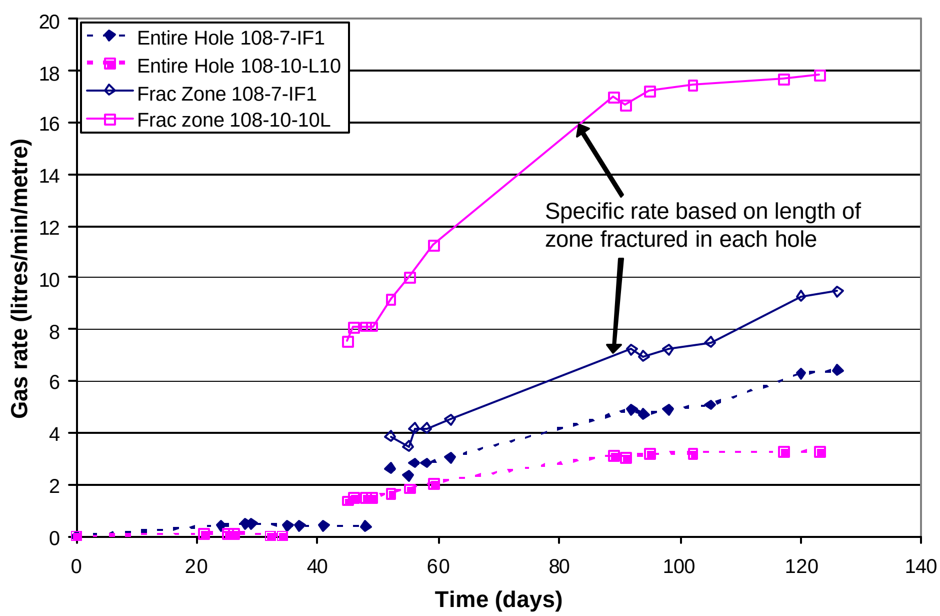

Fig 6 - Measured gas rate before and after sand-propped fracture stimulation. The fracturing occurred during the period in the data that is not connected by a line.

STIMULATION AND DRAINAGE OF LW9

As anticipated, hole 108-10-L10 which was drilled along the axis of the panel gave the best stimulation results. In addition, holes with this orientation allow few holes to be drilled to effectively cover the panel with propped hydraulic fractures, since the fracture propagate in the direction of the maximum horizontal stress which runs east-west across the panel. Therefore, the drain holes drilled in LW9, for the fracture treatments, were drilled to align with the long axis of the panel (see Figure 1). The holes were drilled from three locations, at cut-through 13, 9 and 6 with five holes drilled from each site and steered so they were spaced about 35m apart across the panel.

By the time the hydraulic fracturing in LW9 had started, the longwall was retreating. Approach of the longwall face limited the time available to fracture and drain all the holes that had been drilled so some holes were not treated and others had fractures placed every 6 m rather than every 3 m along them. Sections of the fractured holes that crossed near pre-existing fan-array holes were skipped over to avoid the possibility of the hole breaking out into the nearby existing hole. Such breakout could damage packers inflated there or lead to cross flow between the fractured hole and the older fan array hole. Table 1 contains a summary of the fracture treatments carried out in LW9 during this project. A total of 624 fracture treatments were carried out to stimulate 3174 metres total of 11 drain holes. Figures 7, 8, and 9 show the specific gas rate for each hole.

Table 1 - Summary of fractures in LW9 at Dartbrook

Hole number	Number of fractures	Hole length fractured (metres)	Fraction of hole stimulated (percent)	Average fracture spacing (metres)	Sand per fracture (kg)
109-13-F1	54	195	72%	3.6	78.3
109-13-F2	50	294	85%	5.9	81.2
109-13-F3	4	18	5%	4.5	100.0
109-9-F1	44	258	85%	5.9	86.1
109-9-F2	54	297	90%	5.5	84.7
109-9-F3	108	366	94%	3.4	95.6
109-9-F4	104	413	94%	4.0	83.4
109-9-F5	77	486	95%	6.3	86.8
109B-6-F1	14	110	26%	7.9	
109B-6-F3	59	373	94%	6.3	71.6
109B-6-F4	56	364	93%	6.5	75.2
Totals/ Average	**624**	**3174**			**84.3**

Overall the gas rate from the unstimulated holes averaged 0.74 litres per metre per minute and 3.6 litres per metre per minute after stimulation. The average stimulation factor was, therefore, 4.9 for all three cut throughs. These averages include hole F3 at 13 cut through, which had only 5% of its length stimulated and hole F1 at 6 cut-through, which was stimulated over only 25% of its length. With more complete coverage of the holes, a stimulation ratio above 5 would be expected to result for conditions in LW9. In Figure 8, holes F1 and F3 show signs of being blocked by debris or sand which then is cleared at 110 to 120 days on the graph. Similarly, F1 and F4 at 6 cut-through (Figure 9) appear to be blocked. The gas from these holes has, evidently, found its way into holes F2 and F5, which were not stimulated but show a large increase in gas rate after the hydraulic fracturing work in the other holes at this site. Such a connection between holes can be formed either through a number of propped hydraulic fractures or directly by a hole-to-hole intersection.

Some of the sand proppant was produced back from the fractures into the drain holes. A portion of this sand was carried into the gas drainage pipe work. Sand production can be controlled by adding sand stabilizers to the proppant when it is pumped. It may also be worthwhile to consider cleaning the entire hole after the fractures are placed since most proppant is produced soon after the stimulation work is carried out. Sand production also becomes less of a problem as the closure stress on the fractures increases.

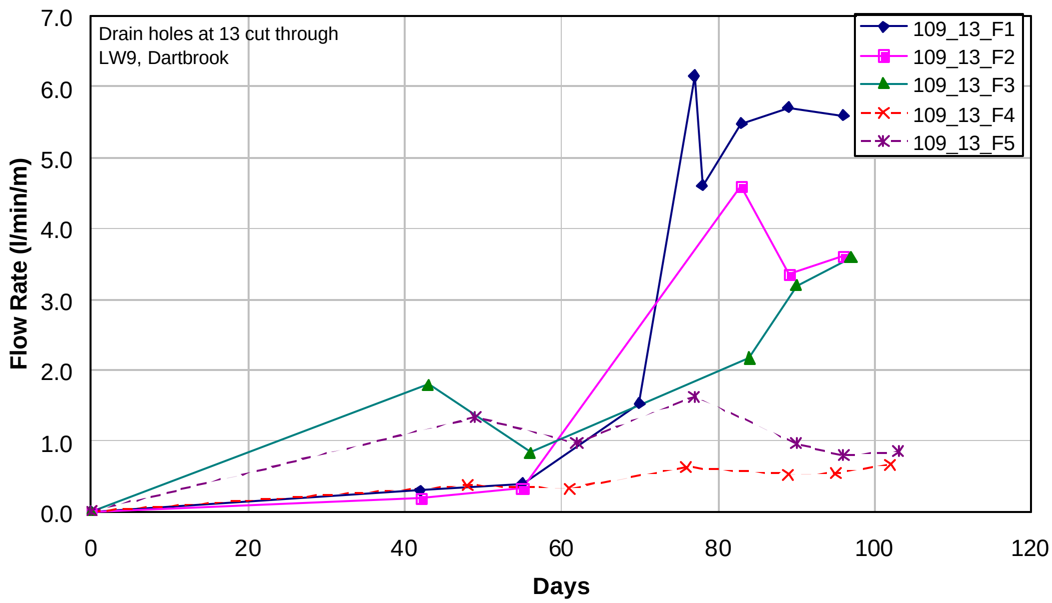

Fig 7 - Specific gas rate from drain holes drilled at cut-through 13.
Dashed lines indicate holes not fracture stimulated.

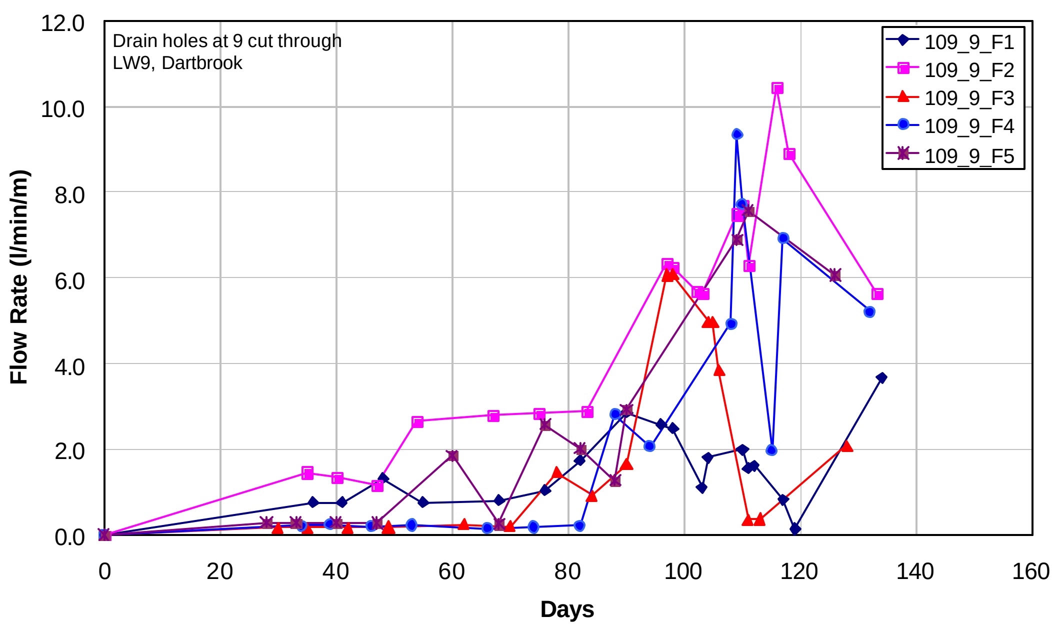

Fig 8 - Specific gas rate from drain holes drilled at cut-through 9. All holes were stimulated.

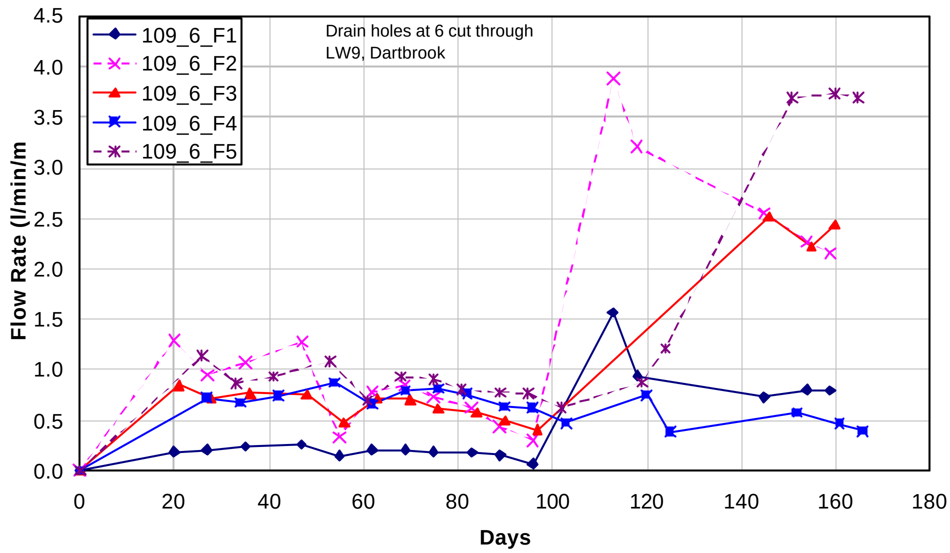

Fig 9 - Specific gas rate from drain holes drilled at cut through 6. Dashed lines indicate holes not fracture stimulated

DISCUSSION AND APPLICATION TO OTHER MINES

The effect of sand propped hydraulic fractures on the gas drainage rate depends on the seam parameters such as permeability and thickness and on the hydraulic fracture parameters, such as fracture conductivity, propped length and spacing between fractures. If coal seam permeability is higher, the fracture conductivity and propped length must be increased (by pumping more sand into each fracture) if the same stimulation ratio is to be obtained. This fact partly explains why the stimulation work in LW9 provided a stimulation ratio of about 5 while at the trial site in LW8 the stimulation factor was 22 and 180. The coal in LW8 was less permeable and pre-stimulation gas rates were lower than those in LW9, but no change was made to the amount of proppant in each fracture and the average spacing between fractures was actually increased in LW9 (because of the approaching longwall face). Nevertheless, the stimulated drainage holes in LW9 were deemed successful, producing a faster drainage rate which allowed mining of LW9 without any gas-related delays occurring. A stimulation factor of 5 implies that, for example, 1 month of stimulated drainage will drain the same gas volume (but probably from different parts of the seam) as 5 months of unstimulated drainage.

The coal strength and the stress conditions at Dartbrook are such that horizontal drain holes can be drilled with little difficulty and these holes, by and large, remain stable. Good hole conditions made possible the use of standard open-hole inflatable packers to carry out the fracturing work. Initial packer life in this project was considered less than desired and adjustments to the standard inflation pressure and the downhole tool were implemented to increase the number of fracture treatments that could be obtained per packer. The packer manufacturer also supplied stronger packers. In addition, the locations of existing fan array holes were known and, as part of the fracturing procedure, packers were not set near points where the old and new boreholes were close to one another. The holes drilled for the fracturing project were positioned in the upper part of the working section of the seam, to avoid intersection with existing fan array holes. With these changes, packers lasted for about 60 fracture treatments before failing. Higher setting pressure or less stable borehole conditions, which exist at many other mines, will lead to shorter packer life and higher costs for carrying out each fracture stimulation. In many cases, without some form of hole stabilization, it may not be practical to use open-hole packers to place the fractures.

Alternative hole completion methods, such as casing the hole before fracturing, are being investigated (Jeffrey and Mills, 2002) in order to allow sand-propped hydraulic fracture stimulation to be carried out under a greater range of sites and coal seams conditions.

CONCLUSIONS

The trial in LW8 demonstrated that sand-propped hydraulic fractures were effective in stimulating gas drainage rates from horizontal drain holes and the best stimulation resulted for holes drilled so that the fractures extend in a direction perpendicular to the hole axis.

The sand-propped hydraulic fracture stimulation work carried out in LW9 at Dartbrook, on average, increased the rate of gas drainage by a factor of about 5. The increased rate of gas drainage allowed the gas content to be reduced in LW9 to a level that was sufficiently low so that no gas-related delays were experienced in mining the panel. This was a considerable improvement over conditions experienced in mining the previous panel, which was not drained with the aid of sand-propped stimulated drain holes.

ACKNOWLEDGEMENT

The authors thank Anglo Coal and CSIRO Petroleum for supporting this work and for permission to publish this paper. The fracturing equipment was operated throughout by crews from Valley Longwall Drilling and a variety of operational problems were solved by various VLD people during the project.

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