A radar-based highwall rib-thickness monitoring system

G.L. Mowrey, C.W. Ganoe and W.D. Monaghan

Abstract — *In addition to developing various types of coal-interface detection systems, the US Bureau of Mines is actively involved in developing a coal rib-thickness monitoring system for highwall mining applications. One particular system that shows promise uses a ground-penetrating radar system to detect the coal-air boundaries of coal ribs. Based on preliminary laboratory and field tests, results indicate that this method can be applied successfully in highwall mines to maintain a constant rib thickness. The coal seam should be relatively clean in the vicinity of the antenna (e.g., have minimal partings or dirt bands) for best results.*

Introduction

The US Bureau of Mines (USBM) is developing technology for mining machines that will be capable of tracking the boundaries of a coal seam and extracting only the desired material (Schnakenberg, 1989). One critical element associated with providing an automatic seam-tracking control for the mining machine is a coal-rock interface detector (CID) system. This CID system must be capable of measuring one or more distinguishing geophysical properties of coal and the adjacent formation and then must be able to make intelligent decisions such as identifying the type of geological material being cut, locating where the coal-rock interface is and/or determining the thickness of the coal remaining below the roof or above the floor.

Due to recent advances in sensor technology and computer-processing capability, the USBM has been investigating several CID concepts that can be applied to both current and future mining systems. The basic concepts presently being investigated include natural gamma radiation (NGR), thermal infrared (TIR), ground-penetrating radar (GPR), mining-machine vibration and video cameras (Mowrey, 1992; Mowrey et al., 1992). Other concepts being pursued include motor current/power, displacement rate, hydraulic pressure and/or flow rate, and total cutting energy. Mining systems that incorporate one or more appropriate CID-sensor technologies should be able to extract a higher-quality product more easily, at a faster rate and with increased safety. CID sensors could be used on existing continuous-mining machines, longwall shearers, highwall miners, bucket excavators and on any other type of surface or underground mining machines.

In conjunction with this CID research, the USBM is using GPR to develop a coal rib-thickness monitoring system, specifically designed for highwall mining applications.

Highwall mining operations

Highwall operators have been looking for a convenient, cost-effective method for measuring and maintaining a constant coal rib thickness. For example, for any given geological conditions, there is an optimum coal rib thickness that is wide enough to provide adequate support of the ground, yet does not waste coal. Highwall operators desire to maintain this optimum thickness throughout the depth of the entry. If it becomes too thin, there is a high risk of ground fall, which could result in having to dig or pull out buried equipment and even in injuries or fatalities. If it becomes too thick, permanently unrecoverable coal is left behind.

The highwall practice now in use is to take accurate surveys and align the mining machine properly with respect to these measurements. Current technology limits the depth of penetration of the cut. Thais is because of inaccuracies in setting the direction of the equipment and in the ability to measure and control the direction of the mining machine (e.g., cuts may intersect, causing an area of unsupported roof that may collapse onto the equipment), which results in less coal being recovered. In addition, both the coal geology and operating characteristics of the mining machine will affect how well it will track the previous cut (despite how accurately it is initially aligned). One method being evaluated by the USBM and some mining companies is the use of a highly accurate inertial-guidance system developed for military applications (Sammarco, 1993). This technology, based upon ring-laser gyroscope (RLG) technology, has an azimuth accuracy of about 0.028°, which translates to about 30 cm in uncertainty at a distance of 300 m. Some success has been achieved by using the RLG in either of two ways:

- to set the initial azimuth of the machine equal to that of the prior entry and ensuring the machine heading remains at that value during the first few feet of the cut; or
- to monitor and correct mining machine-direction throughout the length of the cut.

The accuracy of these procedures has not yet been fully determined. Disadvantages of the RLG are its cost (greater than $100,000), an initialization process that requires an accurate surveying of the RLG coordinates, a periodic requirement (for full accuracy) of a few seconds of non-production activity every minute or so to allow the RLG to rereference itself and that the RLG does not produce a direct measurement of rib thickness. Ignoring the initialization procedures reduces the RLG accuracy. If the requirement of periodic referencing is ignored, the accuracy of the RLG will degrade to a drift of 0.015 to 0.020 m/hr.

As a possible alternative to the RLG, the USBM is concurrently investigating the application of ground-penetrating radar (GPR), which is capable of seeing through the coal seam and measuring the coal rib thickness to the previously cut entry. The advantages of GPR are that it directly measures

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the coal rib thickness between the mining machine and the previously cut entry and that the current cost is about one-fourth that of an RLG system. The main disadvantage of the GPR is that some coal seams are "dirty", i.e., that there are partings and dirt bands in the coal that can attenuate the GPR signals, so that the reflected echo signals are too small and/or noisy to be used to determine coal rib thickness.

Ground-penetrating radar system

Background. The idea that radar could be used to monitor the thickness of coal ribs was based on research done by Cook (1975). Cook found that clean coal is relatively transparent to ground-penetrating radar (GPR). The success of a radar system at a given location primarily depends upon two electrical parameters of the material being tested, namely, electrical conductivity and dielectric constant.

Electrical conductivity is the ability of a material to conduct electrical current, and it determines the depth of penetration of the radar signal, i.e., greater conductivity results in lesser depth of penetration. Conductivity, expressed in Siemens per meter (S/m), can vary greatly for geological materials and is primarily governed by the water content and the amount of dissolved salts, as well as the density and temperature of the material.

The dielectric constant ε_r is a dimensionless measure of the capacity of a material to store a charge when an electrical field is applied, and it can range between one (air) and 81 (water). The ε_r ranges of materials found in coal mines are as follows: coal, 4 to 5; saturated silt or clay, 8 to 12; dry sand, 4 to 6; water-saturated sand, 30; and limestone, 7 to 9. It is important to note that radar signals are reflected by changes in the dielectric constant in its path (e.g., by different geological boundaries). Larger changes in the dielectric constant over shorter distances result in larger reflections. Reflections are even greater if the boundary is nearly planar and perpendicular to the direction of the radar. The coal-air boundary of the coal rib provides an excellent condition for radar reflections. In addition, layered geological formations, typically found in coal-bearing strata, lend themselves to being detected and measured by radar techniques. Hence, a radar-based system could also be used to measure thickness of coal left on the roof or floor, if mining practices required that to be done.

Knowing the dielectric constant of the material (e.g., coal) will provide velocity and travel time information. Conversely, by measuring the travel time and measuring the distance between the antenna and the boundary of interest, the dielectric constant of the material can be determined. For example, the velocity of the radar signal through a particular geological material is related to the dielectric constant:

$$V_m = c/\div\varepsilon_r \qquad (1)$$

in m/sec, where

V_m = radar signal velocity in the material (m/sec);
c = speed of light in a vacuum ($3 \xi 10^8$ m/sec); and
ε_r = dielectric constant of the material.

The travel time slowness (reciprocal of velocity) is also related to the dielectric constant as follows

$$TT = 3.33 \times \div \wp \varepsilon_r \qquad (2)$$

where TT = travel time slowness (in ns/m).

The two-way travel time is what is actually seen on a radar plot, i.e., outgoing travel time plus return signal travel time Two-way travel time per meter of depth is

$$2 \times 3.33 \times \div \wp \varepsilon_r \qquad (3)$$

in ns/m.

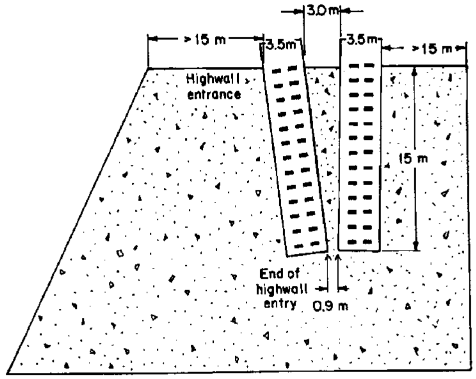

Fig. 1 — Diagram of prepared highwall field site for radar testing.

Another consideration is the effect of air gap that exists between the radar antenna and the formation. Ideally, the antenna should be placed as close as possible to the formation being tested for optimum coupling and to minimize energy losses due to significant dielectric-property contrasts between air ($\varepsilon_r = 1$) and various geological materials ($\varepsilon_r = 4$ to 6). The further the antenna is away from the formation, the greater the amount of signal attenuation; generally, the spacing should be no more than 10 cm (4 in) away from the formation.

System description. A commercially available pulse-based radar system, the SIR-10, made by Geophysical Survey Systems, Inc. (GSSI),[1] can provide instant continuous-profile radar records (in either color or black and white) that indicate the location and depth of strata and buried objects (buried up to more than 6 m (20 ft), depending upon the antenna frequency and target size and geometry) within the subsurface of soil, sand, concrete, asphalt, rock, water, ice and other materials. Profile data are displayed on an EGA (640 x 350 pixels) color monitor in either a color line-scan or a black-and-white wiggle-plot format. Scan rates can be set from 3.2 to 256 scans per second with either 128, 256, 512 or 1,024 samples per scan. Signal amplitudes can be set at either 8-bit or 16-bit resolution. Either manual receiver-gain adjustment or an automatic gain can be used, with up to eight individually adjustable gain points. Collected radar data can be stored on a 2.3-GB internal cassette-tape drive.

The USBM currently has radar antennas that operate at 300, 500, 900 and 1,000 MHz. Depth of penetration is primarily dependent upon the antenna frequency (i.e., as the frequency increases, the depth of penetration decreases). For example, the 500-MHz antenna has been found to have a range of approximately 0.5 to 5 m (1.5 to 15 ft) in coal and the 900-MHz antenna has a range of approximately 0.2 to 1.5 m (8 in. to 5 ft) in coal.

[1] Reference to specific products does not imply endorsement by the USBM.

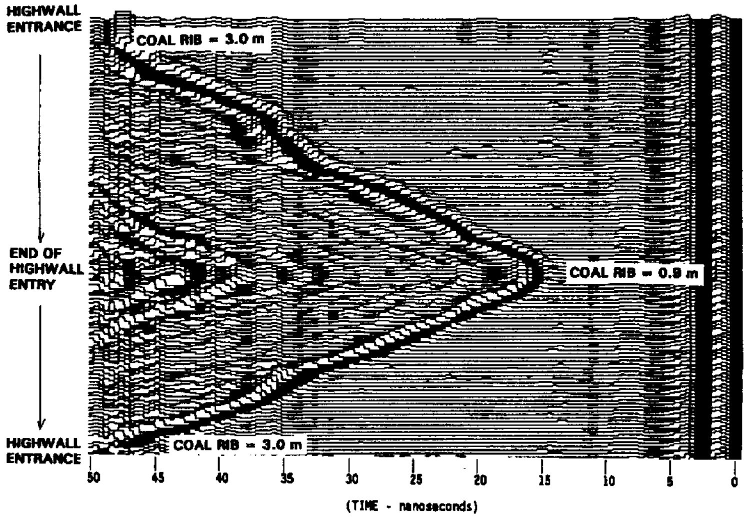

Fig. 2 — Wiggle-line radar plot of Test 1 (no air gap between antenna and coal rib).

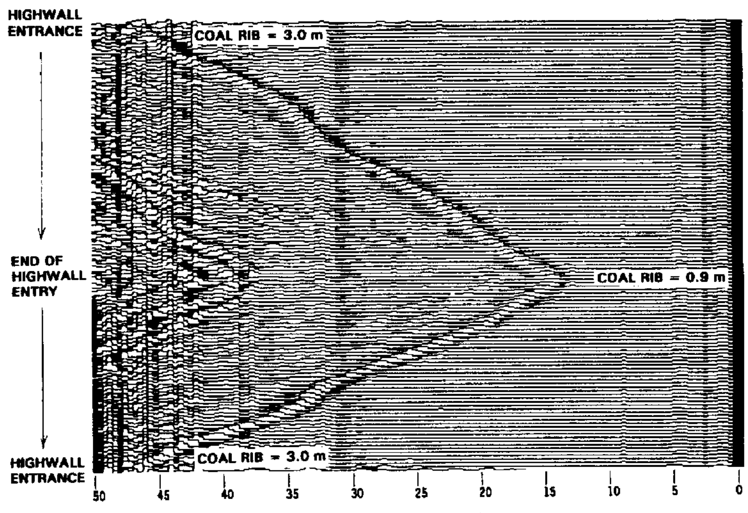

Fig. 3 — Wiggle-line radar plot of Test 2 (10-cm (4-in.) air gap between antenna and coal rib).

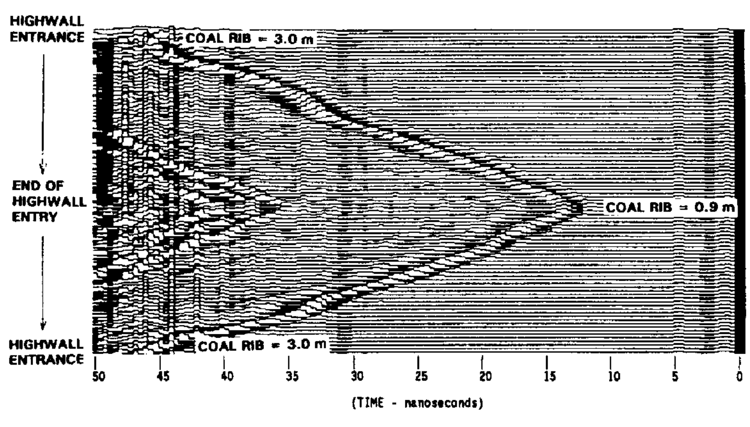

Fig. 4 — Wiggle-line radar plot of Test 3 (5-cm (2-in.) air gap between antenna and coal rib).

GPR test at highwall site

The SIR-10 system was taken to a highwall mining site in Kentucky in March 1993 for the purpose of evaluating the feasibility of using GPR to measure coal rib thickness and to obtain information regarding the depth of penetration and the effect of air gap on GPR response. A 500-MHz antenna was used and was found to be capable of measuring coal rib thickness from 0.9 m (3 ft) to more than 3 m (10 ft). The best results were obtained with the antenna being at no more than 5 cm (2 in) from the coal surface. The antenna was positioned near the top of the coal seam, because the cleanest coal was located there.

The highwall mine operator prepared two highwall entries, each being approximately 15 m (50 ft) in length, 3.5 m (11.5 ft) in width and 1 m (3.2 ft) high (Fig. 1). The first entry was driven straight into the highwall. The second entry was driven in about 3 m (10 ft) from the first and was deliberately angled in such a way as to come to within approximately 0.9 m (3 ft) of the end of the first entry. The overburden consisted primarily of shale and was approximately 15 m (50 ft) thick.

USBM personnel ran several basic radar tests. The first test consisted of placing the 500-MHz antenna directly against the rib wall in the angled entry and moving it continuously from the entrance to the end of this entry and back to the entrance. A wiggle plot of the entire test is shown in Fig. 2. For the next test, a 10-cm (4-in) piece of Styrofoam was placed in front of the antenna, and the antenna was continuously moved from the entrance to the end and back to the entrance (Fig. 3). A third test consisted of replacing the 10-cm (4-in) piece of Styrofoam with a 5-cm (2-in) piece of Styrofoam and rerunning the same test a third time (Fig. 4).

The amplifier gain settings were adjusted for optimum performance for the first test and were kept at the same values for the remaining tests. Also, due to the difficult operating conditions at the site and inclement weather, USBM personnel decided to run the antenna without its surrounding metal shield and a radar-absorbing material, which would be needed when it was mounted on a mining machine. Laboratory and underground GPR tests at the USBM have shown that, by surrounding the 500-MHz antenna with 5 to 10 cm (2 to 4 in) of the radar-absorbing material and placing it in a metal box, the GPR response is approximately the same as the GPR response without the metal box and radar-absorbing material.

In all three cases, the radar was capable of "seeing through" the coal rib at thicknesses ranging from 0.9 m (3 ft) to more than 3 m (10 ft).

Prototype coal rib-thickness monitoring apparatus

Based on the results of the tests done at the Kentucky highwall site, a prototype apparatus was constructed for highwall coal rib-thickness monitoring applications.

The apparatus consists of the following basic components:

- A commercially available pulse-based radar system, which operates in the 100 to 1,000 MHz range, provides the transmit pulse and the receiver electronics (e.g., GSSI SIR-10 system or equivalent).
- Mine Safety and Health Administration- (MSHA-) approved barrier box, which provides the necessary electrical isolation between the radar antennas and radar system.
- MSHA-approved radar transmit and receive antennas, which are designed to be intrinsically safe for use in a coal-mine environment.
- A 386-based (or better) personal computer with color display, which provides the means for performing signal processing and displaying rib thickness (absolute or relative) continuously, for the guidance of the mining machine, e.g., rib thickness displayed in real time (immediately as the mining occurs).
- Software that provides the radar signal processing and display for the highwall machine operator.

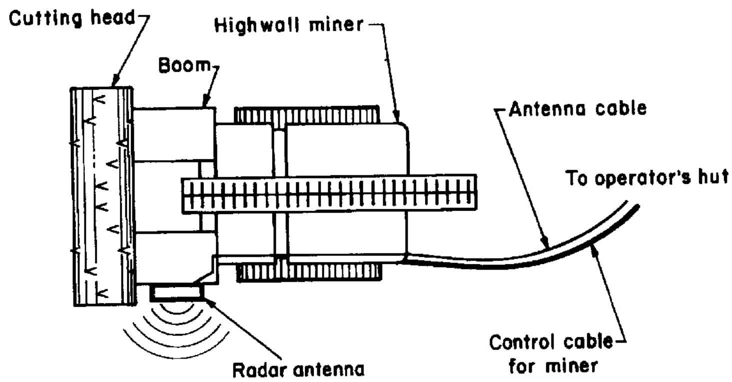

Fig. 5 — Conceptual diagram of the radar antenna mounted on a highwall miner.

The antenna assembly, which contains MSHA-approved radar transmit-and-receive broad-band bow-tie antennas (e.g., 500-MHz), is mounted on the side of a highwall miner in a protected enclosure near the cutting head, as shown in Fig. 5. An electrical cable connects the antenna to an MSHA-approved barrier box that is located outside the highwall entry, as shown in Fig. 6. Other components include the radar-controller system, operator interface (radar keyboard), personal computer and operator display (monitor). The radar-control system generates the transmit pulses and receives the return signals. A specially trained operator makes adjustments to the radar system (including scan rate, scan range, time and amplitude resolution and receiver amplifier gains) to get the best radar signal possible. Then, the highwall machine operator periodically views a computer display monitor that provides the highwall coal rib thickness in feet and inches (e.g., the thickness of the coal that exists between the entry that is being cut and the previously cut entry).

The radar-control system sends out a radar pulse through the barrier box to the transmit antenna. A portion of this pulse then leaves the antenna and propagates through the air to the surface of the coal rib. Some of the transmitted radar energy is reflected at this initial coal-air boundary and is detected by the receive antenna as shown in Fig. 7. Another portion of this radar pulse passes through the entire coal rib and a second reflection is produced at the second coal-air interface. This second reflection is also detected by the receive antenna, although it is at a reduced amplitude, depending upon the thickness and dielectric properties of the coal and other geological materials present in the coal rib.

The computer program reads a series of radar scans and averages the scans into a composite scan, which helps to reduce noise spikes and other signal anomalies. Each scan consists of the transmit pulse and one or more reflected pulses. Using the composite scan, the program determines the maximum peak associated with the transmit pulse and assigns this point the time of "T_0," which represents the starting time. After a preset delay after the transmit pulse, the program searches for the first peak above a predetermined amplitude threshold level and computes the time difference between the two peaks. The program then uses the two-way travel time for radar waves through coal (e.g., 14.8 ns/m (4.5 ns/ft)) to compute a coal rib-thickness value. The operator has the option of using preset (default) values (e.g., 30 scans per second, 14.8 ns/m (4.5 ns/ft), etc.) or selecting other values. The operator can also put boundaries on the data, e.g., where "T_0" begins, when to start to look for a reflection peak and what level of threshold is needed for best results.

The optimum procedure in using this apparatus consists of installing the radar antenna on the highwall mining machine as near as practical to the cutting head. Another important consideration is to position the antenna as close to the coal rib as possible to maximize the amount of energy that can be transferred into the coal rib. A third consideration is to have the antenna mounted on the mining machine, so that the antenna is positioned in the vicinity of the cleanest coal in the seam.

The highwall miner, after mining the first entry into the highwall without radar guidance, is aligned parallel to the first entry. The highwall miner then begins cutting into the second entry, again without radar guidance, until the radar antenna is inside the highwall at least 3 m (10 ft). The operator then adjusts the radar controller to obtain a good radar reflection signal from the other side of the coal rib. A good radar reflection signal is needed for this method to work successfully. Typical radar parameters would be 16-bit data, 512 data points per scan and 30 scans per second. Assuming a two-way travel time of 14.8 ns/m (4.5 ns/ft) through coal and having a 1.5-m (5-ft) rib, the total travel time should be on the order of 22.5 ns. The operator would then use a personal computer to begin reading the radar data and computing coal rib thickness. If the computed coal rib thickness is acceptable, the operator can begin to perform normal highwall mining activities. If it is not acceptable, the operator must determine if the radar signal looks normal, based on previous experience. If it does not look normal, the operator should try readjusting the radar for a good return reflection in the expected time window (e.g., at approximately 20 to 25 ns for a 1.5-m (5-ft) coal rib). If the signal appears acceptable and is arriving at the expected time, but the coal rib thickness, as reported by the radar, is definitely wrong, then either the amplitude threshold may not be properly set

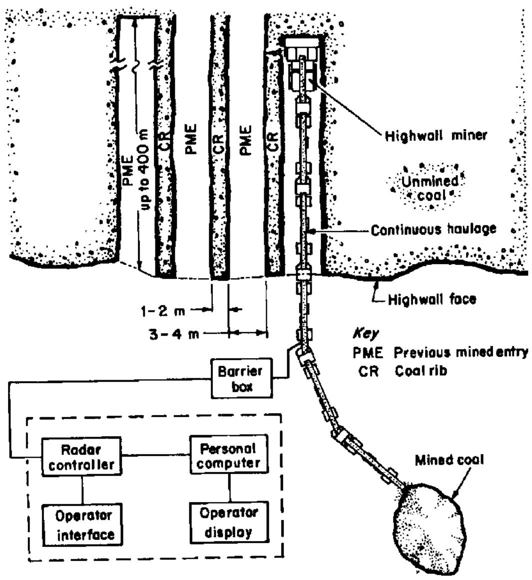

Fig. 6 — Complete radar system as it would be applied to a highwall-mining operation.

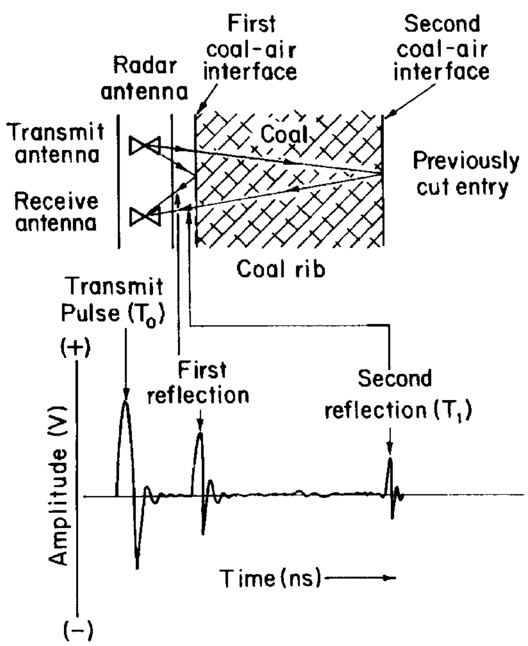

Fig. 7 — Basic principle of the radar-based coal rib-thickness-measurement method.

or the two-way travel time should be changed to give the proper coal rib thickness.

Summary and comments

A ground-penetrating radar (GPR) system has been used by the USBM to verify the feasibility of the radar technique for determining coal rib thickness in highwall applications at a selected field site. A prototype GPR-based apparatus has been developed and constructed. The accuracy of the coal thickness measurements will be determined by the dielectric characteristics of the coal at each location.

For the GPR technique to work properly, the main requirements are as follows:

- A continuous portion of the coal seam should be relatively clean (at least the width of the antenna, e.g., 0.6 m (2 ft) or more) with little or no partings or dirt/clay bands.
- Rib thickness should be between 0.6 to 3 m (2 to 10 ft).
- GPR antenna should be within 5 cm (2 in) of the rib.

The advantages of the GPR system mounted on a mining machine vs. drilling horizontal holes through coal ribs to determine rib thickness are:

- Drilling is not required.
- Roof support is not needed.
- Workers are not required to enter the highwall.
- Measurements do not require stoppage of production.
- Measurements are made in a timely manner.

Consequently, this system can be used to control rib thickness by providing timely information to an operator or computer, so that the mining machine heading or lateral position can be altered while continuing to mine coal.

Other benefits that can be obtained using GPR include

- increased safety for miners;
- increased production rates, i.e., the mining machine does not have to be stopped in order to obtain a coal thickness reading — thickness readings are continuous and in real time;
- less downtime due to rib instabilities, i.e., more constant and substantial coal ribs result in more stable geological conditions;
- deeper penetration into the highwall, owing to the greater certainty in knowing and maintaining constant coal rib thickness;
- increased recovery of reserves resulting in higher profits and less waste; and
- increased reserves by being able to mine previously unminable seams.

The initial findings in this research have shown considerable promise in confirming that radar-based coal rib thickness sensor technology has the potential for working in a highwall mining environment. It is expected that the end result of this research will lead to the development of a rugged, low-cost, radar-based rib thickness monitoring tool that can be routinely used by highwall mine operators.

In addition to measuring rib thickness, USBM personnel hope to eventually use this type of radar as a CID technique for measuring roof and/or floor coal thickness as well. This will require visiting selected mines having various geologies, so that the equipment can be adjusted for optimum performance.

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