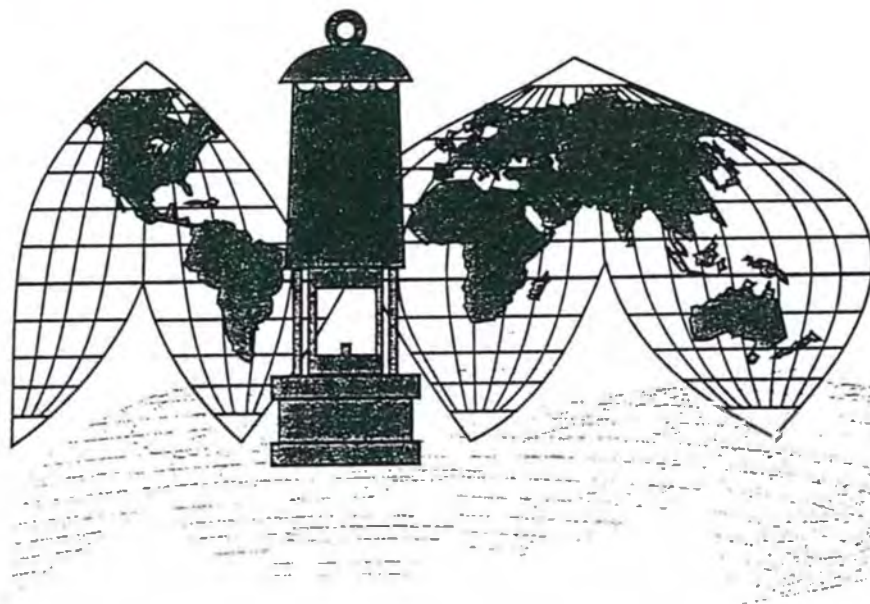


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OVERVIEW OF NIOSH'S MINE SEAL RESEARCH

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ABSTRACT

Within the last 4 years, seven documented explosions of methane and/or coal dust occurred within sealed areas of underground U.S. coal mines. These explosions, believed to be initiated by lightning strikes on the surface, destroyed numerous seals and caused considerable damage external to the sealed area. Fortunately, these explosions did not cause fatalities or injuries. However, the potential for a disaster still exists, emphasizing the need for explosion resistant seals that can perform under various mining conditions. The Pittsburgh Research Laboratory (PRL) of the National Institute for Occupational Safety and Health (NIOSH) has conducted full-scale explosion experiments to evaluate the strength characteristics of several seal designs for isolating worked out areas in underground coal mines. Full-scale seals (11 to 16 m² in cross-section) were constructed in the multiple entry section of the Lake Lynn Laboratory experimental mine and exposed to a series of methane and coal dust explosions with overpressures ranging from 120 to 595 kPa. Seals were fabricated with various strength cementitious-type materials ranging in thickness from 0.175 to 1.2 m. High-strength cementitious seal designs made with a reinforced steel matrix were also evaluated as well as rapid setting designs capable of withstanding 138 kPa overpressures only 27 hours after construction.

A novel seal design employing concrete block and a pre-loading technique with no recessing shows promise as an alternative to the U.S. Code of Federal Regulations' (CFR) standard-type solid concrete block seal design which is recessed into

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the ribs and floor. This new seal design is capable of withstanding 138 kPa and is of particular interest to mine operations that have weak or friable ribs where conventional sealing techniques are not adequate.

Also included is a discussion of PRL's recent efforts to design and construct large test chambers (15 and 42 m² in cross section) for the pneumatic and hydrostatic evaluation of seals, as an alternative to full-scale explosion testing.

INTRODUCTION

Over the past few decades, numerous international incidents in underground mining or tunneling operations have been reported that have been directly attributed to lightning. These incidents involved electric shocks, visible arcing between items of underground equipment, and, in the most severe cases, premature detonation of explosives or the ignition of methane-air mixtures. In addition to the obvious threat to human safety, these incidents can have major economic impact. Between 1972 and 1984, there were 15 incidents in South African coal mines related to lightning, three of which involved fatalities [Geldenhuis 1995]. Six of these incidents involved methane explosions, seven involved initiation of blasting explosives, and the remaining two involved shocks to personnel.

Within the last 4 years, seven documented explosions of methane and/or coal dust occurred within sealed areas of underground U.S. coal mines. These explosions, believed to be initiated by lightning strikes on the surface, destroyed numerous seals and caused considerable damage external to the sealed area. Fortunately, these explosions did not cause fatalities or injuries. One explosion that showed strong evidence of being caused by lightning occurred at the Mary Lee No. 1 mine in Alabama on August 22, 1993 [Hurren et al., 1993]. Evidence indicated that the explosion occurred at 4:40 PM. At the same time, the National Lightning Detection Network observed a 21.7 kA lightning flash in the vicinity of a fan shaft that vented the area where the explosion occurred. Physical evidence at the fan shaft indicated electrification of the metal vent pipe extending from the concrete shaft cap which was blown off during the explosion.

Three explosions occurred in the gob at the Oak Grove Mine, Alabama [Scott et al., 1996]. In each instance, severe thunderstorms and lightning occurred above the sealed gob. With all events, the National Lightning Detection Network documented scores of lightning flashes within the vicinity of a 114-mm diameter steel cased hydro-geological test hole connecting a surface pumping station to the gob. The first explosion destroyed several improperly constructed standard solid block seals. The second explosion destroyed several 1.2-m-thick cementitious seals. Analysis of fractured seal material showed compressive strengths less than required by the Mine Safety and Health Administration (MSHA) acceptance criteria of 200 psi (1.4 MPa). However, one seal, which had been rebuilt after the second explosion, was stronger than required by current regulations. Gob explosions, whether initiated by lightning, roof falls, or spontaneous combustion, forcefully demonstrate the need for adequate seals and sealing procedures to protect mine workers against explosions.

According to Title 30, Part 75.335 of the CFR, abandoned areas of a mine must be either ventilated or isolated from active workings through the use of seals that can withstand a static horizontal pressure rise of 20 psi (138 kPa). Seals are also used to isolate fire zones or areas susceptible to spontaneous combustion. To effectively isolate areas within a mine, a seal should be designed to control the methane and air exchange between the sealed and open areas so as to prevent toxic and/or flammable gases from entering active workings. A seal must be fire resistant and capable of preventing an explosion from propagating into or out of the sealed area. Early research [Mitchell 1971] indicated that it would be unlikely for overpressures exceeding 138 kPa to occur very far from the explosion origin, provided that the area on either side of the seal contained sufficient incombustible and minimal coal dust accumulations. Pressure balancing across the seals should play a key role in all seal deployment strategies. Pressure balancing minimizes the flow of oxygen into the gob and reduces the volume of flammable methane-air atmosphere within the gob.

Many countries have pursued research in explosion-resistant structures for underground mining. These include the U.S., Australia, France, Germany, Poland, and

China. In the U.S., cooperative research in explosion testing of mine seals has been underway at the PRL's Lake Lynn Experimental Mine (LLEM) since the early 1990's. The PRL and MSHA have been jointly investigating the ability of various existing and new seal designs to meet or exceed the requirements of the CFR. This seal program has already resulted in the development and implementation of alternative seal designs and construction materials to that of the previously approved standard-type seal design constructed with solid-concrete-blocks. Unfortunately, evaluating seals by explosion testing makes it difficult to determine the precise conditions for seal failure, thus making it difficult to obtain the seal's safety factor for strength. Therefore, construction is now underway at the LLEM on two test chambers for the pneumatic and hydrostatic evaluation of mine seals. This paper provides an overview of seal research conducted at the LLEM and an alternate approach to full-scale explosion testing of seals.

EXPERIMENTAL MINE EXPLOSION EVALUATIONS OF SEALS

All of the explosion and air-leakage determination tests on the various seal designs were conducted at the LLEM, located near Fairchance, PA [Triebisch and Sapko, 1990]. Figure 1 is a diagram of the seal test area in the LLEM. Each of the three drifts contains ten data-gathering stations, and each station houses a transducer to measure the static explosion pressure and an optical sensor to detect the flame arrival. All of the seals were constructed in the crosscuts between B- and C-drifts. These crosscuts are approximately 2 m high by 5.8 m wide. The average cross sectional area of the crosscuts was 11.6 m². For the explosion tests, methane was injected into the closed end of C-drift. A plastic diaphragm contained the methane-air mixture within the first 14 m. An explosion-proof fan mixed the methane and air. Prior to the ignition of the gas, a concrete/steel bulkhead was positioned across E-drift to contain the explosion pressures within C-drift. The ignition of the 9-10 % methane-air zone generated a peak pressure

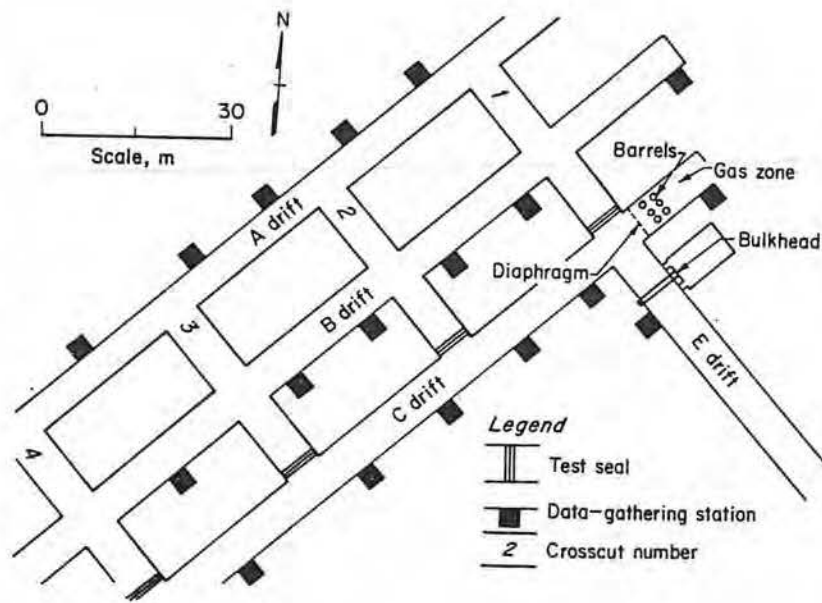


Figure 1.--Seal test area in the Lake Lynn Experimental Mine.

pulse of approximately 140 kPa. This peak pressure pulse remained relatively constant throughout the seal test zone in C-drift. To generate higher pressure pulses, pulverized coal dust was placed on foam shelves which were suspended, on 3-m intervals, near the mine roof outby the gas zone.

An important factor to be considered for any seal design is its impermeability, or its ability to prevent or reduce the exchange of gases from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after the explosion tests and compared to MSHA-established guidelines. These guidelines are as follows: for pressure differentials up to 0.25 kPa, air-leakage through the seal should not exceed 2.8 m³/min; for pressure differentials over 0.75 kPa, air leakage should be less than 7.1 m³/min.

Since the early 1990's at the LLEM, numerous research studies on explosion testing and air leakage for alternative seal designs and evaluation of water traps were conducted in entry geometries similar to those of current U.S. coal mines. Designs that were evaluated included: (1) the standard solid concrete block seal; (2) numerous

modifications to the standard solid concrete block seal; (3) cementitious foam seals with various compressive strengths; (4) low density block seals; (5) composite seals made from blocks which held gravel and polyurethane foam; (6) reinforced seals (using steel mesh) that were anchored to the ribs, roof, and floor with bolts and made with high strength cement with varying curing times; and (7) pre-loaded seals. The seal evaluations at the LLEM are discussed in roughly chronological order in the following paragraphs.

Concrete Block Seals: In the early 1990's, tests were performed [Greninger et al., 1991] in the LLEM on solid concrete block seals with 11- to 12-m² cross sections and varying thicknesses and designs. The standard-type block seal was constructed of solid concrete blocks (152 by 203 by 406 mm); it was 406 mm thick, keyed at the floor and ribs, wedged at the roof, with fully mortared block joints, and with a center pilaster. The keying or hitching was simulated by using steel angle, bolted to the floor and ribs. Of the seven concrete block seals tested, only the 406-mm-thick standard-type seal maintained its integrity when subjected to a 138 kPa pressure wave from a gas explosion. A concrete block seal that was similar to the standard-type seal but without floor keying failed. A concrete block seal with no pilaster but with floor keying failed. All the thin-walled (203 mm thick) seals with fully mortared block joints failed; neither the use of a center pilaster nor floor keying provided sufficient strength against the 138-kPa explosion with these thin walled designs. The addition of coatings did not significantly augment the seal strength. After being subjected to repeated explosions with overpressures ranging from 140 to nearly 310 kPa (45 psi), the standard-type solid concrete block seal showed only a small hairline crack with air-leakage rates within the acceptable guidelines.

Cementitious Foam Seals: Tests were then performed on pumpable seal designs [Weiss et al., 1993] of varying thicknesses and compressive strengths made from Tekseal⁵, a cementitious foam manufactured by Fosroc. Following a 30-day cure period,

⁵Reference to specific products does not imply endorsement by NIOSH.

the 1.2-m thick and 2.4-m thick seal designs consisting of cementitious foam of at least 1.4-MPa (200-psi) compressive strength withstood the required overpressure of 138 kPa while maintaining air-leakage rates well within the established guidelines. The LLEM explosion results showed that a non-reinforced seal consisting of 0.35 MPa (50 psi) or less compressive strength cementitious material was not capable of withstanding the required 138 kPa pressure pulse even at seal thicknesses of 2.4 m.

Low Density Block Seals: Several seal designs were constructed at the LLEM using Omega 384 low-density block manufactured by Burrell Mining Products, Inc. Omega 384 is a glass-fiber reinforced, lightweight cementitious block (0.4-m by 0.6-m by 0.2-m with a density of 383 kg/m³). A cementitious, glass-fiber reinforced bonding agent, Burrell Bond, was used as the block mortar and surface coating and allowed to cure for at least 28 days. Simulated keying (hitching) on the floor and ribs using steel angle was applied to all of the seal designs. Each seal was wedged against the mine roof. All of the block joints were staggered and mortared in each design. A 6-mm-thick surface coating was applied to both sides of each seal. The seals ranged in thickness from 0.6-m to 0.8-m. Four of the seal designs had two pilasters (positioned one third of the distance in from each rib) and two seal designs had only one center pilaster; each pilaster had dimensions of 1.2-m-thick by 1.2-m-wide. Another seal was designed with one large center pilaster 1.4-m-thick by 1.8-m-wide. All of the low density block seal designs withstood the 138 kPa explosion pressure pulse with little or no outward signs of damage. Omega 384 block seal designs were judged to meet the requirements of 30 CFR Part 75.335(2) if constructed in the same manner as the seals in the LLEM [Stephan 1990]. Two additional seal designs utilizing the low-density cementitious block (Omega 384) using an alternative mortar and surface bonding material have also been evaluated with successful results.

Composite Polymer Seals: In the mid 1990's, the seal programs focused on composite polymer seals, cellular concrete seals, and water traps [Weiss et al., 1996]. Seals designed with a 40-cm-thick polymer (polyurethane) and stone aggregate core between two dry-stacked (no mortar) concrete block walls (coated on outby sides)

withstood a 138-kPa pressure pulse while maintaining acceptable air leakage rates. Similar seal designs utilizing a 97-cm-thick, 91-kg/m³ density, polymer-only (no stone aggregate) core did not survive. However, a 51-cm-thick, 203-kg/m³ density, polymer-only core seal successfully withstood the explosion pressures.

Reinforced Seals: In 1997, novel seal designs and formulations from Australia were explosion tested in the LLEM under a cooperative research agreement. This research program was in direct response to the 1994 Moura No. 2 Mine disaster in Australia which killed 11 miners and one contractor within 22 hours after sealing a gob area. One immediate recommendation resulting from this disaster was the need to have quick setting formulations available for gob areas that would result in the seals having reached nearly full-strength within a few days. This cooperative research effort with Tcrete Industries Pty. Ltd. and BHP Australia Coal resulted in several important findings [Mutton and Downs 1997 and Weiss et al., 1999]. High strength incombustible cementitious ventilation stoppings (40 to 75 mm thick and reinforced with steel mesh) were evaluated at pressures from 23 to 115 kPa. High strength cementitious seals (175 to 325 mm thick and with a reinforced steel matrix anchored into the mine roof, floor, and ribs) were evaluated at pressures from 120 to 455 kPa. A seal made from rapid curing cementitious grout was found to withstand 138 kPa overpressures within 27 hours of completion. The PRL seal performance evaluation procedures now make use of linear variable displacement transducers to characterize seal displacement and failure conditions under dynamic loading. These various stopping and seal designs can meet overpressure ratings from 14 kPa (2 psi) to 455 kPa (66 psi), depending on the thickness. The special anchoring approach with the Tcrete seals, coupled with the high strength grouting to the seal surfaces and surrounding strata, may have application in U.S. mines having friable strata conditions.

Other Seal Designs: In late 1997, several pumpable cementitious seal designs manufactured by Heitech, Virginia, were evaluated in the LLEM. These non-reinforced seal designs ranged in thickness from 600 mm to 900 mm (2 to 3 ft) with average compressive strengths varying from 2.8 MPa to 5.3 MPa (400 psi to 750 psi); the thinner

designs using the higher compressive strength material. These seal designs are being used throughout the U.S. mining industry based on the successful evaluations conducted at the LLEM.

Similarly, two high-strength reinforced cementitious seal designs, a water stopping design, and an overcast design manufactured by Barclay Mowlem Construction Ltd. of Australia have been successfully evaluated in early 1998 at the LLEM and are currently being used in the Australian mining industry. These seal designs are based on a large multi-compartment vinyl bag form that is filled with cementitious foam.

Pre-loaded Seals: In May 1998, NIOSH and MSHA participated in a joint research effort at the LLEM to evaluate the strength characteristics and air-leakage resistance of pre-loaded solid-concrete-block seal designs. These seals were designed for use in areas of coal mines where the standard method of hitching or keying of the concrete block seal into the mine ribs is impractical due to the friable or weak coal conditions; this problem was recently encountered at the Jim Walter Resource's (JWR) Blue Creek Coal No. 5 Mine in Alabama. The United Mine Workers of America (UMWA) and JWR provided the seal design, materials, and labor support for this program. The seal designs were very similar to the standard-type, solid-concrete-block design described in the CFR. The primary difference is the use of high strength bags, pressurized with cementitious grout, on the mine ribs and/or mine roof in place of hitching. These pressurized bags are referred to as packsetter bags and are positioned at the interface between the seal and the mine roof and ribs. Grout is injected to achieve an internal bag pressure of 250 kPa or 300 kPa. Full-scale explosion testing has shown that the pre-loaded concrete block designs with mortared joints provided the necessary resistance to the required 138 kPa pressure pulse.

Quality Control: An important issue in underground coal mines is quality control in the construction of seals. Maintaining quality control in the harsh underground mining environment where temperature and humidity can vary significantly from one mine to another and/or from one sealing location to another can and does create challenging problems when mixing cementitious materials, applying polymer, and many other aspects

of seal construction. For example, if quality control is not properly maintained during the construction of pumpable cementitious seal designs, the density of the cementitious slurry can vary widely, thus causing a great variability in the compressive strength which can lead to seal failure. Likewise, high humidity or excess surface moisture can adversely affect the densities and subsequent strength of composite polymer seal designs during the polymer cure period. Care must be taken to ensure that seals are installed properly and under conditions which do not degrade the seal construction materials during the curing period.

As a result of seals being destroyed during lightning initiated gob explosions, a concern was that some of the cementitious seals may be degrading or becoming weaker with time as the formulation dries. Comparative studies on the compressive strength of seal samples and the use of a Schmidt impact hammer were conducted as a simple means to verify the quality control of seals. Compressive strength tests were conducted on the cellular concrete seal samples collected during a previous seal evaluation program in the LLEM. Results showed a minimal 3 pct decrease in compressive strength after 4 years of curing. These very limited experimental results are encouraging but may not be representative of other types of cementitious materials, such as the cementitious foams, and do not have bearing on seals which were not installed to the proper compressive strength specifications. Therefore, additional comparison studies need to be conducted. Limited evaluations also showed that the Schmidt hammer technique for measuring the compressive strength of aerated cellular concrete agreed well with standard ASTM procedures. The hammer also shows promise as a device for the in-situ compressive strength determination of cementitious type seals installed and cured in underground mines. The technique cannot measure the uniformity throughout thick seals but can show any floor to roof variations in compressive strength and any significant deviations from the required 1.4 MPa or greater design values near the surface of the seals.

MONITORING EXPLOSIONS IN GOBS

In June 1995, mine management of the Gary No. 50 Mine, Pineville, West Virginia, reentered the 4 North and West Main sealed areas and discovered that an explosion had occurred in by the West Main seals [Sumpter et al., 1995]. The cause of the explosion could not be determined, but lightning directly over the sealed area during the time frame of the explosion makes lightning the most probable ignition source. None of the cementitious seals were damaged and all had contained the explosion pressures. Since lightning is prevalent over many mining operations, could gob gas explosions occur within other sealed areas and go undetected and, if so, what is the magnitude of the resulting explosion overpressures? NIOSH undertook a study to identify and evaluate passive, inexpensive pressure measuring techniques to help answer this question.

Evaluation studies were conducted in PRL's 20-L laboratory explosion chamber and in the full-scale LLEM to evaluate the response time and accuracy of various indicator type tire pressure gauges to overpressures generated from gas and dust explosions. The first series of tests was conducted in the 20-L chamber. The chamber explosion pressures are typically measured using an electronic strain gauge pressure transducer. The tip of the candidate pressure gauge (car tire type) was cut off, and the gauge was cemented with epoxy into a pipe union and attached to the test chamber. The laboratory tests evaluated the tire gauges over the range from 40 to 480 kPa. A second series of tire gauge evaluation tests was conducted at the LLEM during full-scale explosion testing of seals at overpressures ranging from 120 to 595 kPa. On the back or non-explosion side of the test seals, modified tire pressure gauges were attached to 6-mm diameter tubing which passed through the seal, providing pneumatic explosion coupling to the test gauge. Several tire gauges with pressure ranges from 7 to 138 kPa (1 to 20 psi) and 70 to 520 kPa (10 to 75 psi) were used on the back sides of several seals. The axis of the gauge was mounted at 90 degrees to the plane of the seal to minimize the shock coupling of any seal movement to the stem of the gauge giving rise to inaccurate readings. In both these laboratory and full-scale explosion tests, the

maximum explosion overpressures measured by the electronic strain gauge pressure transducers and the modified tire gauges were in good agreement. This indicated that the simple, inexpensive passive device can be used to record overpressures within the sealed gob area or to record the explosion pressure at which a mine seal fails.

After installation of the tire pressure gauge on a mine seal, any pressure rise could be identified during routine weekly examinations of the seals or shortly after lightning has occurred in the area. Such an inexpensive device would be useful as part of a surveillance study to help answer the question of frequency and magnitude of explosion events which might occur in sealed areas of underground coal mines initiated by lightning or some other source, with or without seal failure.

PNEUMATIC AND HYDROSTATIC EVALUATIONS OF SEALS

The PRL has recently constructed two large-scale chambers underground in the LLEM for the pneumatic, hydrostatic, and/or explosion testing of candidate seals for use in coal mines. Figure 2 shows the larger of these two chambers. It is 9.1 m in width and 4.6 m in height, giving a cross sectional area of approximately 42 m². The smaller of the two chambers is 6.1 m in width and 2.4 m in height, giving a cross sectional area of

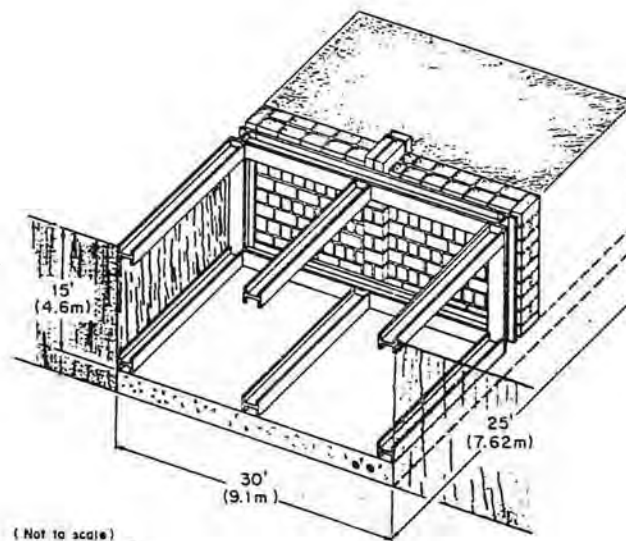


Figure 2.—Test chamber for pneumatic and hydrostatic testing of seals.

about 15 m². The figure shows the steel beams around the periphery to simulate keying. This example shows a concrete block seal with water behind it for hydrostatic testing.

Before MSHA will permit the use of a mine seal, the design has to be evaluated and in some instances undergo explosion testing. These new chambers will allow the pressure testing of mine seals, with minimum impact on the full-scale explosion research at LLEM. They will provide a means for evaluating hydrostatic effects, extend the duration of the pressure loading, facilitate testing up to failure to determine the seal's strength safety factor, and facilitate testing the strength and leakage characteristics of both explosion resistant and water impoundment seals. Conducting large-scale explosion tests in the multiple-entry area of LLEM is costly and requires considerable maintenance of the instrumentation system that undergoes damaging effects from each explosion conducted.

It is felt that a hydrostatic or pneumatic approach, if shown to be equivalent to explosion testing, could even be used in an operating mine to determine the acceptability of a mine seal under the actual mine rib and floor conditions. The results from smaller scale studies conducted previously at PRL suggested that the hydrostatic approach has many benefits, including in-situ mine performance testing under actual end use geologic conditions [Chekan et al., 1983, Rice et al., 1930, Rice et al., 1931].

The two hydrostatic chambers constructed at the LLEM will provide the following research capabilities: (1) explosion loading from a tailored fixed volume methane-air mixture, (2) pressure loading from compressed air, and (3) hydrostatic pressure loading from water. In addition, the two different sized chambers will facilitate the development of geometric scaling guidelines.

The ultimate goal for this in-situ pneumatic and hydrostatic approach is to provide MSHA and the mining industry with an alternative method to the full-scale gas and dust explosion testing which can only be done in an experimental mine such as the LLEM.

CONCLUSIONS

Over the last decade, the PRL and MSHA have participated jointly in a research program to evaluate strength characteristics of various seal designs for use in underground coal mines. Over 30 full-scale seals were constructed in the LLEM and subjected to pressures pulses of 140 kPa and greater. Many of these seals were commercialized and are used extensively within the U.S. mining industry. Studies continue to develop alternative methods and guidelines for the in-situ evaluation of seals within the mining horizon thus eliminating the need for expensive large-scale explosion tests that do not readily allow for the determination of safety factors, failure modes, or the ability to develop and validate important geometric size scaling relationships. The recent observations of lightning-initiated gob explosions emphasizes the need for improved, reliable explosion-resistant seals and construction techniques that ensure the safety of miners.

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