Demonstration of remote mine seal construction

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Abstract

Mine seals can be remotely constructed in underground coal mines through vertical boreholes when direct access to a fire is impossible or considered to be too dangerous. This method has great merit because the boreholes can be drilled to specific mine areas, and the seals can be positioned close to a fire zone. The technology, however, can be largely ineffective if the constructed seals do not provide effective barriers to airflow or if they cannot be used to impound water and other inert materials. Unfortunately, no viable alternatives exist to sealing the entire mine at the ground surface. Full-scale remote mine seal construction research is being conducted at the National Institute for Occupational Safety and Health's (NIOSH) Lake Lynn Laboratory (LLL). Under this effort, Howard Concrete Pumping Company and GAI Consultants Inc. have joined forces to evaluate a potentially significant improvement to the current state of the art. This paper covers the development of novel technology for remote mine seal construction, the evaluation of the materials used, the construction practice and the follow-up testing.

Introduction

Mine fires constitute one of the greatest threats to the health and safety of those working in the underground mine environment. From 1991 through 2000 there were 76 underground coal mine fires and 61 underground metal/nonmetal mine fires reported to the Mine Safety and Heath Administration (MSHA, 2003). In the early stages of a mine fire, miners try to fight the fire if possible with water, foam, dry chemical powder, rock dust or sand. This practice, however, can place miners dangerously close to the fire zone and is typically only effective in the very early stages of a mine fire. When a mine fire grows out of control and is too dangerous to fight directly, the fire area is often sealed to limit the inflow of oxygen and contain the fire. Mine seals can be built by miners underground, but such efforts become problematic when underground conditions become unsafe for reasons including the potential for a mine explosion.

An effective solution when underground access is impossible is to build airtight mine seals remotely through vertical boreholes. The need to evaluate, improve and develop new technology to remotely construct mine seals was identified jointly by NIOSH and MSHA in 2001, and this need resulted in a three-phase NIOSH research project (NIOSH, 2001). In addition, MSHA agreed to serve as a cooperator in this effort.

Phase One involved the qualitative review of existing technology used to remotely construct mine seals. The review included materials used to construct mine seals, including cement and polyurethane foam, and an analysis of the available material mixing technologies (surface versus downhole mixing) (Trevits and Urosek, 2002).

Phase Two of the research (ongoing through December 2004) involves the remote construction of mine seals at LLL. The services of Howard Concrete Pumping Company (Howard), Cuddy, Pennsylvania, were contracted by NIOSH to construct the seals for Phase Two. GAI Consultants, Inc., (GAI) of Monroeville, Pennsylvania, provided technical expertise to Howard for remote seal design and for developing the implementation procedure.

Phase Three of the research was tentatively planned to begin sometime after January 2005 (pending approval and funding). The work involves a field demonstration at an actual mine site

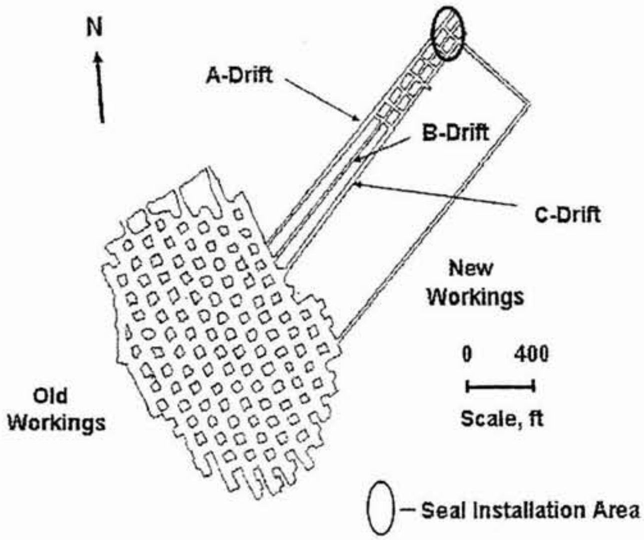

Figure 1 — Layout of the Lake Lynn Laboratory Mine.

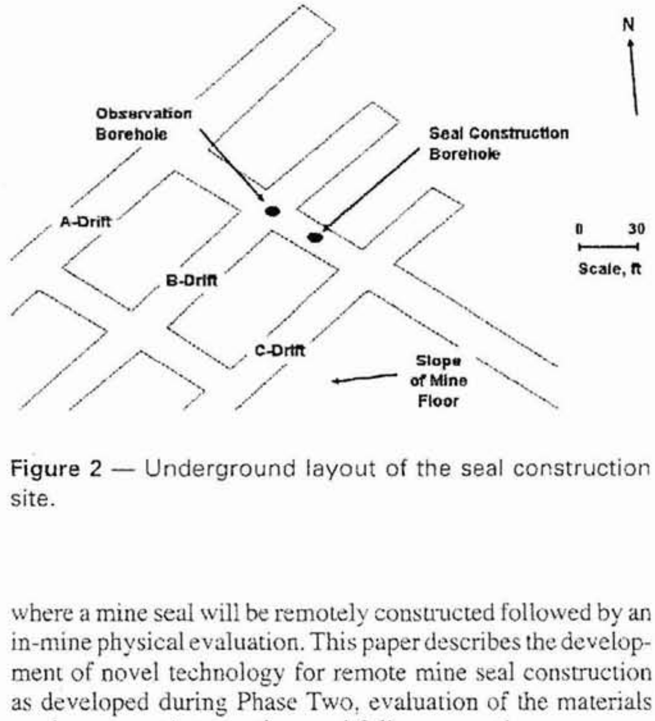

Figure 2 — Underground layout of the seal construction site.

where a mine seal will be remotely constructed followed by an in-mine physical evaluation. This paper describes the development of novel technology for remote mine seal construction as developed during Phase Two, evaluation of the materials used, construction practices and follow-up testing.

Project plan

The objective of this project was to develop a specialty grout product and a method for placing the product through a borehole into a mine opening to form a mine seal at a reasonable cost. Several additional engineering design constraints were imposed by NIOSH and included the following:

- the methodology developed must be capable of being deployed quickly;
- the mine seal must be capable of being rapidly installed;
- the material used must be locally available;
- the seal must be made of noncombustible material;
- the grout material must be of a consistency to allow placement in a free space without excessive flow if the mine is open and unobstructed but have flowable characteristics should the mine opening contain roof fall debris, cribbing, equipment or conveyor structures;
- the grout and the methods of application must facilitate mine roof-to-floor and rib-to-rib closure; and
- the seal must be strong enough to withstand the force of a mine explosion, up to 140 kPa (20 psi).

The work was conducted at LLL. The Lake Lynn Laboratory is a highly sophisticated underground and surface laboratory located about 100 km (60 miles) southeast of Pittsburgh, Pennsylvania, and 16 km (10 miles) northeast of Morgantown, West Virginia, where large-scale explosion trials, mine fire research and a myriad of other mine safety and health research programs are conducted. The underground workings are sized to match those of commercial mines, thus making them true, full-scale test galleries. Movable bulkheads permit the setup of single-entry, triple-entry and longwall face configurations for experiments (NIOSH, 1999) (Fig. 1).

Previously, a 152.4-mm- (6-in.-) diameter cased borehole was completed in the first crosscut between the B and C Drifts of the experimental mine, and it was determined that this borehole was suitable for the seal construction work (Fig. 2). The thickness of the overburden in the area of the borehole is about 60 m (200 ft). The crosscut in the mine measured 5.8 m (19 ft) wide, 12.2 m (40 ft) long and 2.1 m (7 ft) high. The floor sloped on the order of a 1.13% gradient. A second borehole, located about 9 m (30 ft) away, was available for viewing the mine seal installation through use of a downhole video camera. In-mine to surface communication was facilitated through the use of a mine pager phone system.

Grout material. Constructing an effective mine seal through a single borehole is a difficult engineering challenge. The grout mixture cannot be too fluid or it will flow away from the borehole. If the grout mixture is too stiff, it will tend to build quickly forming a mound at the bottom of the borehole and will not flow and fill the mine roof-rib areas. The Howard/GAI team determined that two different grout placement techniques, and grout mixes were needed to meet this design challenge. It was decided that the first material to be placed in the mine would fill most of the open space. This was also the less costly component of the fill material and would help to lower the overall cost of the seal. The design of the bulk-fill material for the mine seal called for fly ash, Portland cement and a 2A (-19-mm, -3/4-in.) crushed limestone aggregate. A conventional concrete admixture was used to accelerate the set of the grout. The material was blended to achieve a pumpable mixture that had adequate strength and rapid setting properties. The amount of fly ash added was sufficient to produce a mix that could be pumped to the borehole, travel down the borehole without segregation and provide a moderate degree of flowability. Once the grout was in place, the aggregate would provide sufficient shear resistance for the grout to be somewhat immobile until the mix set. Typical initial set time for this mixture could be achieved in 15 to 20 minutes and would support foot traffic in 30 to 45 minutes.

The second material to be used to fill any remaining open space above the bulk fill along the roof-rib line was a two-part grout blend that was developed with the assistance of Master Builder's Concrete Products Laboratory in Cleveland, Ohio. The basic grout was to be a blend of ASTM Class-F fly ash and Portland cement. The initial testing of the grout indicated that a conventional shotcrete accelerator would not produce sufficient stiffening in the desired time frame. Additionally, it did not exhibit suitable rheological and hardening properties required for the grout application. Further testing determined that Master Builder's TCC system was more effective in providing the desired grout characteristics than conventional admixtures.

The Master Builder TCC System is made up of two-parts. Part A improves the pumping characteristics and provides a reaction platform for Part B, and it is added just prior to injection into the pump. Part B is a liquid, high performance shotcrete and grout accelerator that reacts with Part A to create an immediate stiffening of the grout. Part B is added at the spray nozzle via a stream of air that transports the grout to the mine roof-and-rib surface. The reaction between the Part A and Part B admixtures essentially provides the initial stiffening through a flocculation process that is unrelated to the chemical hydration of the cement products in the grout. Therefore, a concrete accelerator was also added at the nozzle to accelerate the hydration process. The addition of the accelerator along with the cement content of the grout facilitated rapid strength development of the in-place grout spray.

To improve the stiffening properties of the grout and produce the required stickiness for the grout spray to adhere to the mine roof-and-rib areas, the water content of the mix was adjusted while retaining the fluidity and pumpability of the mix through the addition of a high-range water-reducing additive.

As the material development phase progressed, it became apparent the uniform, consistent blending of the constituents in the sprayed grout was critical to the grout performance. The final portion of the grout mix design work focused on a sensitivity study that identified the grout's reaction to deviations in the blending process. It was concluded that it would be necessary to very finely meter the ingredients in the grout mix to achieve the desired performance from the sprayed grout.

Grout placement techniques. As mentioned above, the Howard/GAI team determined that two grout placement techniques were needed. It was believed that placement of the bulk fill would form a mound below the borehole and would leave an open space near the mine roof-rib area. Therefore, a second placement technique was needed to address the remaining open areas.

The first process was designed to use a technique very similar to that used when placing bulk grout with a tremie pipe. The concept called for the bottom of the injection casing to be slotted to facilitate some directional control of the grout stream. The bulk grout material would be placed in separate lifts with time between lifts to allow the material to begin to stiffen. The second placement technique required the use of two strings of pipe (one inside of the other) to convey two streams of material to a spray nozzle. The spray nozzle permitted the blending of the two-part grout accelerator mix while allowing sufficient air velocity to transport the grout to the mine roof-and-rib areas. A spray nozzle was designed by GAI for this purpose (refer to Fig. 3). In both techniques, an on-site volumetric mixing plant was used to blend the grout mixture. The bulk grout was pumped to the borehole using a positive displacement pump and the sprayed grout was moved to the borehole using a conventional grout pump and compressed air.

Mine seal construction

Prior to constructing the mine seal at LLL, a model mine opening was constructed at Howard's facility in Cuddy, Pennsylvania. The model mine opening was constructed for testing and direct observation of the performance of the downhole nozzle and pumping equipment. The model mine opening consisted of a small excavation in a hillside (Fig. 4). The roof of the model mine was formed using crane mats so a drill rig could be located over the mine void to hold the pipe for the spray nozzle.

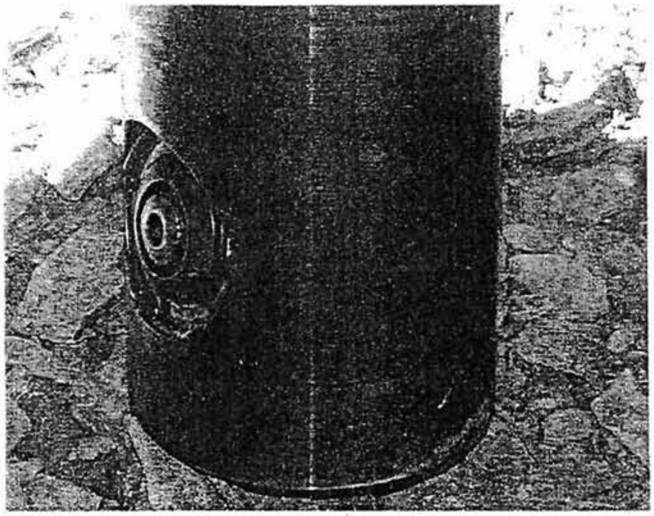

Figure 3 — Spray nozzle.

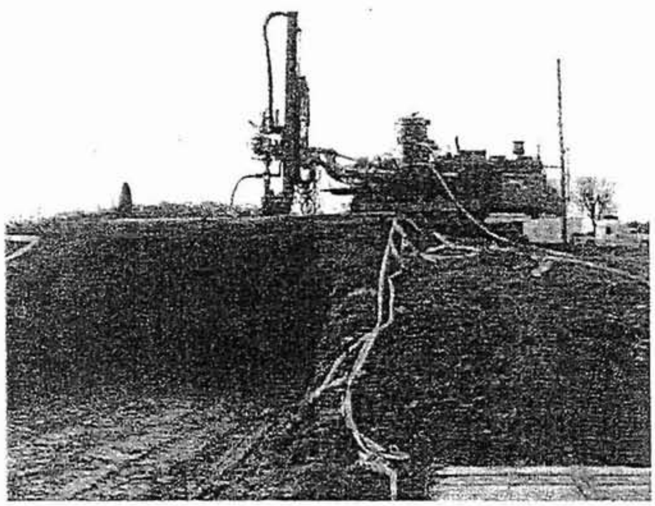

Figure 4 — View of the model mine.

The equipment necessary for a test was assembled at the demonstration site, and a small quantity, i.e., 3.8 m^3 (5 cu yd), of test material was mixed in a concrete transit mixer truck. Material was sprayed into the model mine void and the results of the test were evaluated. During the spraying process, several adjustments to the admixture formulation were made as well as air transport velocities and spray rotational velocity. Samples of the grout were prepared for strength evaluation and time-of-set. From the information collected during the initial demonstration, modifications were made to the nozzle and the drill rig used to support the pipe string. Changes were also made to the cement content, admixtures and additive ratios to improve stickiness, time-of-set and application uniformity. Some laboratory work was also conducted to improve the grout blends by modifying admixtures and additive ratios. After additional shop trials and modifications to the equipment, a second full-scale surface demonstration was conducted to evaluate the

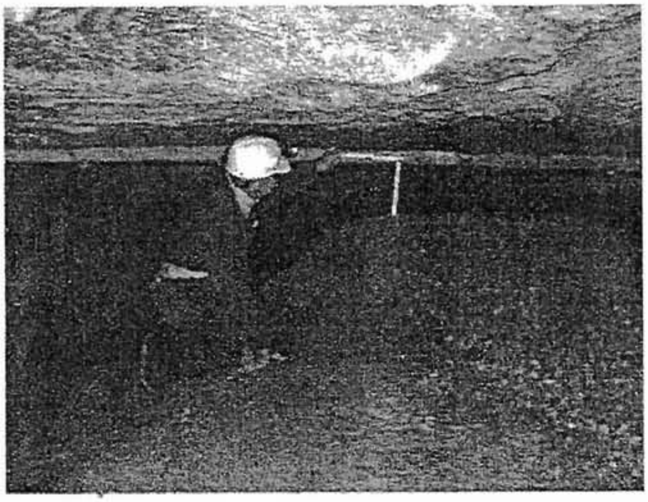

Figure 5 — Underground view of bulk fill material for seal No. 1.

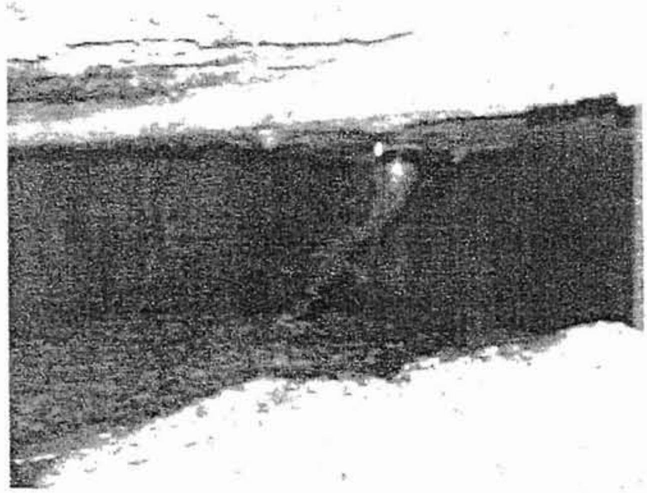

Figure 7 — Underground view of elbow placing bulk fill.

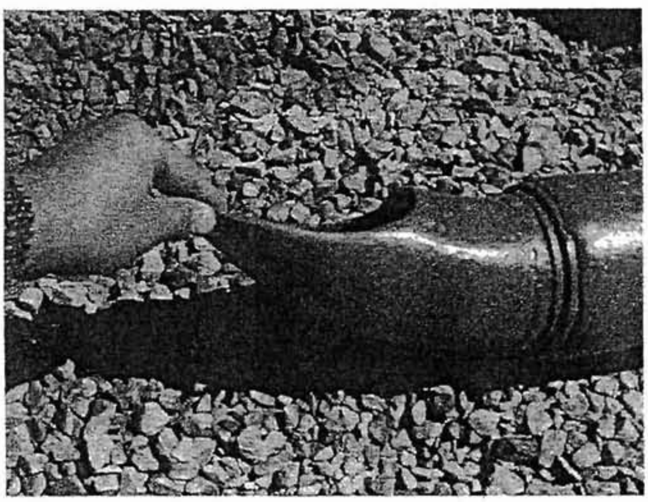

Figure 6 — Elbow for bulk fill placement.

impact of the modifications to the materials and equipment on the characteristics of the resultant grout mix. The result of this demonstration was used again to modify materials, equipment and equipment usage.

Mine Seal No. 1. On July 19, 2002, Howard mobilized their mixing, pumping and injection equipment to LLL. The equipment included a volumetric mixer batch plant, cement storage silo, water tanks, group pumps, air compressor, a drill rig and miscellaneous support equipment such as trucks and loaders. Initial operations included calibrating the batch plant so that a uniform flow of bulk material could be mixed to produce a rate of approximately 23 m^3 (30 cu yd) of material per hour.

On July 22, 2002, placement of the bulk fill for seal No. 1 was initiated using a mixture composed of 2A crushed limestone aggregate, fly ash and cement. This mixture was pumped into the mine opening using a string of casing. Bulk fill was pumped over different time intervals with a pause between intervals to allow the in-place grout to stiffen. This process was used in an attempt to control the extent of lateral material flow out of the mine cross-cut areas. The pumping time and the pause intervals were determined by visual observation via a downhole video camera and communication with the mine pager phone. Pumping was terminated after approximately 86 m^3 (112 cu yd) of material had been placed into the crosscut (Fig. 5). Underground examination revealed that the mine opening had not been completely sealed (open spaces were observed at the mine roof-and-rib areas), and some of the bulk fill material had flowed into the adjacent mine areas.

A dual string of drill pipe and casing affixed with the spray nozzle was then placed into the borehole in preparation for the second part of the mine seal construction. On July 23, 2002, pumping began to complete construction of the mine seal. Unfortunately, after only a few minutes of pumping, a critical hose failed on the surface and the pumping operation was terminated. Underground examination of the sprayed areas indicated that the spray mixture did not stick to the mine rib areas and flowed away. Also, because minimal space, about 300 mm (12 in.) between the bulk fill and the bottom of the borehole was available, it was decide to remove 450 mm (18 in.) of bulk fill material below the bottom of the borehole to provide sufficient space for follow-up backfilling work.

The disappointing results of the spray nozzle application indicated that additional work was needed to further refine the material mix components before the spray nozzle was used again. In the interim, after reviewing the progress made during the placement of the bulk fill, it was decided to fit the end of the casing string of pipe with an elbow to provide a means of directionally controlling the placement of grout material (Fig. 6). It was also thought that this elbow configuration could facilitate roof-rib closure with the bulk fill material.

On August 2, 2002, a newly designed elbow was lowered into the mine opening from the surface borehole. Once the elbow was positioned in the mine opening, pumping of the seal material began using a 2A limestone aggregate, fly ash and cement mixture. Compressed air was added to the flow stream to facilitate movement of the material towards the mine rib areas. This material was pumped into select locations along the mine rib areas in an attempt to fill the mine opening (Fig. 7). Pumping was terminated after approximately 75 m^3 (100 cu yd) of material had been placed into the crosscut and after the elbow became plugged.

Underground examination revealed that the mine opening had not been completely sealed, some of the material had

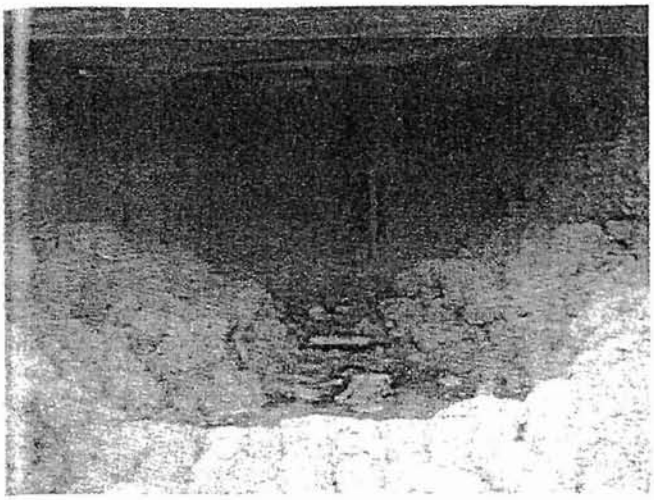

Figure 8 — View of fill placement at model mine.

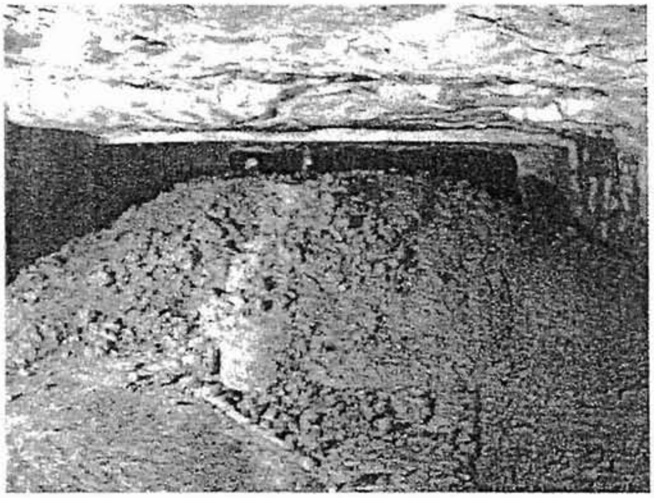

Figure 9 — View of bulk fill placement for seal No. 2.

flowed beyond the crosscut and into the adjacent mine areas. The area directly below the borehole and in the immediate vicinity of the elbow had been completely sealed to the mine roof. Several unsuccessful attempts were made to dislodge the plug in the elbow, but it was ultimately decided to terminate the construction of mine seal No. 1 and remove the elbow from the hole. In general, before the elbow became plugged, significant progress had been made towards filling the mine opening. A subsequent meeting with Howard/GAI team revealed that additional design and demonstration work was necessary before installation of seal No. 2 could begin. Later, mine seal No. 1 was removed from the LLL site using permissible explosives and permissible blasting techniques.

On October 8, 2002, a test of the spray nozzle was successfully conducted at the Howard model mine site. During the 10-m^3 (13-cu yd) test, engineers were able to successfully spray and build up material on the mine rib areas. The material was sprayed to an estimated thickness of 300 to 380 mm (12 to 15 in.) on the mine rib areas (up to the roof) with no build-up on the floor below the spray nozzle assembly (Fig. 8). This was a much different outcome as compared to that seen during previous tests and during the construction of mine seal No. 1. The GAI engineers attributed the successful outcome of this test to adjustments in the equipment used to control material feed and a significant improvement of the material mix.

Mine Seal No. 2. On October 8, 2003, the Howard/GAI team initiated the remote installation of mine seal No. 2 at LLL. Pumping of the first part of the remote seal (bulk material) began using a sand, fly ash and cement mixture. This material was pumped into the mine opening using the elbow. The bulk material was pumped in a series of lifts to fill the mine opening. Pumping was terminated after approximately 42 m^3 (55 cu yd) of material had been placed in the crosscut. It should be noted that communication with underground personnel was required to orient the elbow and complete the construction of the base.

Underground examination revealed that the mine opening had not been completely sealed. However, the seal material was placed to within 0.46 m (1.5 ft) of the mine roof below the borehole and within 0.76 to 0.9 m (2.5 to 3 ft) of the mine roof near the rib areas (Fig. 9). It was decided to remove an additional 152 mm (6 in.) of material below the bottom of the borehole to allow sufficient room to test the capability of the spray nozzle.

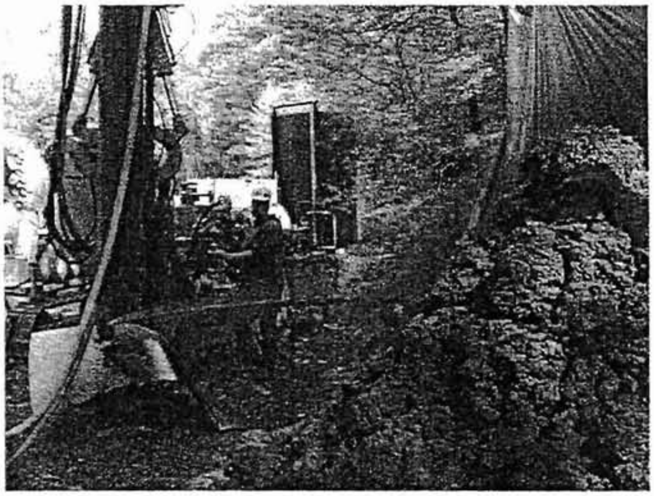

Figure 10 — Surface test of spray grout system.

On October 14, 2003, a 7.6-m^3 (10-cu yd) surface test of the final component of the seal mixture (fly ash, cement and accelerators) was conducted at LLL (Fig. 10). The result of the test showed that the mixture would perform as required (little to no slump). A dual string of drill pipe and casing affixed with the spray nozzle was then placed into the 152.4-mm- (6-in.-) diameter borehole in preparation for the second part of the seal construction.

On October 15, 2003, the second part of the mine seal was installed using the spray nozzle. The material was spayed in a back-and-forth motion along the mine rib areas to fill in the gaps. Interaction between observers underground and engineers on the surface ensured that the nozzle was aimed in the proper direction. Good mine roof-and-rib contact was made with the sprayed material. The problematic corner areas at the mine roof-rib intersection were filled before the grout began to build up and migrate towards the spray nozzle (Fig. 11).

Filling of the remaining area near the borehole was accomplished by lowering the spray nozzle into the wet material

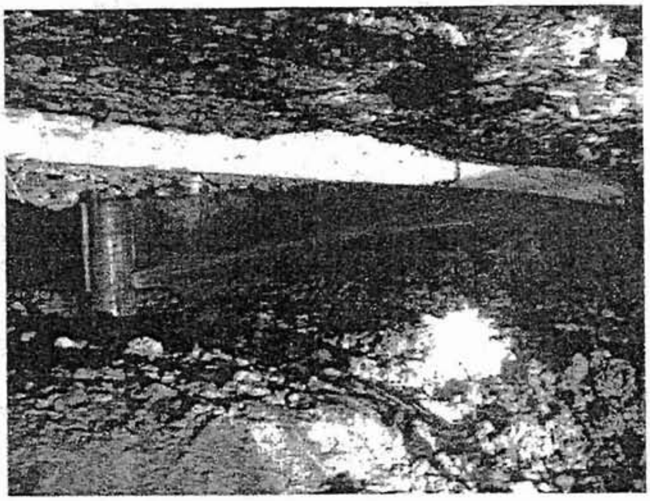

Figure 11 — Underground view of spray nozzle during seal No. 2 construction.

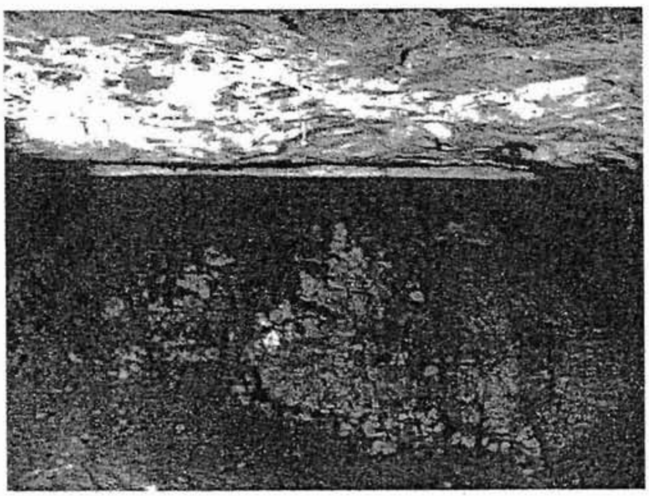

Figure 12 — Underground view of mine seal No. 2 from the B-Drift.

below the nozzle and then rotating the spray nozzle through a 360° arc. Eventually, the material built up around the nozzle and closed the mine opening (Fig. 12). In all, a total of 17.2 m^3 (22.5 cu yd) of sprayed material was used to close the mine opening. An underground examination showed that the mine seal material (both bulk and sprayed material) had flowed about 3.7 m (12 ft) from the borehole towards the B-Drift and only about 2.7 m (9 ft) from the borehole towards the C-Drift. The shape of the seal approximated a truncated pyramid whose base measured 5.8 m (19 ft) wide (the width of the cross cut) by 6.4 m (21 ft) deep and whose top measured 5.8 m (19 ft) wide (the width of the cross cut) by 0.9 to 1.5 m (3 to 5 ft) deep.

Material and mine seal tests

Unconfined compressive tests were conducted on 76-mm- (3-in.-) diameter cylinder samples (cylinder area = 4,560 mm^2 = 7.07 sq in.) that were collected during the construction of seal Nos. 1 and 2. Some samples were collected on the surface from equipment tanks and others were collected underground as the material was being placed in the mine void. The results of the tests are shown in Table 1. As can be observed in the table, the compressive strength of the bulk fill material is substantially higher than that of the sprayed fill material. The reason for the lower compressive strength of the sprayed material is that the sprayed mix does not contain sand and had air bubbles trapped in the mixture.

Although the major thrust of this research effort was aimed at development of material mixes and mine seal construction techniques, the benefits of constructing the seal at the LLL facility included the option of testing the seal's ability to confine mine air and also to withstand the forces of a mine explosion. Air-leakage tests were conducted by building a frame on one side of the mine seal and covering that frame with brattice cloth. Next, an opening was made in the brattice cloth the size of an anemometer to facilitate air velocity measurements. Once this work was completed, airflow in the mine was adjusted to produce a desired differential pressure and the air leakage through the seal was measured. Air-leakage tests were conducted on mine seal No. 2, and the results are shown in Table 2 (Weiss, 2003).

Prior to conducting the air-leakage tests, several approximately 25.4-mm- (1-in.-) diameter holes were observed in the seal near the mine roof area. Therefore, the air-leakage values observed in the table were not totally unexpected.

To conduct the explosion test, a known quantity of methane gas was injected in the end of the C-Drift near the crosscut where the seal was installed. This area was temporarily closed with a frame and brattice cloth to confine the gas. The gas was diluted with air to achieve an explosive concentration. The gas was then ignited producing an explosion. An explosion test was conducted on mine seal No. 2 on November 24, 2003. The mine seal withstood a pressure of 124 kPa (18 psi) with no visible signs of damage (Weiss, 2003).

Research findings and recommendations

The overall objective of the work was to determine if a mine seal could be constructed remotely from the ground surface. This objective was achieved as a seal was successfully built through a borehole and was confined to the crosscut of the mine opening. The technology used to build the seal was tested and the correct material mix design was developed. The results of follow-up testing showed that a strong and robust seal was constructed as required in the design constraints. The issue of air leakage can be addressed by slowing the rotation of the spray nozzle to allow for a more substantial build-up of seal material. As an additional remedy, it may also be possible to insert the spray nozzle into the observation borehole and spray the entire face of the seal to close and fill any holes.

Results of the work to date suggest that this remote seal construction system may have merit for isolating a mine fire. This technique however does require additional trials because considerable communication with the subsurface personnel was needed to achieve rib-to-rib and roof-to-floor closure. One of the fundamental keys to successful in-mine construction is the ability to directly observe the progress of construction. Because this was a research and demonstration project, communication between the surface operation and the underground seal location was permitted. This will not be the case when a mine fire occurs. Additional research is therefore proposed to further refine the construction method. A mine seal should be constructed at LLL without voice communication with the surface. The only means of observing the progress of construction should be via the nearby borehole equipped with a downhole video camera with sufficient resolution capabilities and lighting. Experience gained during this work also suggests that a downhole laser

Table 1 — Results of compressive strength tests on cylinder samples.

Seal 1 Bulk Fill[1]		Seal 1 Bulk Fill[2]		Seal 2 Bulk Fill[3]		Seal 2 Spray Fill[4]	
Age, days	Comp.. strength, psi (MPa)	Age, days	Comp.. strength, psi	Age, days	Comp.. strength, psi	Age, days	Comp.. strength psi
1	542 (3.74)	1	765 (5.27)	9	2,403 (16.57)	5	230 (1.59)
3	1,254 (8.65)	3	1,045 (7.21)	28	3,818 (26.33)	7	270 (1.86)
7	1,440 (9.93)	7	1,575 (10.86)	–	–	28	468 (3.23)
28	2,526 (17.42)	28	2,505 (17.27)	–	–	56	765 (5.27)

[1]Sampled from material pumped on July 22, 2002.
[2]Sampled from material pumped on August 2, 2002.
[3]Sampled from material pumped on October 8, 2003.
[4]Sampled from material pumped on October 15, 2003.

or radar imaging device should be constructed that offers real-time imaging and is capable of penetrating smoke, dust or the fog that tends to form in the mine opening as the seal material begins to set.

A 152.4-mm (6-in.) borehole was used during the trials at LLL, and the downhole equipment was designed to meet this need. The issue of working with this equipment in smaller diameter boreholes should be addressed along with the fact that deeper overburden depths will undoubtedly be encountered. Perhaps an additional spray nozzle should be constructed to facilitate remote seal construction in small-diameter boreholes.

Finally, it is suggested that this technology should be further evaluated through construction of a mine seal at LLL in a mine entry that is obstructed with debris (roof fall material) and mine structures (possibly cribbing, track or conveyor structures). This approach will test the ability of the seal material to flow around obstructions and still form a seal while closely matching the conditions most likely found in an underground mine.

Acknowledgments

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Table 2 — Results of air-leakage tests on mine seal No. 2.

Pressure, inches of water gage	0.52	1.05	1.52
Air leakage rate, cu ft/min	252	322	426

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