THE STRUCTURAL PROPERTIES OF COAL AND THEIR EFFECT ON COAL EXCAVATION BY HIGH PRESSURE WATERJET IMPACT

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ABSTRACT
Faculty at the University of Missouri-Kansas City have carried out research on the application of high pressure water jets as a means of excavating coal for over 15 years. During the course of this time, a number of different concepts have been explored—the most recent of which has been the use of high pressure water jets as a means of extinguishing an underground coal seam fire. This paper will examine the use of some of these technologies and will consider the results as a basis for discussion of further applications of water jets in the future. The structural properties of coal that distinguish it from other materials and provide a considerable advantage to water jet cutting, will also be presented and the advantages of using this tool will be discussed.

INTRODUCTION
Conventional methods of underground coal excavation can be divided into two different approaches. The first method involves the use of mechanical cutter bars to undercut the coal. The overlying block of coal is then drilled with shot holes which are then filled with explosive and fired, blasting down the coal which is then loaded up by machine. This is typically referred to as conventional coal mining and is still responsible for a substantial portion of the coal mined from the smaller mines in the United States and around the world.

A more prevalent method of mining is to use a large machine which will grind the coal physically from the solid by the abrasion, chipping, spalling and crushing action of a series of picks set in a cylindrical drum which is rotated against the coal surface. The application of the drum can be either through a continuous miner which attacks the coal sensitively at the face end of a tunnel; or, it can be through the use of a shearer drum which sensibly attacks the coal along the side wall of a tunnel which then moves laterally into the coal seam. In either case, the action of the rotating drum provides a large amount of dust, which poses considerable hazard to the health of the operators. Concurrently, the impact of a pick on any abrasive material in the coal seam can generate hot enough spots of material to ignite methane which the coal seam is giving off. Again, this poses substantial risk to the operator. The coal produced by such machines is also generally in the size range below two cm and since modern environmental controls require that this coal be cleaned of dirt before it is sold and used, considerable expense is required in cleaning this coal—much more so than if the coal were of a larger product size.

These disadvantages together have led to a search for other methods of mining which would have improved economic advantage in coal mining conditions. The first of these methods was the application of relatively low pressure, high volume flows. This work was originally pioneered in the Soviet Union (Ref. 1), although concurrent work was also carried out in New Zealand (Ref. 2) prior to the Second World War. In the original application of the technology, itself borrowed from a system originally pioneered by the Romans in Spain (Ref. 3) for the removal of alluvium from gold deposits, the coal was blasted down, as in conventional mining, and the water was used to wash the coal into flumes which carried it out of the mine. (This procedure is now gaining favorable recognition as a means of handling the gold ore in the steros in South Africa.)

During the development of this technique it became evident that if the pressure of the water jet were increased then it would cut the coal without the need for the blasting cycle, thereby improving the production performance. As a result of experiments that were carried out in the 1930’s and following the hiatus caused by the Second World War, a hydraulic mine was established in the Soviet Union in 1952, the Tyranskie-Ulkozy Mine (Ref. 4). This was followed by the development of other mines in the Soviet Union and the technology has grown with a production level in the order of

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ten million tons per year has been achieved. The potential advantages of the technology were such that it has since been adopted in China, Japan, and Canada. Experiments have been carried out in Britain and Germany into the possibility of its application in those more difficult conditions and very recently a mine has begun development in the United States at which it is intended to use hydraulic mining as the major method of excavation.

This conventional use of high pressure water jets requires a relatively large volume flow rate, on the order of 3000 liters per minute, and a water jet pressure of approximately 10 MPa. However, the large volume flow limits the application of the technology to relatively thick, steeply dipping seams where entries can be driven at a sufficient grade that hydraulic transport from the stope can be used to extract the coal. In conditions where the seam is more shallow and there is an insufficient gradient to carry all the water away, then the interaction between the underclay and the water will lead to very rapid disintegration of the floor and the abandonment of the section with economic repercussions.

WATERJET USE IN COAL MINING

In order to apply the water jets to flat lying deposits a number of different techniques have been examined. Much of this development has been as a result of experiments funded by the U.S. Bureau of Mines, beginning in the mid 1970’s. In early experiments three different concepts were considered. Two of these involved the use of very high pressure water jets in application to continuous miner operation (Ref. 5, 6) while the third suggested that water jets could more effectively be used at the pressure of approximately 70 MPa, but at a greater flow rate (Ref. 7). After a year of experimentation it became evident that a much superior performance could be obtained from the use of the lower pressure water jet system as opposed to the higher for reasons which will be discussed later in this paper. As a consequence to the first year of experiments, further developments of water jet cutting of coal in the United States have been largely confined to pressures of 70 MPa and below.

Although recent attention has returned to addressing the problem of using water jets in room and pillar mining, this technology has largely been in abeyance since the mid 70’s and the major application of water jet technology has been confined to longwall mining of coal. Very simply, the technology which was proposed with the lower pressure system was to use high pressure water jets oscillating along the leading edge of the coal plow in order to cut a relieving slot into which the wedge of the plow could be fed. The wedge shape of the plow edge will break off the cantilever developed, producing thereby large blocks of coal with no dust and no potential sparking hazard.

Initial trials with a preliminary design of the system occurred in a surface mine in Missouri in the fall of 1976.

The results from the initial experiments demonstrated that the design of the machine was relatively web-insensitive; in other words, providing one of the jets was used to oscillate in the horizontal plane at the bottom of the seam section, the width of the block of coal which was peeled off by the plow had relatively little effect on machine load. It was, for example, demonstrated that such a plow could peel off, not the half a meter originally anticipated, but a slice of one meter width could be achieved with no significant increase in the haulage load on the machine. This is because the coal block has significantly little strength in tension, a major advantage to the application of water jet technology.

In the original experiments the experimental cutting head was able to work in a seam height of up to 1.5 meters, and achieved traverse speeds of up to 3 meters per minute. Because of the very limited period of time available for this testing and the limited conditions of test the full potential of the machine could not be developed in this experimental program although sufficient advantage was demonstrated that further work was carried out. Although the American program stopped shortly after a second generation machine had been built, work was continued in the Federal Republic of Germany. Two different competing designs were developed. The first of these was the "Hydrohebel" developed by Westfalia Lünen (Ref. 8). In this device fixed jets were placed along the edge of a coal plow to act in conjunction with conventional mechanical pick teeth. Although performance improvement for such a machine was on the order of 10%, the additional energy required argued against its use and that particular development has been abandoned.

A second device was developed, based more on the results of the American work, in which an oscillating water jet system was placed at the back of the plow cutting wedge (Ref. 9). This machine was tested underground at the Lüheberg mine and achieved production rates on the order of 20 tons per minute. The performance of the machine produced larger coal and eliminated the spark and respiratory dust problems as had been anticipated. However, because the lack of undercutting of the cantilever, the width of the web which could be achieved by the machine was limited. Further because the water jets oscillated only over portions of the plow face, using a different
design to the American machine, this prototype was less able to deal with dirt bands and other inclusions in the coal, and this program is also currently being pursued at a less accelerated rate.

**WATERJET DRILLING**

At the same time as work was progressing on the application of water jets to mining, an equivalent effort was being made in order to use this new tool in drilling applications. The original program had been directed at using water jets to drill roof bolt holes. The advantage anticipated from that effort was again multi-faceted. High pressure water jets can drill through some abrasive materials in a faster and more economical manner than can be achieved with conventional carbide drills, since there is no contact between a water jet drill and the rock surface.

Perhaps the best demonstration of this was in an underground lead mine in the United States where the lead occurs in a very abrasive sandstone (Ref. 10). With conventional pneumatic drilling, drilling rates of approximately 2.5 meters per minute were achieved, but the drill bits had to be replaced at least twice during the course of each hole. In contrast, a water jet drill operating at approximately 60 MPa and a flow rate of 60 liters per minute was able to drill blast-holes at an equivalent speed but with brass nozzles which showed no sign of any damage after drilling from five to ten holes in the abrasive material. An additional advantage demonstrated during that experiment was that holes could be drilled which intersected one another at an angle of less than 15 degrees. The second hole could be drilled without deviating from the first hole without any deviation. This would obviously allow a much more precise location of drill patterns than is often the case today.

The technology developed for water jet roof bolt drilling has since been adopted by two commercial companies and water jet roof bolting equipment is now on test both in the United States and South Africa. Within the United States the drilling problem has also progressed into examining the potential for drilling of coal (Ref. 11). The first set of experiments in this program was carried out in order to examine better methods for in situ gasification and methane drainage from coal. Conventional methods of coal gasification require that two adjacent vertical wells be sunk down to the coal seam and that a flame front be developed from one to the other by reverse combustion burning. This process is relatively slow and the position of the flame front cannot always be easily controlled. The University of Missouri-Rolla was asked to develop and demonstrate a technique for using a high pressure water jet drill to drive a hole along the bottom of the coal seam from one bore hole to the next. This required that a high pressure water jet drill be developed which was capable of turning a 90 degree radius and drilling out from a one meter diameter chamber reamed by water jet, at the bottom of the first vertical hole.

The method developed was demonstrated first in surface trials and then later, at Sandia Laboratories, in application from a vertical well into an underground coal seam where it was shown that it is possible to use such a system to drill out up to 30 meters from a vertical well and interconnect it to adjacent wells. The potential advantages of this technology are that the water jet is capable of creating this horizontal hole without the need for large excavation and sending men down into the coal seam in order to carry out the horizontal drilling. The result is a very rapid and inexpensive means of creating horizontal holes in coal, allowing the tapping of coal seams for methane drainage ahead of the mining cycle, providing both an economic fuel source and a safer mining method.

This water jet drilling concept which was used in creating the horizontal drill has since been applied in a modified form to extinguishing burning coal seams underground (Ref. 12, 13). Burning coal will develop temperatures in the coal seam in excess of 1200 degrees Centigrade. The overlying cap rocks can themselves be heated to temperatures in excess of 800 degrees Centigrade, baking clay and other materials into a fireclay consistency. Such high temperatures make the use of conventional drills difficult since the handling of drilling materials becomes problematic. There are also large quantities of carbon monoxide given off by the burning material, which makes close supervision of the work dangerous.

In the summer of 1983 a research team from the University of Missouri-Rolla, under the direction of the principal author, went to a site in eastern Montana where a coal seam outcrop was burning to a depth of approximately seven meters. As the coal seam burned the overlying rock collapsed over the seam making identification of the exact location of the coal difficult. A high pressure water jet drilling device was designed and it was clearly demonstrated that water jets were very easily capable of drilling along the flame front, extinguishing the burning material and removing it. A single water jet drill flowing approximately 60 liters per minute at a pressure of 70 MPa, created a cavity roughly 70 cm by 70 cm in a single pass along the burning coal front. It was possible in this manner to extinguish and remove all the burning material in the fire zone of the coal seam.
It did not, however, in those initial experiments, prove possible to totally extinguish all the coal, because the flame front did not migrate through the coal in a vertical plane but rather extended over a considerable lateral distance as the flame burned from the top to the bottom of the coal seam. As a result of this, it was possible to leave very small areas of burning material which lay outside the direct impact zone of the water jet drill. These small pockets of fire re-ignited the major portion of the coal seam over the period of approximately two to three days after the original fire had been extinguished. A different strategy has therefore had to be developed for this procedure. The strategy which has been developed, as does all other ideas for use of high pressure water, revolves around the peculiar characteristic of coal as it responds to water jet action and the purpose of the remaining portion of this paper is to address that topic.

WATERJET CUTTING TECHNOLOGY

Coal is a material which is defined in most deposits by fairly strong bedding planes in a horizontal direction and the presence of relatively closely spaced vertical joints which are commonly referred to as cleats. Although, in most coal seams, the evidence of this is only seen on a relatively large scale, experiments which are being carried out at the University using high pressure water indicates that the structure is carried through to a microscopic level and that the presence of the vertical and horizontal bedding defines small particles of coal which exist throughout the coal section. The advantage of this is more apparent in water jet attack than in mechanical cutting of the coal and relates to the method of coal fragmentation.

Conventional mechanical tools crush the coal and create a zone of fine material which acts as a plastic shield to the fresh coal face as the mechanised tool continues to cut into the surface. The result of this is that relatively high forces are required to remove the coal and the coal material is produced in solid form. In contrast, high pressure water jets penetrate into the material by working along the cracks which exist in the material surface. Any crushed and liberated material is immediately removed from the impact zone by the action of the water. The presence of the high density of cracks identified by the bedding and cleat provides easy passages for the water jets to get into the coal seam. As the water penetrates into these cracks the arrival of subsequent slugs of water will pressurise the water in the crack sufficiently to cause the crack to grow further. The growth of the crack in turn, will lead to its coalescence with adjacent cracks, liberating additional particles of coal from the surface. The free particles are then carried away by the water jet action.

The relatively large sizes of the original cracks in the coal seam means that little force is required from the jet in order to grow the cracks to the point of material failure. Relatively large volumes of material can thereby be removed at a relatively rapid rate. Success of this technology is clearly demonstrated by the results of the experiments described above. The advantages of the tool actually however, go beyond the dramatic reduction in the force required to fail the coal, since it is broken in tension rather than in triaxial compression. The first of these relates to the horizontal hole drilling in the coal. Because the water jets penetrate along horizontal and vertical cracks in the coal seam the water will develop a crack along the uppermost and lowermost horizontal bedding planes which are exposed by the drilling action. Thus, where a conventional mechanical drill will drill a round hole in the coal up to and down to a bedding plane, the water jet will drill a square hole, since the penetration of the water along the horizontal and vertical bedding planes will cause the material between that bedding plane and the hole section to be blown off by the water pressure in the crack.

The advantage of this type of hole lies in the control it affords to the hole direction. If the nozzle design is chosen with sufficient care, the drill will remain within those four limiting planes as the drill moves forward. In this manner, for example, the jet and thus the drill will be confined within the same section of the seam as the drill advances over the full hole length required. Thus by its own action, a water jet drill provides a self-generated, self-steering attribute to the drill which can then be used to drill over considerable horizontal distances, even though the seam section may vary within the vertical plane. This ability will require that there is sufficient flexibility within the drill stem to follow the contour. However, since the water jet will typically drill a hole that is on the order of 20 cm across, at an advance rate of two to three meters per minute, this is not a difficult constraint. It is practical to make a large enough hole to allow flexibility, but this solution has the disadvantage that it becomes difficult to get all the cuttings out of the hole since the water flow is insufficient to transport the cuttings since the annular velocity is too low.

The ability of the water jets to discriminately cut through material can also be put to good use on longwall faces and continuous miner sections as a means of improving the steering ability of the cutting drums. Dual
orifice waterjets can be configured to cut adjacent slots in the coal face, which are close enough that the intervening coal between the jets is removed by the migration and subsequent pressurization of the water jet along the bedding planes in the material. Thus the jets, cutting upward through the coal, will leave only a single wide slot through the coal. When, however, the jets cut up into an adjacent rock section this material has a finite tenacity strength and much smaller pre-existing cracks than does the coal. The result is that the intervening material between the adjacent jets is not removed. This will then leave a protruding between the two jet paths, as the jets enter the rock, and leave the coal. This surface provides a means of identifying the coal-rock interface and provides a restriction to cutting head movement, allowing development of a very simple and inexpensive method for automatically steering the machine.

One final advantage to the use of water jets should also be mentioned which resulted from the testing of their use in the lead mine. It was clearly demonstrated that water jets remove material by crack growth. Most mineral deposits contain different materials, each of which is defined by cracks along the intervening grain boundaries. Attacking water jets will grow these cracks to the point where the individual components of the ore are liberated on the grain size of the material. Since the mineral and the host rock are frequently in different size ranges, the result of this is that a relatively inexpensive method can be developed for mining material at the mining face and producing a feed which is already naturally segregated by size distribution for the different minerals contained in the ore deposit. A simple screen or similar device, at the mining machine can substantially enrich the feed from the machine into the transport system and dramatically lower the haulage and treatment costs of the ore from the mine.

A similar technology can be developed and applied in the mining of coal since many of the dirt bands and associated minerals which are found in the coal occur in relatively thick layers which can be separated from the coal at, or close to, the mining machine. This will dramatically reduce the amount of dirt contained in the coal as it is fed to the coal preparation plant. This will in itself reduce the cost of the cleaning but since the coal feed into the plant will also be in a different size range to that normally handled, significant additional savings in cleaning cost can be readily developed, which go beyond the initial advantages foreseen when water jets were first introduced into mining practice, namely the improvement in miner's safety and health.

The practical advantages of the water jet system is perhaps demonstrated by the growing list of advantages to its use which have been discovered as the technology has evolved, which all go much beyond the original view that there would be a compensating cost to be paid for the health and safety improvement. In the event there is not only less cost, but a cheaper, and more productive set of machines can be developed.

REFERENCES

3. Pliny, (42). **Natural History.** Opus 33.
