Development of in-seam drilling for the production of methane

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ABSTRACT

This paper looks at new and appropriate technology for drilling horizontally in-seam for the commercial production of methane from coal seams. The drilling approach required is a hybrid of existing technologies from different backgrounds welded together with some new ingredients to produce a new technology.

INTRODUCTION

In-seam drilling is the principal method by which mines degas virgin coal seams prior to mining. The introduction of directional control using downhole motors has extended the range of such drillholes four fold from 250 m to 1 km. The potential exists to double this distance and to do so from surface as well as underground.

This paper examines the potential for drilling longer in-seam holes and drilling them from surface, such as that shown in Figure 1. It specifically looks at the limitations on drilling, namely directional control, drag on the drillstring and hole cleaning. In addition the paper looks at hole completion and economics.

History and Current Practice

Directional drilling in seam from underground roadways has essentially grown from the oil industry in the late 1970's and early 1980's principally for the purpose of methane drainage. This in seam drilling initially used rotary drilling techniques and later adopted the use of downhole positive displacement motors (PDM's) to drive the bit. The latter avoided the need to rotate the drill string and permitted the bit to be pointed in the desired direction by the use of a bent housing or sub to correct trajectory or azimuth. This type of drilling has been developed through the 1980's to the present.

In the latter portion of the 1980's the oil industry saw the value in directional drilling to recover oil and gas from vertically fractured low matrix permeability reservoirs. Horizontal drilling could reliably intercept the fractures that were only reached occasionally by vertical wells. This is the same reason that horizontal degasification boreholes in coal seams have been so successful. Characteristically the oil industry has put an intense effort into developing this type of drilling as a production tool and currently companies offering downhole tools abound, though actual equipment seems a little scarcer.

The oil industry approach to near horizontal directional drilling has been entirely based on downhole positive displacement (mono pump style) motors which drive rotary drill bits at the end of what is either a drill string that is slowly rotated or held against rotation. Slow rotation of the drill string is designed to have the effect of drilling an enlarged straight hole. Deliberate changes in trajectory can be facilitated by holding the string stationary so that it deviates in the direction of the bent sub or housing.

Directional surveys have either been by *measurement while drilling (MWD) survey* systems or by cable operated steering tools. Both of these give a continuous tool face angle read-out. The MWD systems now all operate by causing pulsations in the pressure of the mud being pumped down the string.

The oil-well drilling techniques used to control trajectory are substantially different from those used for in-seam drilling from underground. In the underground case a motor assembly with a fairly high angle build capability is used to counteract the tendency in coal drilling for a sudden drop in dip of a borehole assembly. Dip control is achieved by first turning the bent housing first one way and then the other while usually maintaining an upwards direction on the bit. The result of this is a continually snaking hole with the deviations from one side to the other. Surveying has principally been by the use of single shot camera type survey tools. To date there has been no MWD consistently available to the underground coal mining industry.

FACTORS AFFECTING DIRECTIONAL DRILLING PERFORMANCE

Rock Type

The material being drilled is of principal importance in any drilling operation as some suitable drilling method is required to induce material fracture. In terms of directional drilling this means a suitable bit and mud motor combination followed by a drill string that will enable a suitable load to be applied to the bit. The material also affects the choice of muds which will help keep the hole open.

Drilling in coal measures presents extremes in materials. The rocks surrounding the coal seams range from being weak mudstones to extremely hard and abrasive quartzitic sandstones. The coal seams themselves are weak and are often faulted and invariably contain cleat systems.

Where in-seam drilling has intersected faults containing significant gouge material it has often been impossible to continue drilling because the large volumes of material produced have clogged the annulus. Where the material has been cleared enough to continue drilling it has often subsequently fallen in on the rod string or after drilling.

Bit, Motor and Stabilizer Combination

In oilfield directional drilling three types of bit are used, the roller bit, the Poly-crystalline Diamond Cutter Bit (PDC) and lastly the diamond set bit. The tricone roller bit is the most commonly used and it has proven to be robust and good for directional control. However it requires a high level of thrust. The PDC bit provides high cutting rates with less weight on the bit. It however provides less directional control and is less robust in resisting impacts on the hole bottom or in hard materials. Diamond set bits are reserved for occasional use in hard formations.

Bit rotation rate is slowest for roller bits, increasing through PDC to diamond set bits.

In seam drilling started with the use of tungsten carbide edged drag bits and with roller bits being used through hard rock zones. Since then PDC bits (usually labelled PCD in the mining industry) have taken over as these have the capability to drill rock and coal.

The positive displacement motors come in a variety of shapes and sizes. They range from 9 1/2" diameter to 1 3/4" diameter units. Currently underground in-seam operations use 2 7/8" and 2 3/8" motors behind BQ OR NQ drill rods. For longer holes with larger diameter drill rods 3 1/4" or 3 3/4" high torque motors are probably desirable. Drilling from surface to in-seam requires a larger hole so that the pump can be installed and permit gas to flow around it. To permit this a minimum internal casing size of about 140 mm is needed. This requires a hole size of about 220 mm. Drilling such a size hole requires a 6 1/2" motor and a fairly heavy drill string.

Directional change is accomplished by the placement of bends either in the motor housing or behind the motor. These may either be fixed or adjustable kick offs (AKO's). In addition stabilizers are generally used to locate the assembly in the hole.

Drillstring Mechanics

To be able to drill it is essential to maintain the right load on the bit. This is influenced by the drill string's buoyant weight, its stiffness, the coefficient of friction between the drillstring and borehole and the changing inclination of the borehole. Numerical torque and drag models are used in the oil and gas industry to estimate the bit load and the load and torque in the drill rods. Typically these models treat the drill string as being "soft" ie, lacking stiffness (Johancsik *et al.*, 1984). The frictional drag is the product of the lateral load on the borehole wall and the coefficient of friction between the rod and the borehole wall. The loads on the borehole wall are calculated as being made up of gravitational load and the lateral component of drillstring load due to the transfer of the string's axial load around borehole curves.

This soft string approach is certainly valid in cases where the borehole has few changes of curvature and where drill string axial loads are high compared to the bending loads. This is the case in deep oil wells but is far less certain in shallow holes with multiple changes of curvature. A comprehensive analysis for this case is however not a trivial exercise.

In deep vertical and sub-vertical holes the drill rods are designed to operate principally in tension and the stiffness of the drill rods is of little importance. This however is not the case where drilling becomes sub-horizontal. In this case the rods have to be pushed. A drill rod is a thin flexible structural member which can buckle.

Buckling can take two forms, first sinusoidal buckling (Paslay and Bogy, 1964) which is a lateral buckling phenomena, then helical buckling as compressive loads increase (Chen *et al.*, 1990). Helical buckling means that the drill string takes on the form of a helix or screw thread within the borehole. The compressive load that leads to the onset of buckling depends on rod weight, inclination, and the stiffness of the drill string. Buckling poses problems because, depending on hole diameter, it can impose significant stresses on the rod string. Stresses that furthermore oscillate, if the drill string is rotated, with the potential for fatigue damage. In addition the possibility for frictional binding of the rods in the hole exists with the onset of helical buckling. This is because a helix tends to expand its diameter when loaded axially. In a confined situation such as a drill rod within a borehole the helix cannot expand and the load between rod and borehole wall increases. Helical buckling loads for exploration drill rods in typical hole sizes are given in Figure 2. It should be noted that the onset of helical buckling occurs at a load 1.414 times that for the onset of sinusoidal buckling in the absence of a torsional load in the rods. In a normal drilling situation torsional loading will exist in the drillstring and this will reduce the load at which helical buckling will occur.(Yang and Yau, 1989).

Drilling Fluids

Effective hole cleaning is essential to a drilling operation. Without it the drill string will become stuck in the hole. In the oil and gas drilling industry large sums of money are spent on drilling fluid additives to ensure cuttings removal. It has been found that laminar flow in the annulus gives the best cuttings removal in vertical holes while in highly deviated holes the best cleaning is achieved by turbulent flow. For a given flow rate and annulus dimension turbulence is achieved by a low viscosity drilling fluid.

It is highly desirable to avoid the settling of cuttings in the hole during periods when circulation is stopped. Such settling is very serious in the sections of hole between 20 and 70 degrees of inclination from the vertical as particles will gather on the bottom side of the hole and then slide downwards as in an underwater mudslide. The result is a blocked annulus and a stuck drillstring. To slow settling the drilling fluid should have a very high viscosity. It should be noted though that not only do high viscosity fluids prevent turbulence in the annulus but they also require high pressures to pump them which may lead to excessive fluid loss or even hydrofracturing of the strata.

The specifications for a drilling fluid for directional drillholes have apparently conflicting requirements, needing both high and low viscosities. The solution to this conflict is the use of a shear thinning fluid. This has a very high viscosity at low shear rates (when not drilling) which subsequently thins when circulation restarts. Such an additive requires the use of a proper mud cleaning system which can remove particles out of a fluid that forms a gel under static conditions. This is rendered particularly difficult during in-seam drilling by the low density of coal. This makes conventional gravity based settling, hydrocyclones or centrifuges less efficient than they would be on equal sized rock particles.

The drilling fluid has to perform other tasks also. It lubricates the hole so as to reduce friction and in addition helps form a filtercake to prevent the loss of drilling fluid into the strata being drilled. Quoted friction factors using the different drilling muds from the oil industry are as shown in Table 1 from Williams (1990). From these the effect of an oil based mud in lubricating the hole can easily be seen.

In underground in-seam drilling in Australia the only drilling fluid used has been water. At the flow rates used (200 litre/min) using NQ drill rods and an 86 to 89 mm hole diameter turbulent flow is achieved. Hole cleaning has not been a significant problem except in one case where a lower flow rate motor (160 litre/min) was used with resulting problems presumably associated with the laminar flow situation that will have existed.

ANALYSIS OF FIELD DATA

In 1987 some very important drilling trials were conducted at Appin Colliery in New South Wales (Hungerford *et al.*, 1988). Of several holes drilled one was an in-seam borehole (BH6) which was drilled to 1004 m in the Bulli seam. Another (BH9) was drilled downwards, across measure, through stone, and then in the Balgownie Seam to a total length of 923 m. Both these holes represent a substantial achievement in drilling which has probably reached the limits or the equipment being used. This was an NQ rod string with a Slimdril 2 7/8" high torque motor drilling 89 mm holes and using an Eastman single shot camera survey tool.

By courtesy of ACIRL the writer has been provided with full borehole survey and hydraulic ram pressures for these holes. Using a soft string torque and drag model (TORDRG) the friction factors for these holes have been found by back analysis.

An analysis has been conducted of the survey results from borehole BH6. These were taken at 6 m intervals. The standard deviation of the borehole inclination away from a moving average inclination over 66 m length was found to be 0.99 degrees. The standard deviation figure for azimuth was 1.42 degrees. A typical trajectory section for such a variation is shown in Figure 3.

Borehole BH6 shows a consistent friction factor throughout drilling of 0.57 to 0.60. BH9 does not provide such a consistent friction factor, lying between 1.0 and 1.2. The origin of the variation of the latter is uncertain possibly being made up of the difference in friction between stone and coal and by a failure to clear cuttings up slope. These friction factors are far higher than those measured in the oil industry. The most likely cause of this is the lack of use of a lubricating mud.

MAXIMUM HOLE DEPTHS ACHIEVABLE

The onset of helical buckling represents approximately the limit of load that can be placed on a drill string before a rapid increase in drag occurs due to borehole wall friction. It is possible to calculate the horizontal distance to which a particular string can be pushed before helical buckling occurs. This has been done for rods in water in a hole with a coefficient of friction of 0.6, similar to that for borehole BH6. The results are presented in Table 2. Those rods with the highest stiffness to unit weight ratio can be pushed the furthest. This means a large diameter thin wall rod is the most effective. It should however be noted that rod joint strength should also be taken into account when choosing a rod string.

SIMULATION OF A POTENTIAL DRILLING EXAMPLE

To see just what might be achieved in a long hole in-seam drilling exercise from surface the rod load values for the hole shown in Figure 1 and dimensioned in Figure 4 have been calculated using the computer model TORDRG. The coefficient of friction for this exercise has been chosen as being 0.4, a value considered to be conservative for lubricated drilling fluids but much lower than those calculated from the hole drilling exercise at Appin Colliery.

The simulation involved firstly looking at a smooth hole as drawn in Figure 4. This is called the "Smooth" profile model. Secondly it involved the superposition of the difference in inclination and azimuth angles for borehole BH6 from its 66 m long moving average angle on the shape shown in Figure 4. This is called the "Rough" profile model and represents the angular control currently achievable. The third simulation involved the superposition of half the difference in angles from the 66 m long moving average on the shape shown in Figure 4. This is called the "Half Rough" model and represents a significant improvement in drilling control over what is currently achieved.

The results of the simulation are shown in Figure 5 where the rod loads are plotted against the rod profile. It can be easily seen from this that the loads are very dependent on how straight the borehole is drilled. Thrust that needs to be applied from surface varies from 114 kN (25700 lb) for the "Smooth" hole through 182 kN (40800 lb) for the "Half Rough to 454 kN (102000 lb) for the "Rough" profile hole. The rated capacity of the CHD 101 rod is 3050 m (10000 ft) corresponding to a tensile load in a water filled hole of 337 kN (75600 lb). Assuming that the joint strength is similar in compression the "Rough" hole could not be drilled using these rods. The "Half Rough" profile could however be drilled provided adequate stabilizers were provided to prevent buckling. A stabilizer spacing of closer than half the predicted buckling pitch should prevent buckling. This spacing is less than 7.57 m in the "Half Rough" case.

HOLE COMPLETION

To date holes drilled in-seam from underground have simply been drilled through a pipe grouted into the seam (standpipe) which forms a sort of wellhead. At the completion of drilling the standpipe is connected by a hose to the methane drainage range. In only one known instance in Australia has some additional completion technique been used for in-seam boreholes. This involved the insertion of copper pipe through the length of holes with a downward slope. This enabled water to be purged out of the hole by periodically manually shutting the main gas valve on the standpipe. The technique was successful in increasing gas flow from the holes.

Screening

It is not current practice to screen boreholes drilled in-seam from underground. While it is assumed that they will stay open little subsequent hole probing has been carried out to test this hypothesis. Cross measure holes that are used to drain adjacent seams to a longwall mining operations have been found to block and require support with slotted steel screening. The use of such material is precluded if the coal is to be mined subsequently.

If extremely long holes are to be drilled then it will become essential to protect this investment against collapse which if it occurs near the borehole mouth will totally block gas production. In areas where mining may subsequently take place then some effort is needed to find or develop a suitable screening material. As most boreholes are self supporting it is likely that this material could take the form of a plastic which would simply support zones containing broken material.

Any screen material will need to have an adequate stiffness to weight ratio so that it can be pushed down the hole. Plastics are not currently used in the underground situation because of concerns about the build up of static charge leading to an ignition. This concern is not relevant to gas drainage operations that will never be associated with subsequent mining as any plastic screening will not be adjacent to a gas and air mixture. From observations of underground gas drainage operations in Australia it seems extremely unlikely that there would in fact be any problems of static build up because the gas flow from boreholes is fully saturated and the boreholes are running salt laden water. This is an area deserving further investigation because of the cost savings associated with the use of plastic screening.

As the majority of the cost of drilling holes from surface to in-seam is in drilling from surface to the seam it appears logical to branch the drainage holes and therefore increase the effective hole length. The actual drilling of such branches is not difficult but maintaining a screen over the junctions is not simple. The oil industry has developed a number of techniques for placing plugs in a casing and subsequently milling windows for branches in the vertical plane. These techniques are not yet developed to the horizontal and are in addition expensive and require a drop in hole size in the branch. Currently the materials used in such operations are steel. Appropriate screening for such branches is required.

Hydrofracturing

While hydrofracturing from vertical holes is commonplace and some oil industry organizations do offer hydrofracture from horizontal holes the latter is not a common completion technique and has not been fully tested in a coal seam situation. The equipment proposed for such work is complex and expensive and is in addition made of steel. One of the prime reasons for adopting horizontal drilling in-seam is to get gas out of seams with unfavourable stress and anisotropy alignment. This means that instead of vertical holes which are fractured up the gas producing cleat set, or horizontally, the hole can be drilled across the cleat. In such situations hydrofracturing will also propagate in the undesirable direction. Where there are less problems with anisotropy the comparative economics of hydrofractured horizontal boreholes versus fractured vertical holes have yet to be considered by the writer. Deimbacher *et al.* (1992) have considered the technical aspects of these options and have come to the conclusion that drilling horizontal boreholes perpendicular to the cleat set and subsequently hydrofracturing is likely to create high production wells.

Pumping Water Out of Horizontal Boreholes

Gas flows from horizontal boreholes or for that matter hydrofractures are strongly influenced by the back pressure that exists in the hole. It is therefore extremely important that water produced is pumped out of the hole.

Sucker rod pumps and helical rotor positive displacement pumps (mono, moyno etc) driven by shaft are currently used for pumping vertical degasification wells. They are ideally suited to the low volume high head applications. Problems however arise when their drive rods are deviated from the vertical as would be required in horizontal wells.

An apparent solution is the use of deep water well submersible electric pumps or their higher head greater flow rate cousins from the oil industry. These pumps have several problems though. They need cooling, which can be difficult in a hole part filled with gas. To pump the heads required they need to be of an undesirable size for directional boreholes. They also need gas separators that will operate while horizontal. Cable costs can in addition become extreme. These problems can probably be overcome by future developments. In the mean time other options might be considered such as helical rotor positive displacement pumps powered by a high voltage submersible motor.

Whatever pump is used some form of sump will need to be drilled at the start of the in-seam section.

ECONOMICS

Provided all options are examined in sufficient detail and provided organizations are prepared to face up to the challenge of trying something new the type of method used to drain gas from coal seams will be decided by economics. The economics is in turn a function of geology and technological cost.

At the present time easily the most economic way to drain gas from underground mines is by in-seam drilling from the mine. The economics advantage of this is twofold, namely in terms of cost per unit quantity of gas drained and secondly in the speed with which drainage can be achieved. The latter point means that less commitment is required by the mine to develop areas before actual mining. Only when drilling cannot be accomplished from underground do mines consider drainage from surface.

Coalbed methane for commercial supply separate from mines has almost exclusively been won by the drilling of vertical holes and subsequent hydrofracture. Present commercial operators in the Bowen Basin of Queensland are looking towards obtaining 300 to 400 mcfd (8500 to 11300 cu.m/day) on a long term basis from a single hydrofractured hole to be profitable. The early hydrofracture trials at Leichhardt Colliery, Blackwater produced a steady flow of 24 mcfd (700 cu.m/day) while recent apparently successful hydrofracture sites in the northern sections of the Bowen Basin have produced widely varying flows generally in the region of 20 to 80 mcfd (566 to 2265 cu.m/day). The cost of these completed holes has been of the order of $600 000 being made up of $350 000 for drilling and casing and $150 000 for fracture and $100 000 for testing and completion. At best these represent a flow of 0.004 cu.m/day per $ of well development compared to a desired figure of 0.02. In the case of multiple seam completions the flow per hole will increase but so will cost.

In-seam drilling in the Northern Bowen Basin has given steady flow rates of 3 to 6 cu.m/day per metre of borehole. Underground drilling and piping costs are about $33 per metre of borehole giving a flow of about 0.14 cu.m/day per $ cost. When in-seam drilling is being accomplished from surface it is much more expensive, principally because of the cost of drilling and completing from surface to in-seam. The cost is also strongly influenced by how much of an oilfield component is required. At current costs it would appear that it would be possible to drill a single branch hole of 1 km in-seam length at a depth of about 350 m for a cost of $500 000. This is made up of $100 000 mobilization, $200 000 surface to in-seam directional drilling equipment hire costs, $30 000 in-seam drilling hire cost, $100 000 drill rig cost and $70 000 completion costs. This corresponds to a daily flow of 0.01 cu.m/day per $ cost. This is better than current hydrofracturing has achieved but less than is desirable.

Extending the amount of in-seam drilling from a single surface to in-seam borehole to 6 km by longer holes and multiple branches should be possible. An example of what such a pattern may look like is given in figure 6. The cost of drilling in-seam hole from surface is expected to be approximately $40 per metre. Allowing an additional $20 per metre for completion to keep the hole open this would mean for an additional $300 000 spent on in-seam drilling the flow per unit cost could rise to $0.037 cu.m/day per $ cost. This is a very competitive figure with hydrofracturing. Deeper seams will drive up the cost rapidly because of the need to use heavier oilfield equipment with oilfield prices.

CONCLUSIONS

Directionally controlled drilling has considerable potential to drain gas from coal seams either for commercial extraction of for pre-drainage of gas from future mining blocks. To make the technique viable it is necessary to drill longer holes than are now being drilled from underground and in addition to develop appropriate completion techniques and equipment.

To achieve useful length holes the following improvements to current drilling practice are required.

It is essential to drill straighter holes than currently accomplished underground. This means better borehole survey equipment and less severe bends in down hole motors. Alternatively it means new technology such as water jet drilling (Kennerley *et al.*, 1991).

The use of drilling fluid lubricants is also necessary. The drilling fluid should also be strongly shear thinning so as to enable turbulent flow conditions to exist in the annulus and prevent particle settle back when not drilling. The use of such fluids means that the drilling fluid cleaning equipment must be properly designed.

The drilling rods need to be as light and stiff as possible so as to prevent buckling. Despite this, buckling of rods will almost certainly be a problem in near vertical sections of the borehole, where buckling loads are low, unless stabilizers are used. Stabilizers need however to be carefully designed to prevent hang-ups on the borehole wall and *drill string entrapment if borehole wall collapse* occurs. Ideally such stabilizers should only be used in cased zones.

If such long range (2 km, or longwall block length) drilling is to be accomplished from surface then drill rigs with a substantial capacity to push as well as pull back are required. This is different from most drilling operations where the rig holds the rod string back against gravity.

When all the improvements noted above have been made a drill still cannot "see" where a seam is ahead. It is necessary to provide some vertical control by surface boreholes or by look ahead geophysics in the drilling system. It should be noted that cuttings are not a suitable means to identify the formation as the time of flow from the bit to surface may be up to one hour, not including breaks in drilling. The monitoring of drilling penetration rate and downhole geophysical probes are essential to confirm that the coal seam is being drilled.

Several developments are required for completion. Screening techniques and materials which are both economic and which can be subsequently mined are needed. These screening techniques really also need to be able to accommodate branches. Pumps are needed which can be installed at near horizontal angles in sumps specially drilled for the purpose. The problems faced in finding suitable solutions to these needs are not expected to be insurmountable.

Provided these developments can be accomplished it is quite likely that where a single seam is the target, surface to in-seam drilling will provide a cost effective option to draining and obtaining methane from coal seams. Where multiple seams exist, each with stress regimes suitable for hydrofracture, then vertical holes with multiple hydrofracture completions will probably be the most economic solution.

Figure 6 shows an example of what a commercial gas extraction panel using horizontal boreholes might appear as. Spacings between boreholes could be narrowed for a mining case where fast gas drainage is sought from an area to be mined in the future.

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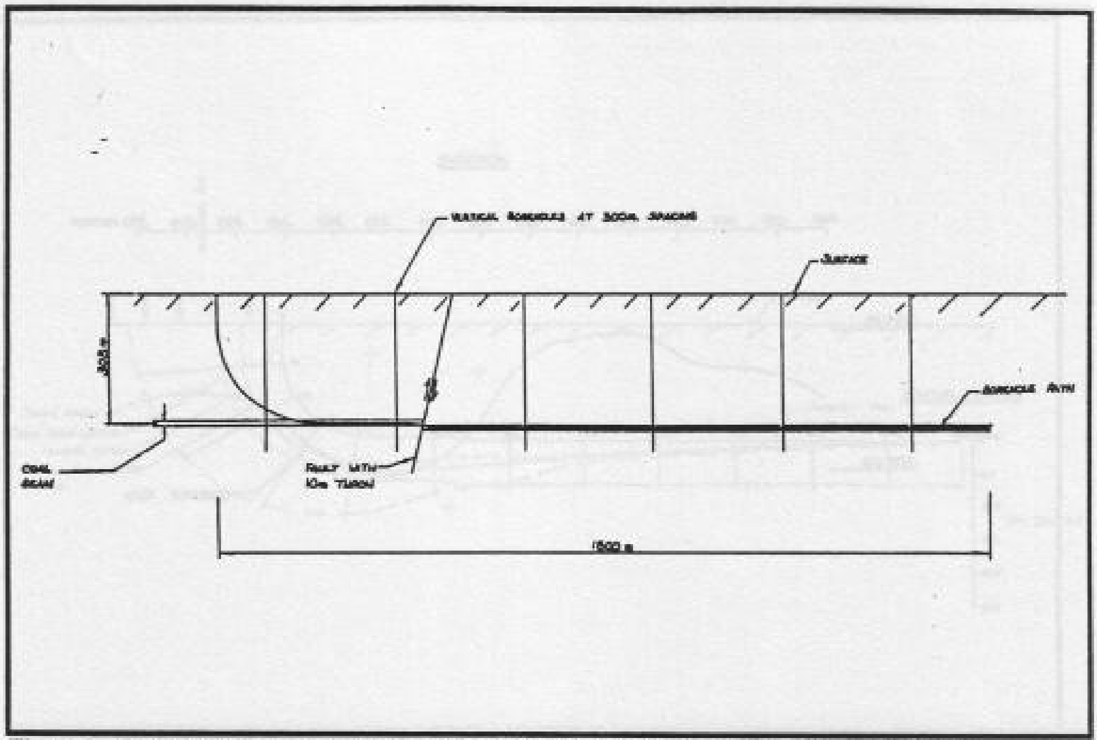

Figure 1. A potential use of in-seam exploration drilling to delineate a longwall block.

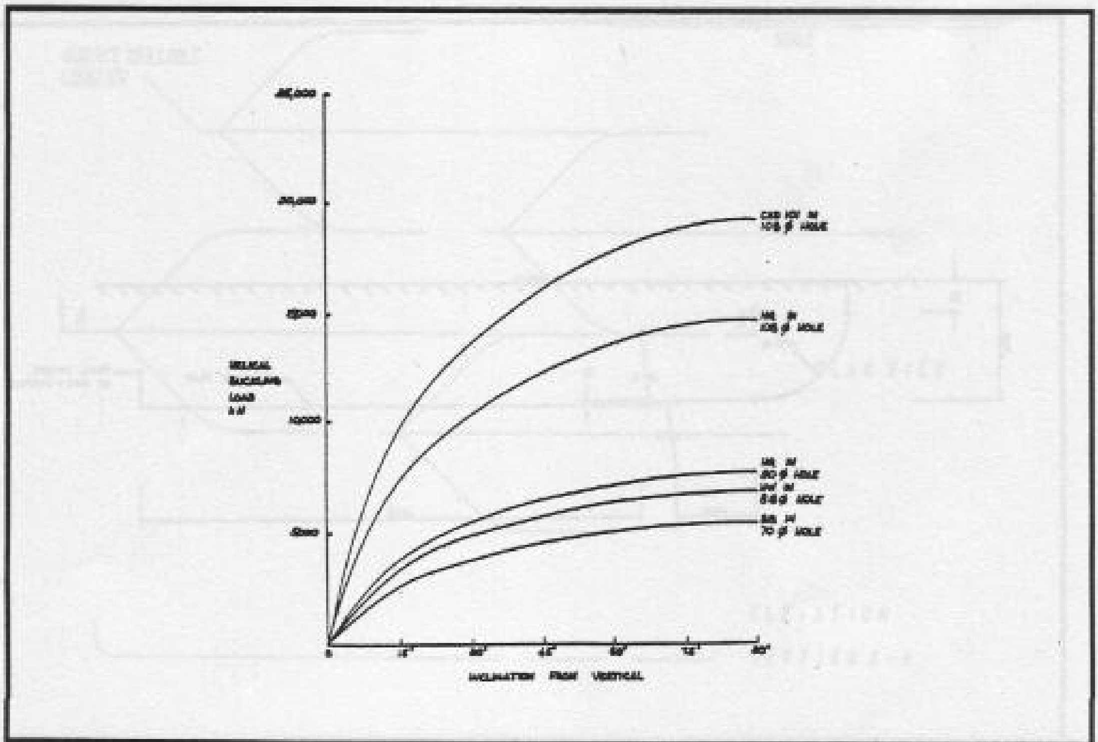

Figure 2. Helical benching loads at varying inclinations of different drill rod/hole size combinations.

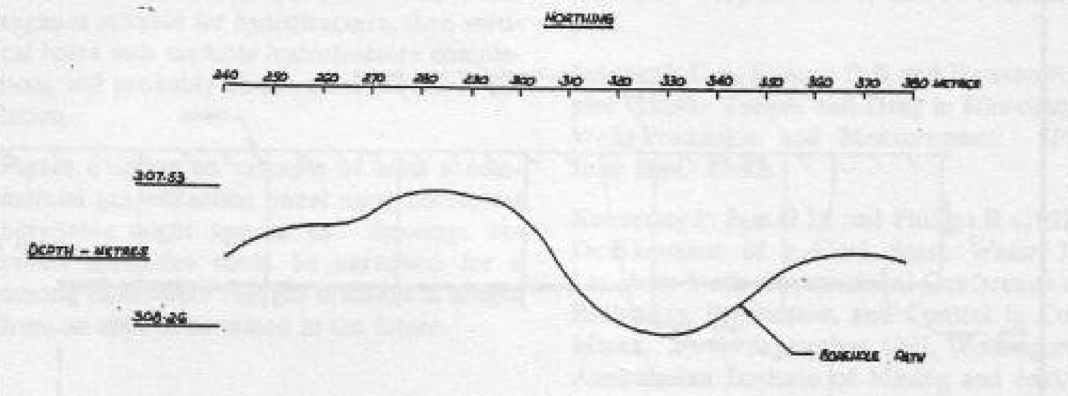

Figure 3. **Typical vertical profile of a section of borehole similar to BH6.**

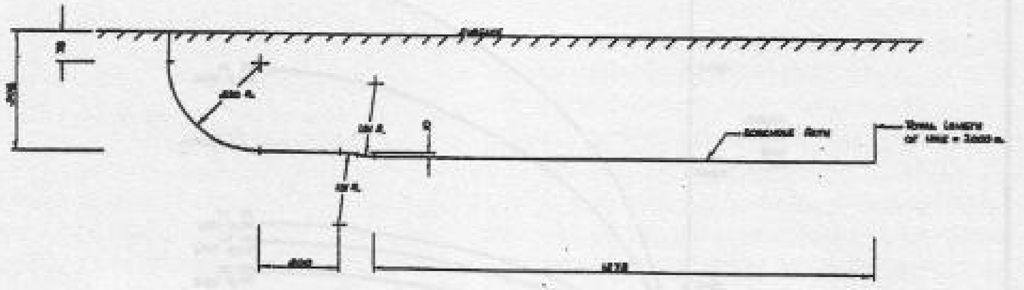

Figure 4. **Dimensions of horizontal hole used in drilling example.**

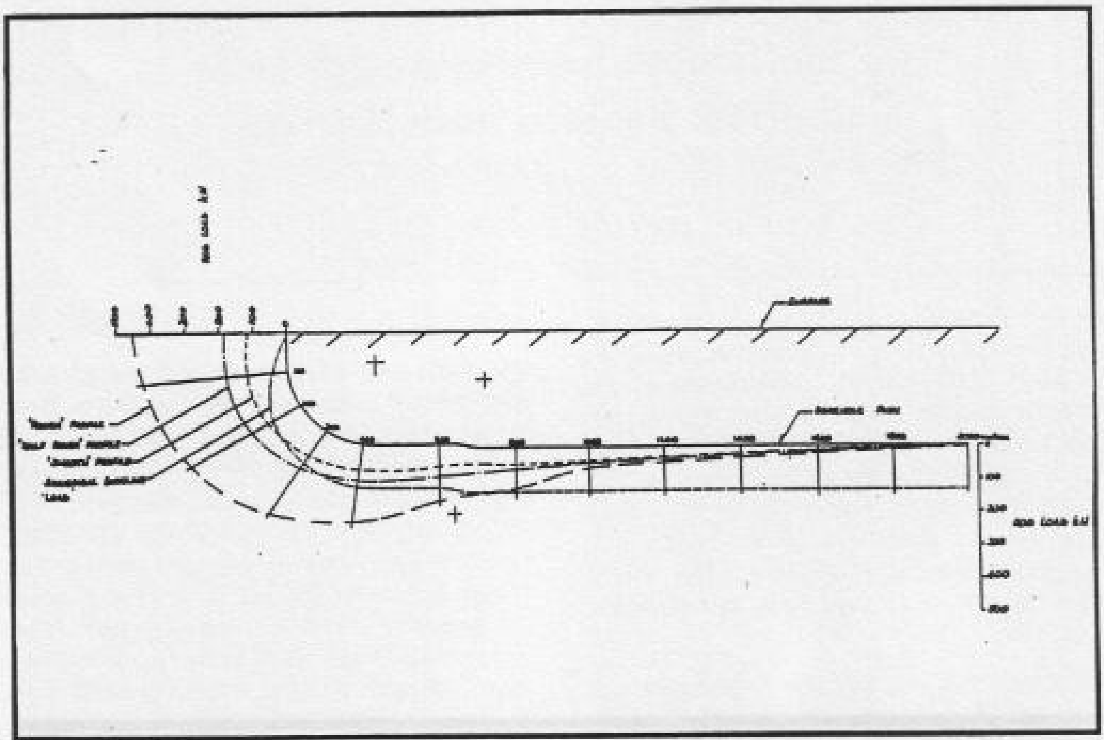

Figure 5. Rod loads for the example cases.

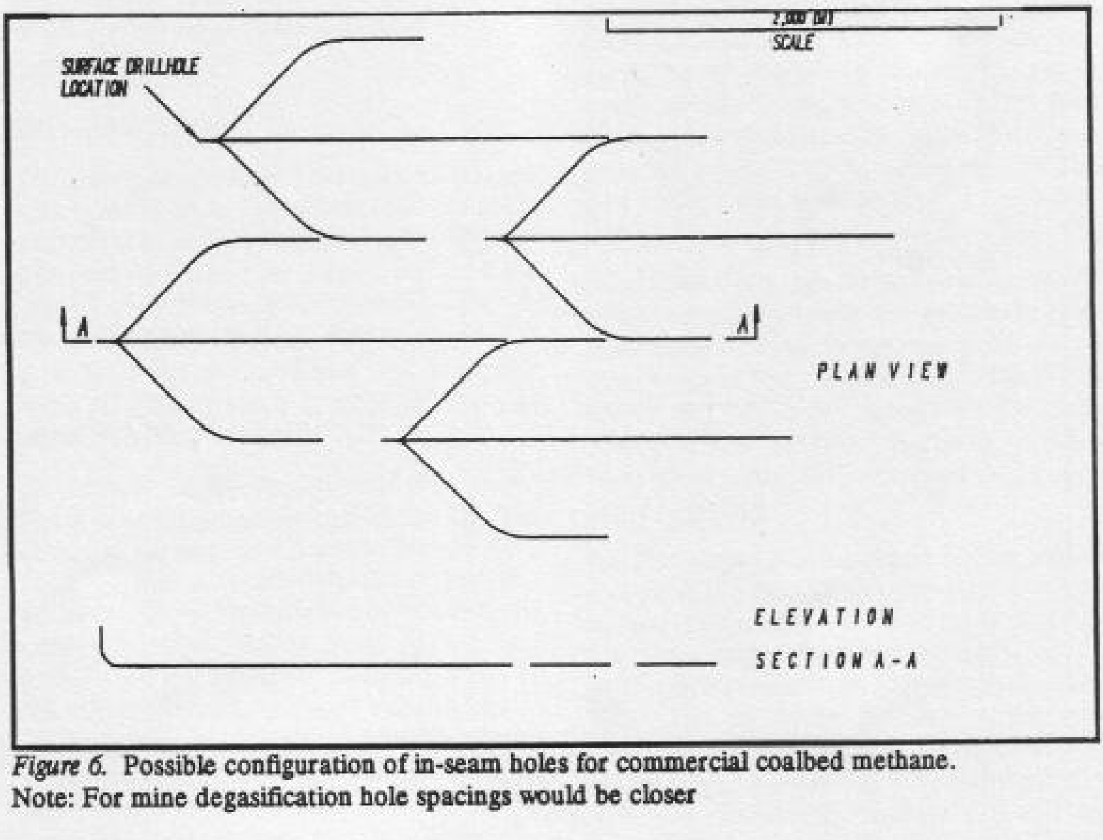

Figure 6. Possible configuration of in-seam holes for commercial coalbed methane. Note: For mine degasification hole spacings would be closer