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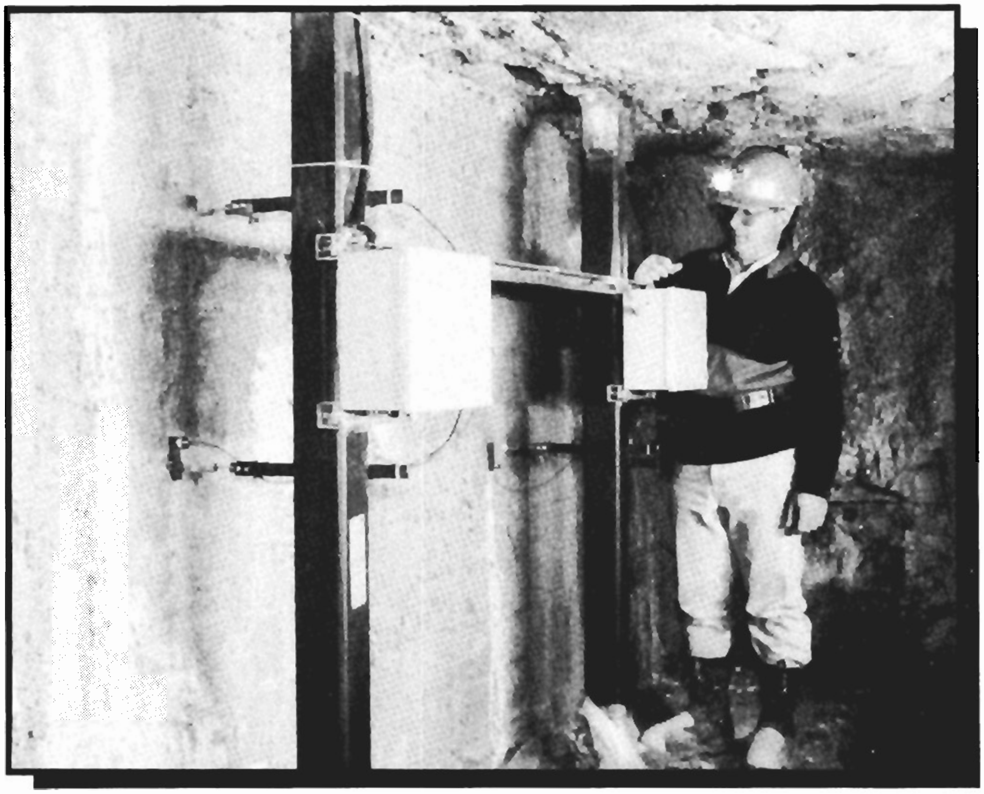
REPORT OF INVESTIGATIONS/1999

Evaluation of Reinforced Cementitious Seals



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Cover photo: Reinforced cementitious seal instrumented with transducers and accelerometers to measure displacement of the seal during an explosion test at the Lake Lynn Experimental Mine. (Photo by Kenneth L. Cashdollar, NIOSH Pittsburgh Research Laboratory.)

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	m^2	square meter
cm^2	square centimeter	m^3	cubic meter
ft	foot	m^3/min	cubic meter per minute
ft^2	square foot	mm	millimeter
ft^3	cubic foot	MPa	megapascal
ft/s	foot per second	ms	millisecond
g/m^3	gram per cubic meter	m/s	meter per second
hr	hour	m/s^2	meter per second squared
Hz	hertz	psi	pound (force) per square inch, gauge
in	inch	psia	pound per square inch, absolute
in H_2O	inch of water	psi-s	pound per square inch - second
kg	kilogram	s	second
kHz	kilohertz	t	ton (metric)
km	kilometer	t/h	ton (metric) per hour
kN-s	kilonewton second	V dc	volt, direct current
kPa	kilopascal	°C	degree Celsius
kPa-s	kilopascal second	°F	degree Fahrenheit
m	meter	%	percent

EVALUATION OF REINFORCED CEMENTITIOUS SEALS

By Eric S. Weiss,[1] Kenneth L. Cashdollar,[2] I. Verne S. Mutton,[3]
Deepak R. Kohli,[4] and William A. Slivensky[5]

ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory, cooperated with Tecrete Industries Pty. Ltd. and BHP Australia Coal in a research program to evaluate the strength characteristics and air leakage of four seal and two stopping designs for use in underground coal mines. A fundamental safety research area for NIOSH is to eliminate the occurrence of coal mine explosions or to mitigate their effects. One approach to achieve this goal is to develop new and innovative seal designs that provide increased explosion isolation protection for the mining personnel against ignitions that originate from within the gob or other worked-out areas of the mine.

Full-scale seals and stoppings were constructed in the Experimental Mine at Lake Lynn Laboratory near Fairchance, Fayette County, PA. They were air-leakage tested, then subjected to a series of explosions with average pressure pulses ranging from 25 to 500 kPa (3.5 to 72 psi). Instrumentation measured seal displacement and acceleration as a function of time, providing data to assist in the development of numerical models for future seal design.

All three seals designed with Meshblock wire formwork and a monolithic shotcrete core withstood the first explosion test, which generated an average maximum pressure of ~140 kPa (~20 psi) while maintaining acceptable air leakage rates. These seals ranged from 175 to 325 mm thick. They included a 2.7-m-high by 325-mm-thick seal that was tested 27 hr after completion against this ~140-kPa explosion pressure, a special requirement of the test program. This seal survived explosions with pressure pulses up to 300 kPa (43 psi). The 2.3-m-high by 325-mm-thick Meshblock seal survived three explosion tests with overpressures up to 455 kPa (66 psi) and satisfied the air leakage criteria.

A 1,200-mm-thick plug seal was constructed of two Gunmesh formwork walls in-filled with shotcrete and a 3,450-kPa (500-psi) strength Aquablend core. This plug seal survived three explosions with pressure pulses ranging from 150 to 430 kPa (~22 to 62.5 psi) with no measurable postexplosion air leakage. Two Gunmesh stoppings with thicknesses of 40 and 75 mm withstood explosion overpressures of 23 and 115 kPa, respectively. Anchoring all seal and stopping designs into the roof, ribs, and floor with steel "roofbolts" provided very effective boundary constraint that is critical to the performance of structures subject to explosion overpressures.

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INTRODUCTION

During the course of underground coal mining, it sometimes becomes necessary to install seals to isolate abandoned or worked-out areas of a mine. This practice eliminates the need to ventilate those areas. Seals are also used to isolate fire zones or areas susceptible to spontaneous combustion. To effectively isolate areas within a mine, a seal must—

- Minimize leakage between the sealed area and the active mine workings so as to prevent toxic and/or flammable gases from entering the active workings;
- Be capable of preventing an explosion initiated on one side from propagating to the other side; and
- Continue its intended function for 1 hr when subjected to fire conditions.

30 CFR[6] 75.335 [1997] requires a seal to "withstand a static horizontal pressure of 20 pounds per square inch [138 kPa]." Previous research by the former U.S. Bureau of Mines (USBM) [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. This regulation formed the basis for previous Pittsburgh Research Laboratory (PRL) evaluations [Greninger et al. 1991; Weiss et al. 1993a; Weiss et al. 1993b; Weiss et al. 1993c; Weiss et al. 1996; Weiss et al. 1997b] of explosion-resistant seals in the Lake Lynn Experimental Mine (LLEM).

In 1993, Tecrete Industries introduced a Meshblock system of seal construction in Australian coal mines. This seal system provided a monolithic structure that could be constructed on a continuous basis. Meshblock is a trade name for a form comprised of heavy metal wire and metal screen that is used to contain the shotcrete in a seal. Details of the Meshblock system can be found in the "Meshblock Seals" section of this report. Previous research [Barzegar 1996a] has shown that the boundary conditions (at the interface between the seal and the mine roadway) influence the ability of the seal to resist horizontal overpressures. Stiffness of the immediate surrounding roadway material and the fixation of the seal at this interface are the most important factors that influence horizontal load resistance for any given seal design. Steel "roofbolts" are an integral part of each Meshblock seal design, providing an effective anchor to the roof, ribs, and floor. The legislation in Queensland at the time these seal designs were introduced to the Australian coal mining industry in 1993 required that permanent seals be able to withstand a pressure of 345 kPa and, in seams prone to spontaneous combustion, that they be installed quickly. A particular hazard in gassy underground coal mines occurs when a section of the workings is sealed because of the effect of spontaneous combustion. If methane is being continually generated, the atmosphere behind the seals could pass through the lower flammable limit for methane-air mixtures in a short period of time, and the spontaneous combustion could provide an ignition source. Under these circumstances, an explosion could occur within a period of a day or two after the completion of the seal.

On August 7, 1994, 11 miners were killed when a methane-air mixture ignited within a recently sealed room-and-pillar panel at BHP Australia Coal's Moura No. 2 Coal Mine in Queensland, Australia [Roxborough 1997]. The most likely ignition source was determined to be the heating caused by spontaneous combustion within the sealed area. The overpressures generated from the methane ignition resulted in the failure of several Tecrete seals that were installed approximately 22 hr prior to the ignition. These 100-mm-thick seals were general mine seals and were not rated for horizontal overpressures. The seals were constructed with a cementitious wet-mix grout called MB400, which was placed with an air-driven Graco President 10:1 piston pump within the Meshblock formwork. This grout was designed to achieve 24-hr strengths of 12 MPa and 28-day strengths of 40-45 MPa.

In 1995, Tecrete Industries funded an evaluation of its seal designs in a research program [Apte et al. 1995] with the WorkCover Authority at Londonderry, New South Wales, Australia. The program was conducted in the WorkCover's explosion gallery, which is a concrete tunnel 2.7 m in diameter and 5.7 m^2 in cross section. A 250-mm-thick Meshblock seal design constructed within the concrete tunnel withstood eight methane explosions with overpressures from 85 to 500 kPa. This seal was fully instrumented to provide time-related pressure and displacement measurements. These data were used to find a suitable computer model [Barzegar 1996b] that reflected the response of the wall under dynamic loads and the increased load capacity due to the stability and strength of the steel bolts. This research provided a basis for the construction, instrumentation, and explosion testing of several Tecrete seal designs in the LLEM.

In late 1996, PRL began a collaboration on a research project with Tecrete Industries and BHP Australia Coal to investigate the capability of various seal and stopping designs to meet or exceed the requirements of the Queensland Department of Mines and Energy's "Approved Standard for Ventilation Control Devices." This standard was the result of deliberations and investigations by Task Group 5, which was formed by the recommendation of the Warden's Inquiry concerning the Moura No. 2 Mine explosion [Roxborough 1997]. Task Group 5 was charged with the reassessment of the regulatory provisions for explosion-resistant seals and the investigation of mine inerting techniques. The research program in the LLEM tested seal designs within a range of overpressures to match the

[6] *Code of Federal Regulations*. See CFR in references.

recommendations of Task Group 5. The overpressure ratings are: 14, 35, 70, 140, and 345 kPa (2, 5, 10, 20, and 50 psi). The Tecrete seal designs were also to be evaluated relative to U.S. pressure and air leakage requirements.

One of the LLEM's crosscuts (cut-throughs) was enlarged to a height of nearly 3 m, forming a roadway with dimensions representative of those found in Australian and some U.S. underground coal mines. One particular requirement of this program was to test an isolating seal design that could withstand an explosion producing a static horizontal overpressure of ~140 kPa within 24 hr of its completion. Several seal designs were evaluated at overpressures of 140 to >345 kPa (20 to >50 psi). Two stopping designs were also evaluated at overpressure ratings of 23 to 115 kPa (3.4 to 17 psi). The expected outcome of the new standard for seals and airlocks in Queensland is that all ventilation control structures will have an overpressure rating based on an assessment of the risk and purpose of the particular control structure. These standards do not address the structural design or the material to be used in seal construction.

Previous full-scale test programs [Stephan 1990a; Stephan 1990b; Weiss et al. 1993a; Weiss et al. 1993b; Weiss et al. 1993c; Weiss et al. 1996; Weiss et al. 1997b] conducted in the LLEM evaluated seals in entry geometries similar to those found in the United States and Australia. These research programs focused on the ability of particular seal designs to maintain their structural integrity while being subjected to a specific methane or methane and coal dust explosion. Seal evaluation had been based on visual observations of damage and measurement of postexplosion air leakage across the seal over a range of air pressure differentials.

The new PRL-Tecrete research program was based on the idea that the resistance of a seal to horizontal overpressures can be predicted from time-related measurements of displacement, static pressure, and acceleration. Therefore, this new research program evaluated the dynamic response of each seal design to explosion overpressures by the use of electrical transducers mounted on each structure. A series of controlled explosions of successively increasing magnitude provided data that can be used to optimize future seal designs in terms of strength and the economics related to material usage and installation times. Data from these measurements will aid in the development of a model that can relate roadway conditions and pressure ratings to a particular seal design requirement.

The installation methods, leakage determinations, and explosion results associated with these Tecrete reinforced cementitious shotcrete seals, stoppings, and the plug seal are presented in this report. Time-related measurements of seal response to explosion loads are summarized in useful graphical and tabular formats. Many of the data in this report were presented previously in a final report summarizing work conducted and funded under Memorandum of Agreement (MOA) No. 14-09-0050-3739 with Tecrete Industries [Weiss et al. 1997a]. Some of the data reported in this Report of Investigations were revised slightly from those in the MOA final report based on a reanalysis of the data.

EXPERIMENTAL MINE AND TEST PROCEDURES

MINE EXPLOSION TESTS

All of the explosion and air leakage determination tests on the various seal designs were conducted in the LLEM [Mattes et al. 1983; Triebsch and Sapko 1990], which is located approximately 80 km southeast of Pittsburgh, near Fairchance, Fayette County, PA. The LLEM is one of the world's foremost mining laboratories for conducting large-scale safety and health research. The LLEM is unique in that it can simulate current U.S. coal mine geometries for a variety of mining scenarios, including multiple-entry room-and-pillar mining and longwall mining.

Figure 1 shows a plan view of the LLEM. The underground entries consist of approximately 7,620 m of workings developed in the mid-1960s for the commercial extraction of limestone and 2,286 m of entries developed by the former USBM in 1980-81 for research [Mattes et al. 1983]. These more recent entries are depicted, in figure 1, as drifts A through D, each of which are ~520 m long and closed at the inby end, and drift E, which is 152 m long and connects drifts C and D. The dimensions of the drifts and crosscuts are typical of modern U.S. geometries for coal mine entries and range from 5.5 to 6.0 m wide and are approximately 2 m high. The LLEM was designed to withstand explosion overpressures of up to ~700 kPa (~100 psi).

Figure 2 shows an expanded view of the seal test area in the multiple-entry section of the LLEM. All of the seals and stoppings were constructed in the crosscuts between the B- and C-drifts. All of the crosscuts were approximately 2 m high by 6 m wide. The roof height in one section of crosscut 3 was enlarged to more closely represent that of typical Australian underground coal mines. Details on the seals are found in the section on "Construction of Seals and Stoppings" later in this report.

Before each explosion test, a 60-t hydraulically operated, track-mounted, concrete and steel bulkhead was positioned across E-drift to contain the explosion pressures in C-drift. Nearly 19 m^3 (661 ft^3) of natural gas (~97% methane) was injected into the closed end of C-drift. An electric fan with an explosion-proof motor housing was used to mix the natural gas with the air in the ignition zone. A plastic diaphragm was used to contain the natural gas and air mixture within the first 14.3 m

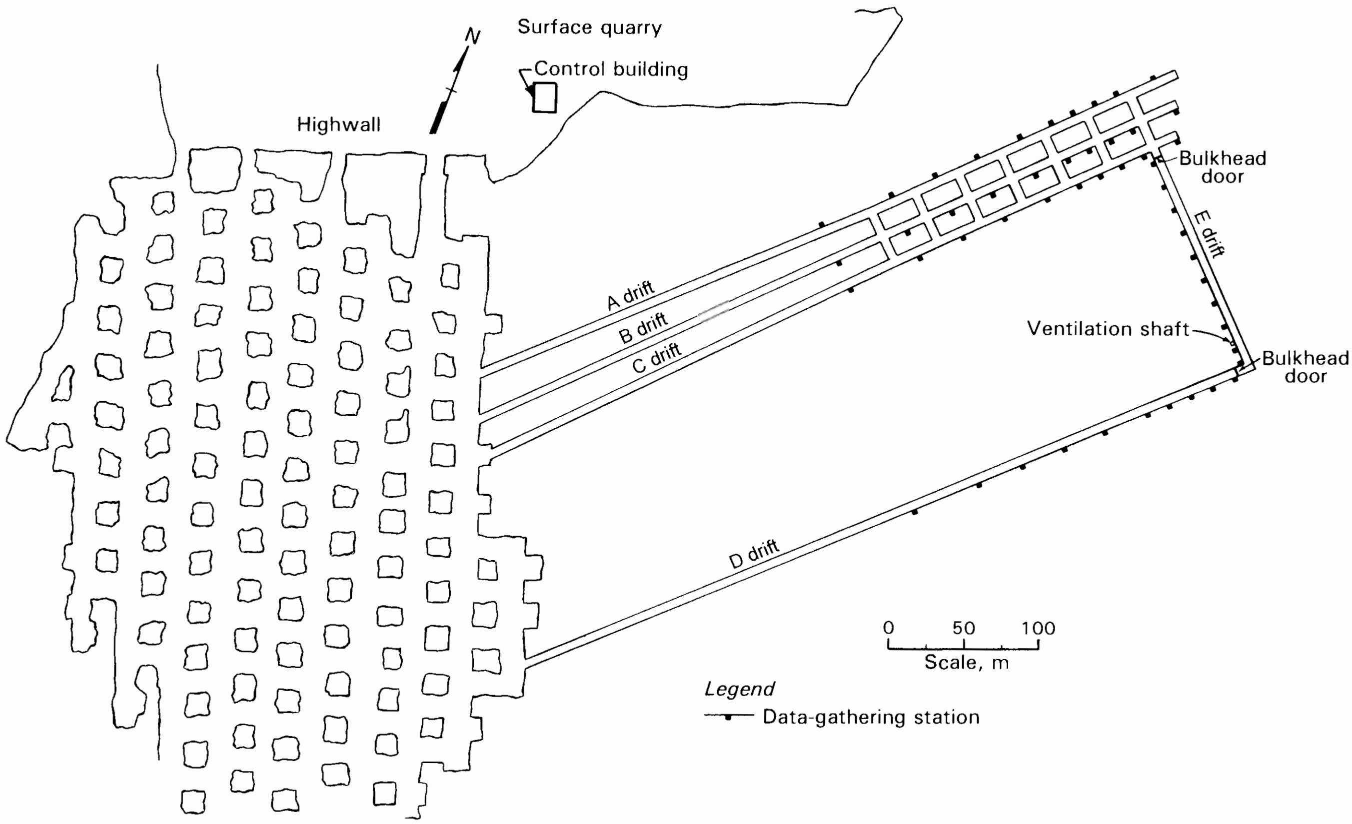

Figure 1.—Plan view of the LLEM.

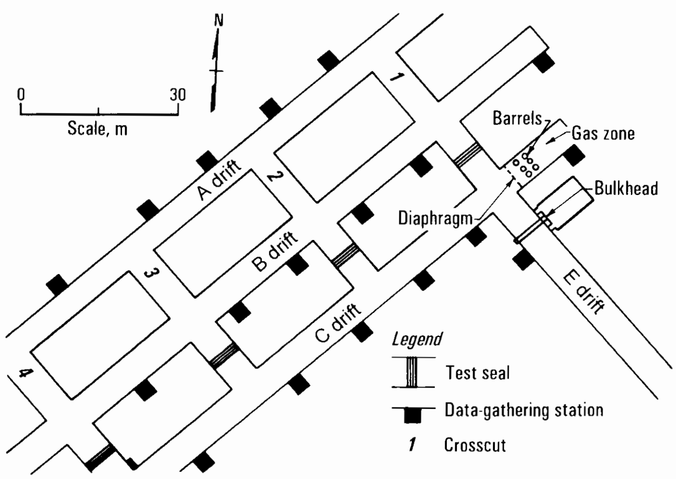

Figure 2.—Seal test area in the LLEM.

of the entry, resulting in a ~210-m^3 gas ignition zone. A sample line within the ignition zone was used to continuously monitor the gas concentrations using an infrared analyzer. In addition, samples were collected in evacuated test tubes and sent to the PRL analytical laboratory for more accurate analyses using a gas chromatograph. The analyses verified the infrared analyzer readings of ~9% methane-air. Three electrically activated matches, in a triple-point configuration across the face (closed end) of the entry, were used to ignite the flammable natural gas and air mixture. Barrels filled with water were located in the gas ignition zone to act as turbulence generators to achieve the projected 138-kPa (20-psi) pressure pulse.

Details on this first explosion test (LLEM test 347), as well as the other tests, are found in table 1. In previous methane-only gas explosion tests, the pressure pulse generated by the ignition of the methane-air zone generally resulted in static pressure pulses ranging from ~152 kPa at crosscut 1 to ~115 kPa at the most outby seal (in some instances as far outby as crosscut 5, or 150 m from the ignition source). Explosion studies have shown that the explosion pressure pulse decays less rapidly with distance in the larger LLEM entries (~13-m^2 cross section) than in smaller entries such as those in PRL's Bruceton Experimental Mine (~5-m^2 cross section), presumably because of the smaller surface-to-volume ratio in the LLEM [Sapko et al. 1987].

To achieve an explosion pressure pulse significantly in excess of 138 kPa, coal dust was used outby the gas ignition zone in C-drift. The coal dust was loaded onto shelves suspended from the mine roof at 3-m increments outby the ignition zone. During the second explosion test (LLEM test 348), a 64-m-long zone of coal dust was used in addition to the gas ignition zone. The pulverized coal dust (Pittsburgh Seam bituminous) was loaded onto the shelves to provide a coal dust concentration of 100 g/m^3; this assumed a uniform

Table 1.—Lake Lynn Experimental Mine explosion tests

Test No.	Date	Average maximum pressure, kPa	(psi)	Average flame speed, m/s	(ft/s)	Type
347	Feb. 11, 1997 . .	140	(20.0)	360	(1,190)	19-m^3 methane.
348	Feb. 18, 1997 . .	335	(49.0)	420	(1,370)	19-m^3 methane + 80-kg coal.
349	Feb. 26, 1997 . .	500	(72.0)	480	(1,570)	19-m^3 methane + 160-kg coal.
350	Mar. 11, 1997 . .	25	(3.5)	NA	NA	8-m^3 methane.
351	Mar. 12, 1997 . .	40	(6.0)	NA	NA	9-m^3 methane.

NA means that the flame speed could not be calculated because the flame traveled only a short distance.

NOTE.—Maximum pressures and flame speeds were calculated from averages over region of C-drift where the seals were located. Pressure data are rounded to nearest 5 kPa (0.5 psi).

dispersion of the coal dust over the entire cross section of the mine entry. A total of 80 kg of coal dust was used during this second seal evaluation. This dust loading was designed to produce an explosion overpressure of approximately 240 kPa (35 psi), based on previous experience. For the third explosion test (LLEM test 349) of the series, the coal dust concentration was increased to 200 g/m^3 (or 160 kg of total coal dust) over the same dust zone length. It was anticipated that this coal dust loading in conjunction with the gas ignition zone would produce an explosion overpressure somewhat in excess of 345 kPa (50 psi). The actual pressures achieved in the latter two explosion tests were higher than expected, as listed in table 1. Possible reasons are discussed in the section on "Explosion and Air Leakage Test Results" later in this report.

To achieve the low explosion pressures (<70 kPa) necessary to evaluate a stopping design during the fourth and fifth tests (LLEM tests 350 and 351), the length of the gas ignition zone was reduced from 14.3 m to only 8.2 m from the closed end of C-drift, giving an ignition volume of 115 m^3. During the fourth test, 8.2 m^3 (290 ft^3) of natural gas was injected within the gas zone, giving a methane concentration of ~7%. When ignited, the resulting gas explosion produced an average overpressure of approximately 25 kPa (3.5 psi). During the fifth test, 9.0 m^3 (319 ft^3) of natural gas was used and resulted in an explosion overpressure of about 40 kPa (6 psi).

INSTRUMENTATION

Each drift has 10 environmentally controlled data-gathering stations (shown in figures 1 and 2) inset in the rib wall. Each data-gathering station houses a strain gauge pressure transducer and an optical sensor to detect the flame arrival. The pressure transducer is perpendicular to the entry length and therefore measures the static pressure generated by the explosion. The pressure transducers were from Dynisco, Viatran, or Genisco. They were rated at 0-100 psia, with 0-5 V output, infinite resolution, and response time <1 ms. The flame sensors used Texas Instruments Type LS400 silicon phototransistors, with a response time on the order of microseconds. These phototransistors were positioned back from the front window of the flame sensors in order to limit the field of view.

Although the pressure transducers measured absolute pressure, the local atmospheric baseline pressure was subtracted from the outputted data traces, so that they were gauge pressure values. The static pressure pulses exerted on each seal were measured by interpolation of the data from the two nearest C-drift pressure transducers, one inby and the other outby the crosscut position. An additional pressure transducer was installed on the C-drift (explosion side) face of the plug seal in crosscut 1. The pressure data recorded during previous seal evaluation programs from this transducer correlated well (<7-kPa difference) with the pressure data obtained through interpolation.

Two additional types of sensors were used during this seal evaluation program: linear variable differential transducers (LVDTs) and accelerometers. These two types of sensors are shown attached to the back (B-drift side) of a seal in figure 3;[7]

[7]All photographs in this report are by Kenneth L. Cashdollar, Eric S. Weiss, or William A. Slivensky of the NIOSH Pittsburgh Research Laboratory.

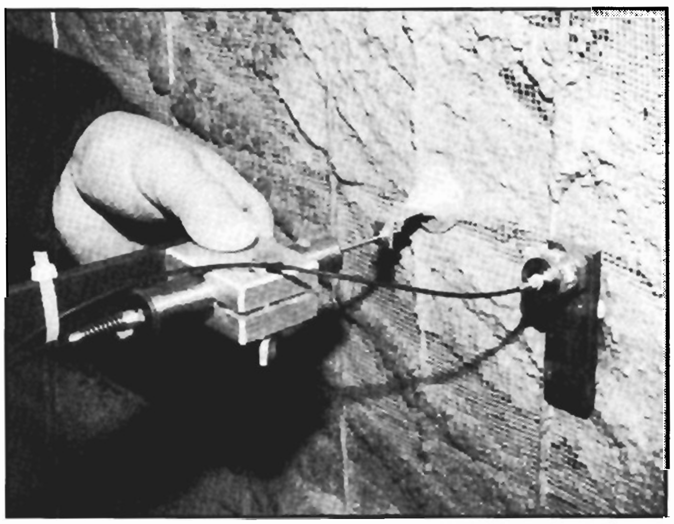

Figure 3.—Linear variable displacement transducer (LVDT) and accelerometer attached to a seal.

the LVDT is on the left, held by the engineer. The Schlumberger Industries, Inc., LVDTs provide a reliable method for precision measurement of linear displacement in the direction of the wall movement, perpendicular to the plane of the seal wall. The LVDT consists of three inductors (one primary and two secondary coils) in a hollow cylindrical shaft around a solid cylindrical core. The two secondary coils are connected in the opposite sense (one clockwise, the other counterclockwise). An input ac signal is generated in the primary. As the core is displaced (in either direction), the amplitudes of the signals induced in the secondary coils vary linearly with the displacement. The signals induced in the two secondary coils are summed and then demodulated into a dc output. The direction of displacement is indicated by the sign of the output voltage. The LVDT is calibrated by varying the position of the core (the thin rod extending from the cylindrical housing in figure 3) by known distances, then measuring the corresponding output voltages.

Accelerometers were used to measure vibration or movement of the seals and stoppings during the explosion testing. The model of accelerometer used for these tests was a Bruel & Kjaer Piezoelectric Uni-Gain DeltaShear type 4370 with a type 2635 12 V dc battery-powered preamplifier. Although the accelerometer had a much higher natural frequency of 26 kHz, the amplifier limited the output frequency to a range of 2 to 1,000 Hz. An accelerometer is shown cemented to a seal in figure 3 (right side). The piezoelectric crystal within the accelerometer produces an electric charge when a force is exerted by the seismic mass under some acceleration. This electric charge is proportional to the motion and, for this program, can be related to the acceleration of the seal during the explosion tests.

The main bodies of the LVDTs and the amplifiers for the accelerometers were attached to steel posts located behind the seals, as shown in figure 4. The square cross-section posts were bolted to the roof and floor. The main cylindrical body of each LVDT was held by an aluminum block (figure 3). The movable thin rod extending from the LVDT was attached to a small plate that was epoxied to the back face of the seal or stopping. Each accelerometer was also attached to the back of the seal with a quick-setting epoxy putty. The accelerometer signal cables were connected to the battery-powered amplifiers located in the two instrumentation boxes attached to the backs of the two posts (see figure 4). These sensors were then interfaced to the nearest data-gathering station.

During the first test, the four seals and the stopping in crosscut 5 were each instrumented with three LVDTs and two accelerometers on the B-drift side (the side opposite to the explosion). An accelerometer and LVDT were installed at the exact center (midheight and midwidth) of the B-drift side of each seal and stopping (referred to as "middle" in the tables in appendix C). These are the sensors below the instrumentation box on the left post shown in figure 4. A similar set of sensors was installed at midheight and quarter-width (halfway between

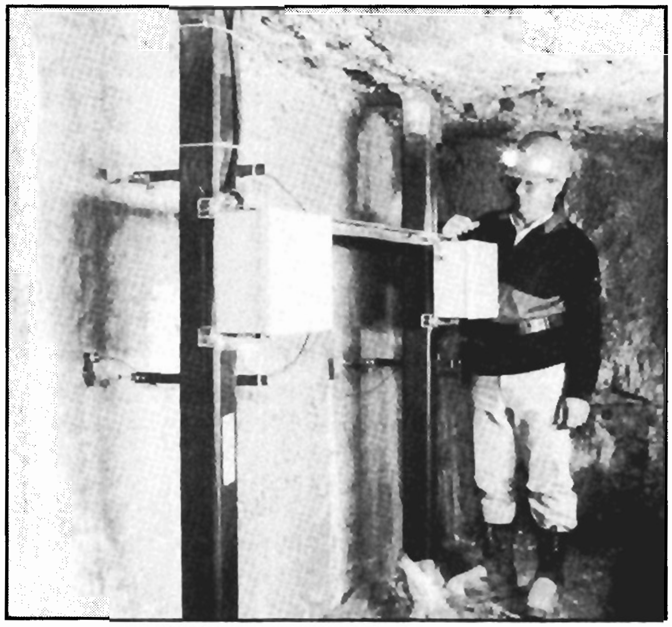

Figure 4.—Support posts and instrumentation on the back side of a seal.

the seal center and the outby rib at the right post in figure 4). (These are referred to as "right" in the tables in appendix C.) A third LVDT was installed at a three-quarters height and midwidth point (above the left instrumentation box in figure 4). (These are referred to as "upper" in the tables in appendix C.) For tests in which some of the lower strength stoppings and/or seals were anticipated to fail, some of the LVDTs and accelerometers were removed so that they would not be destroyed.

The sensor data gathered during the explosion tests were relayed from each of the data-gathering stations to an underground instrument room off C-drift and then to an outside control building. A high-speed, 64-channel, PC-based computer data acquisition system (DAS) was used to collect and analyze the data. This system collected the sensor data at a rate of 1,500 samples per second over a 5-s period. The data were then processed using LabView, Excel, and PSI-Plot software and outputted in graphic and tabular form, which is shown and discussed in the "Explosion and Air Leakage Test Results" section later in this report. The pressure and flame sensor data were also collected by a VAX computer system and outputted as plots. All of the previous seal evaluation programs [Greninger et al. 1991; Weiss et al. 1993a; Weiss et al. 1993b; Weiss et al. 1993c; Weiss et al. 1996; Weiss et al. 1997b] relied on visual readings of the raw pressure transducer traces on analog strip charts and/or VAX computer plots to determine peak pressure values. The recently installed PC-DAS and software used during this program enhanced the data analyses through the capability of expanding the time and pressure scales, thereby differentiating the actual explosion pressure pulse from other noise spikes. The reported pressure data were averaged over 10 ms (15-point smoothing) or 20 ms (31-point smoothing); the former compared most closely to the visual readings reported in previous seal test programs. Because of the scale expansion and the smoothing, the readings from the new PC-DAS were more precise than the previous readings.

AIR LEAKAGE DETERMINATIONS

An important factor to be considered for any seal design is its impermeability, or its ability to minimize air leakage from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after each of the explosion tests. For these air leakage tests, the D-drift bulkhead door (see figure 1) was closed. This directed all of the ventilation flow (from a vertical air shaft in E-drift) to the seal locations in C-drift. A double brattice cloth or curtain was erected across C-drift outby the last seal position (figure 5). This curtain effectively blocked the ventilation flow, which resulted in a pressurized area on the C-drift side of the seals. By increasing the speed of the four-level LLEM main ventilation fan while in the blowing mode, the pressure exerted on the seals increased from approximately 0.25 kPa (1-in H_2O) for the lowest fan speed setting to nearly 1.0 kPa (3.7-in H_2O) for the highest setting.

On the B-drift side of each seal, a diaphragm of brattice cloth was installed across the crosscut with a 465-cm^2 opening near the center (figures 5 and 6). A vane anemometer was used to monitor the airflow through this opening. During construction of the seals, a copper tube was positioned through each of the seals with one end of the tube extending out on each side. This tube served to measure the air pressure exerted by the fan on each seal. During these air leakage tests, a pressure gauge was attached to the copper tube on the B-drift side to monitor the differential pressure across the seal.

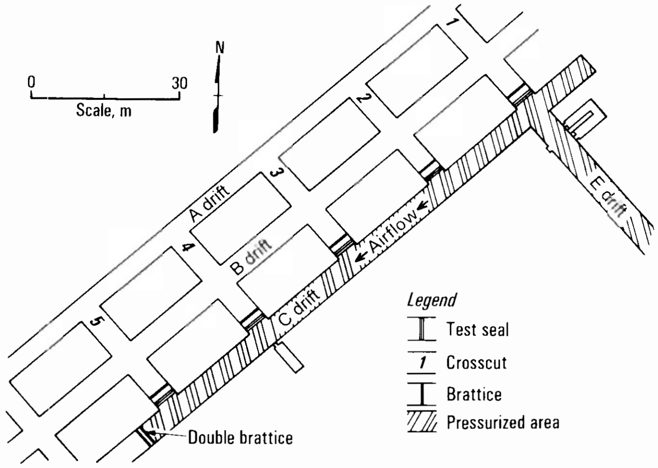

Figure 5.—Pressurized entry for leakage determination rates across the seals.

As the ventilation fan speed was increased, the pressures and airflows through each seal were recorded. Based on data previously collected during the testing program with solid-concrete-block and cementitious foam seals [Stephan 1990a,b; Greninger et al. 1991], guidelines for acceptable air leakage rates through seals were developed for the LLEM seal evaluation programs. The air leakage rates through the seals during both preexplosion and postexplosion leakage tests were

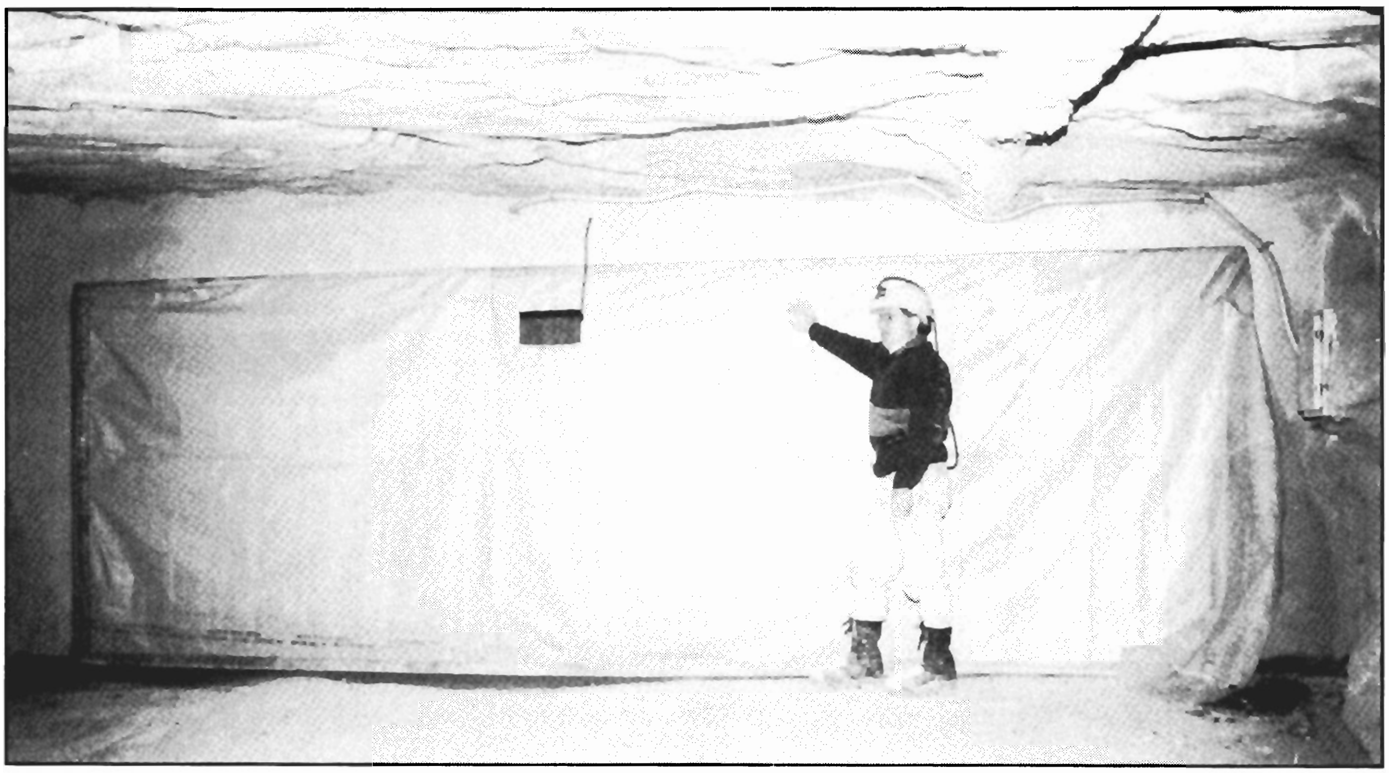

Figure 6.—Brattice in place for seal leakage test.

leakage tests were evaluated against these established guidelines. Table 2 shows these maximum acceptable air leakage rates as a function of pressure differential. For pressure differentials up to 0.25 kPa (1-in H_2O), air leakage through the seal must not exceed 2.8 m^3/min (100 cfm). For pressure differentials over 0.75 kPa (3-in H_2O), air leakage must not exceed 7.1 m^3/min (250 cfm). The pressure differential was measured using the copper tubing through the seal. The flow rate was calculated from the linear air speed measured by the vane anemometer and the area of the opening through the brattice cloth behind each seal.

When postexplosion visual inspection of a seal revealed substantial structural damage, that seal was considered not to meet the minimum standards as specified in the Code of Federal Regulations for an underground coal mine seal and therefore failed. Postexplosion air leakage tests were not performed on seals that exhibited significant damage in terms of large gaping cracks. Seals that withstood the pressure pulse with little or no outward signs of damage were tested for air leakage resistance.

Table 2.—Guidelines for air leakage through a seal

Pressure differential, kPa (in H_2O)	Air leakage rate, m^3/min (cfm)
<0.25 (<1.0)	<2.8 (<100)
0.25 < 0.50 (1.0 < 2.0)	<4.3 (<150)
0.50 < 0.75 (2.0 < 3.0)	<5.7 (<200)
≥0.75 (>3.0)	<7.1 (<250)

CONSTRUCTION OF SEALS AND STOPPINGS

Numerous seal and stopping designs, using specially designed formwork in-filled with shotcrete, were tested in the LLEM. Two parts comprised the testing program. The first involved constructing and testing five designs at explosion overpressures of 138 kPa (20 psi) and above. The second part was the testing of a Gunmesh stopping intended to satisfy the requirements of the Queensland, Australia, coal mining standards for ventilation.

In the United States, a seal is defined, in part, as any structure that can withstand an explosion overpressure of at least 138 kPa. The seals were all built using the Meshblock formwork system, except for the 1,200-mm-wide plug seal, which had Gunmesh and shotcrete walls to contain the wet-mix core. Meshblock is the Tecrete trade name for a form comprised of heavy (4-mm-diam) metal wire and metal screen that is used to contain the shotcrete in a seal. Details of the Meshblock system can be found in the "Meshblock Seals" section later in this report. The two stopping designs, one of which was tested in the first part of the program, were both constructed using Gunmesh formwork and shotcrete. Gunmesh is the Tecrete trade name for a form composed of a mesh and wire backing reinforced with a grid of 4-mm-diam wire, providing a means to contain and support sprayed shotcrete material. Details of the Gunmesh formwork can be found in the "Gunmesh Stoppings" section later in this report.

The shotcrete was applied within the formwork with the dry-mix process using a REED Lova 215 pneumatically operated gunite machine. This recently developed shotcrete machine supplied by REED Manufacturing, Chino, CA, was used in all seal and stopping constructions using the dry shotcrete process. The minus 5-mm aggregate and cement dry mix was designed to be cast into the Meshblock formwork and was also suitable for spraying as a shotcrete onto Gunmesh formwork. The prebagged dry shotcrete mix was fed into the hopper of the shotcrete machine. The dry shotcrete was then pneumatically delivered through a 40-m-long by 38-mm-diam hose to a nozzle, where mixing water was added. This wet shotcrete mixture was then sent through a short delivery hose into the Meshblock formwork or onto the Gunmesh formwork. The REED Lova 215 was operated at casting rates of up to 4 t/h during the seal construction. This is at the lower end of the machine's capabilities. The dust-catching system of this shotcrete machine resulted in a significant reduction in the airborne dust that is usually generated when loading shotcrete into other types of machines. Air was supplied via a 50-mm-diam bull-hose, which provided the 10 m^3/min (350 cfm) necessary to operate this machine when using a 38-mm-diam shotcrete hose. When handling these cementitious products, all material safety data sheet (MSDS) instructions should be adhered to by operators.

A summary of the data for the four seals and two stoppings is found in table 3. Construction details for the seals and stoppings are found in the following sections of this report. The seals were constructed in the LLEM under conditions analogous to those that may be encountered during seal construction in an actual underground coal mine. As in the installation of any seal design, all loose material had to be removed from the seal construction site, leaving competent strata. In the LLEM, the 150-mm-thick concrete slab floor within each crosscut had been laid on gravel, and its stiffness would influence the ability of each seal design to resist horizontal loads. Therefore, the floor was drilled at 600-mm centers across the center line of the intended seal and injected with a grout to provide greater floor stiffness. The mine air temperature during the 2-week construction period (January 28-February 10, 1997) ranged from 9 to 15 °C (48 to 59 °F) and averaged 10.5 °C (51 °F). The relative humidity ranged from 50% to 74% and averaged 59%.

Table 3.—Seal and stopping construction data (in chronological order of construction)

Seal/stopping crosscut No.	Construction date	Crosscut size					Total product used, kg
		Thick-ness, mm	Width, m	Height, m	Area, m^2	
Plug seal 1	Jan. 28-29, 1997	1,200	5.43	1.95	10.6	11,543
Gunmesh stopping 5	Jan. 29, 1997	75	5.79	2.22	12.9	5,239
Meshblock seal 2	Jan. 30, 1997	325	5.76	2.26	13.0	9,366
Meshblock seal 4	Jan. 31, 1997	175	5.97	2.26	13.5	5,307
Meshblock seal 3	Feb. 10, 1997	325	5.82	2.74	16.0	11,045
[1]Gunmesh stopping 3	Mar. 4, 1997	40	5.88	2.10	12.4	1,948

[1]This stopping was erected after the seal in crosscut 3 was destroyed during LLEM explosion test 349.

PLUG SEAL

Previous explosion seal test programs have tested plug seals made with materials such as cementitious foam [Stephan 1990a; Greninger et al. 1991; Weiss et al. 1993a; Weiss et al. 1993b; Weiss et al. 1993c] and cellular concrete [Weiss et al. 1996] up to overpressures of 327 kPa. In this program, two 75-mm-thick Gunmesh and shotcrete stoppings provided the outer walls of the 1,200-mm-thick plug seal. The interior was filled with an injected lower density core of Aquablend with a design compressive strength of 3.45 MPa (500 psi). Samples of the Aquablend mix taken during seal construction achieved a measured compressive strength of 3.81 MPa (560 psi) after 28 days of cure time. A detailed description of the construction techniques of a Gunmesh stopping is presented in the "Gunmesh Stoppings" section later in this report. Aquablend is the trade name for a low-density, pumpable, cementitious product. The entry size in crosscut 1 at the plug seal location was approximately 5.43 m wide by 1.95 m high. The first Gunmesh stopping required 1,837 kg of Quikrete MB500 shotcrete to provide an adequate coverage of the Gunmesh. This prevented leakage of the wet-mix core material during the subsequent injection process. Figure 7 shows the construction of the Gunmesh form for the second stopping. This stopping, closest to C-drift and located about 1,168 mm (46 in) from the first stopping, was sprayed from the C-drift side with 2,313 kg of the Quikrete MB500 shotcrete. A 600- by 600-mm window through this second stopping provided the opportunity to clean shotcrete rebound from the interior floor of the plug seal after the second stopping was shotcreted. This window was subsequently sealed with shotcrete before the wet mix was added. Steel spacers located approximately 1,300 mm from the floor and spaced across the crosscut at 600-mm centers provided lateral support to the two stopping walls, which were subjected to a hydraulic head by the Aquablend wet mix.

After completing these two stoppings (form walls), contractors from Alminco Pty. Ltd. injected 7,393 kg of Aquablend wet-mix slurry between the two stopping walls using an air-driven Langley Placer. A 61-m-long by 32-mm-diam delivery hose was used to inject the Aquablend. Three 32-mm-diam injection ports were cast into the C-drift Gunmesh stopping (figure 8). These ports were located 400 mm from the mine roof. One port was located 900 mm from the left rib, the second port was located at the center of the stopping, and the third port was located 900 mm from the right rib. Plastic extension pipes (air bleeders) were located within the stopping walls 300 mm from the mine roof. These pipes were angled toward the mine roof to the highest cavities to ensure complete filling to the roof. The Aquablend was injected simultaneously through all three injection ports. As the Aquablend reached the roof and came out of the bleeder pipes, these pipes were progressively closed from the outby side of the seal (lower roof height) to the higher inby end of the seal. The last injection port was pressurized until refusal of the placer at 1.38-MPa slurry pressure. This ensured that the slurry level was in direct contact with the mine roof. Figure 8 shows the completed plug seal.

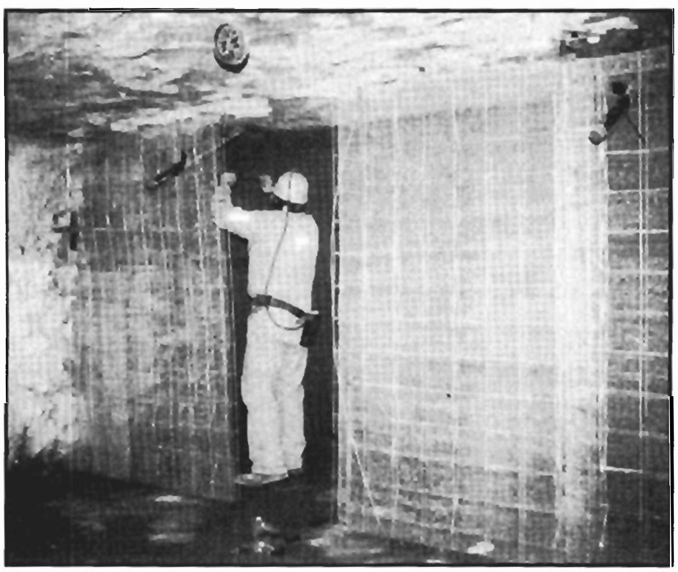

Figure 7.—Construction of second wall of plug seal in crosscut 1.

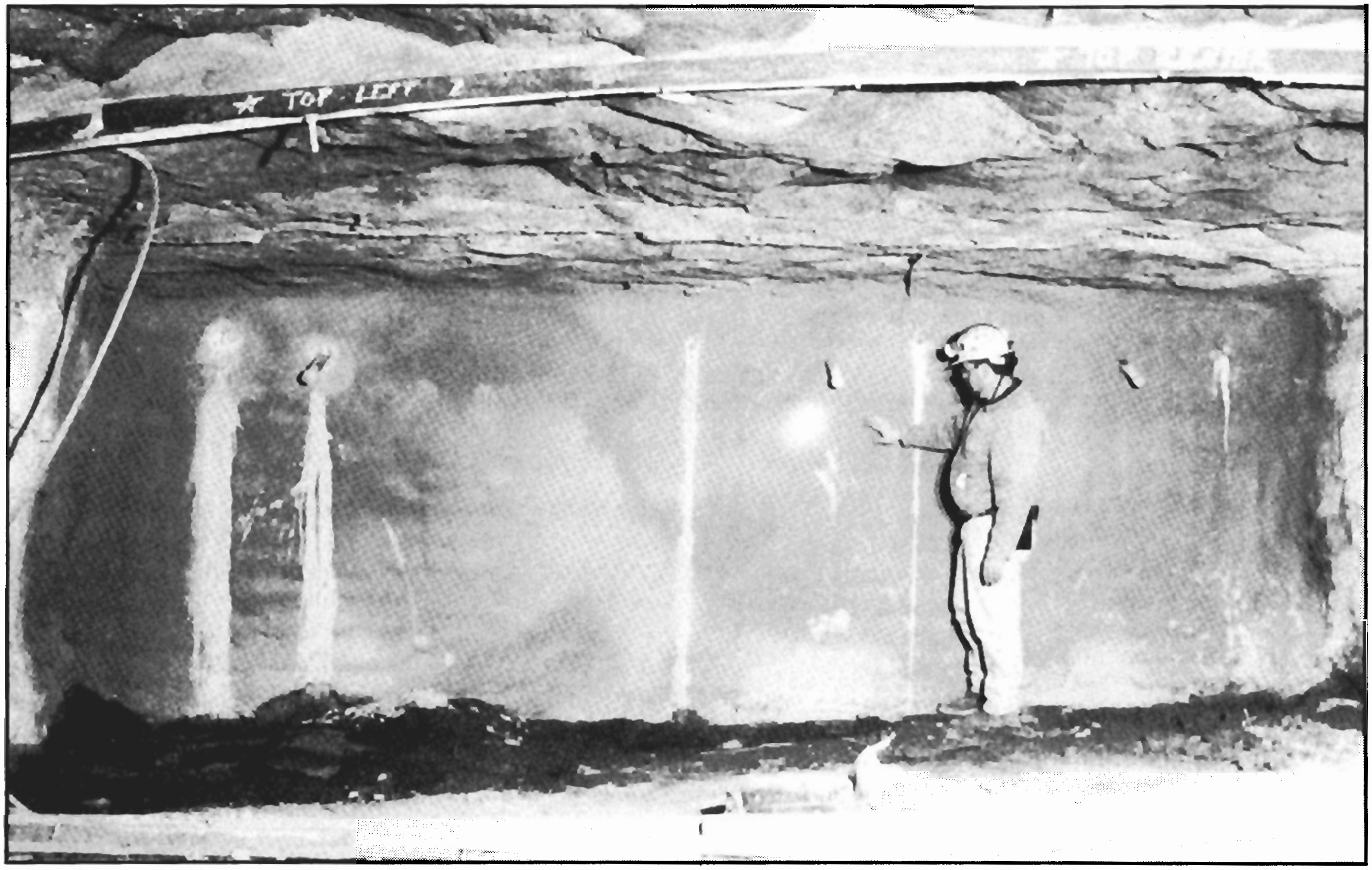

Figure 8.—Completed plug seal in crosscut 1.

MESHBLOCK SEALS

Three Meshblock and shotcrete seals ranging from 175 to 325 mm thick were constructed in crosscuts 2 through 4 between B- and C-drift in the LLEM (see figure 5). They ranged in thickness from 175 to 325 mm. One crosscut was mined to a height of nearly 3 m to simulate the height of entries found in a typical Australian coal mine. Summary data for the seals are presented in table 3.

Roof and floor bolts were installed on 600-mm centers, and rib bolts were installed on 1-m centers, which formed a vertical plane at the center line of each seal. These 24-mm-diam steel bolts were 1.2 m long and fully encapsulated with polyester resin capsules (16-s setting time) within the 600-mm-deep, 30-mm-diam holes. The concrete floor was chiseled to a depth of approximately 20 mm, providing a key and a level footing for each seal. The bolts provided a rigid attachment of the seal to the rock strata, which assists the seal in resisting horizontal loads. It must be noted that the test environment in the LLEM is one of solid, nonyielding strata.

The Meshblock formwork consisted of a U-shaped frame formed as a folded grid of 4-mm-diam steel-wire framework (square grid pattern on 152-mm centers) (figure 9). A 3-mm-aperture steel-mesh screen encloses the sides and is an integral part of this formwork, enabling the shotcrete nozzleman to examine the flowing shotcrete material. The Meshblocks were laid horizontally in rows in which the ends were butted to each other and secured by plastic or wire ties. Normally, two rows of Meshblock were erected at a time and cast with shotcrete (figure 9). The cycle was repeated until seal completion. There

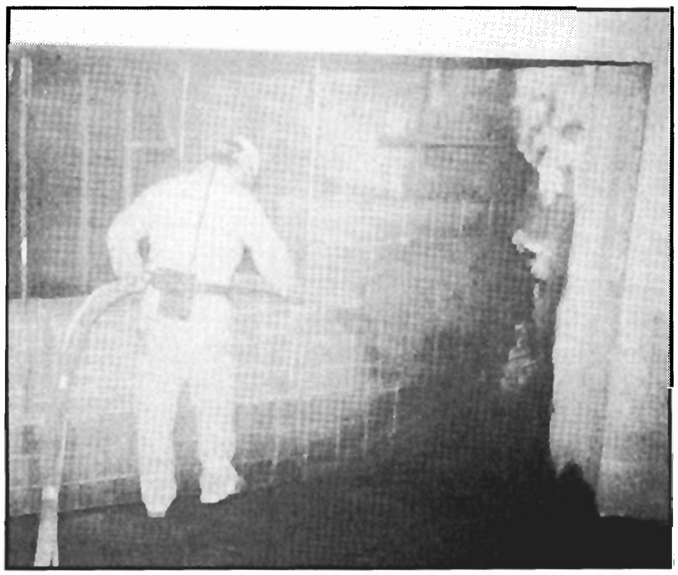

Figure 9.—Construction of Meshblock seal in crosscut 2.

was a 45-mm overlap on each successive layer of Meshblock. The sides of each Meshblock form were secured by five steel clips that were attached to the wire grid to keep the seal width consistent. Care must be taken to ensure that the interval between casting successive layers does not exceed 0.5 hr in order to prevent the forming of a cold joint. All Meshblock seals were constructed in a continuous manner until completion. Each of these three seal designs was sprayed with the Quikrete MB500 shotcrete, which is a mixture of cement and minus 5-mm aggregate.

Steel roof, rib, and floor bolts anchored each seal to the surrounding strata and provided edge restraint for the seal when explosion overpressures were applied. These bolts perform the same purpose as keying. Previous practice during seal evaluation in the LLEM was to provide edge restraint by bolting 152- by 152-mm steel angles (13 mm thick) to the floor and ribs. These steel angles were attached using 600-mm-long, 25-mm-diam, case-hardened grade 8 steel all-thread rod (embedded 450 mm) or 230-mm-long, 25-mm-diam Hilti Kwik bolt fasteners. Both rods and bolts used 450-mm spacings on the floor and rib. Several U.S. operating coal mines have been permitted to use a similar type of edge restraint in areas with hard sandstone floors in which standard keying would be very difficult.

As the Meshblock structure was built upward, the floor steel bolts were extended vertically toward the roof. Steel bolt overlap was 600 mm for the vertically extended reinforcing. Normally, the roof bolts were installed first, and the lower floor bolt holes were aligned by string-line and drilled so that the vertical steel reinforcing formed straight lines. Once all the steel reinforcing was tied together, it formed a vertical plane in the center of the completed Meshblock seal.

Table 3 summarizes the data for these Meshblock seals. Figure 9 shows the miner injecting shotcrete within the Meshblock forms during construction of the 325-mm-thick seal in crosscut 2; figure 10 shows the completed seal. Samples of the Quikrete MB500 shotcrete used in this seal were collected during construction. The measured compressive strength of the shotcrete was 38 MPa after 7 days and 46 MPa after 28 days. Figure 11 shows the details of the reinforcing bolts attached to the rib and roof for the 175-mm-thick seal in crosscut 4. Figures 12 and 13 show the shotcrete being sprayed into seal 4. Figure 13 shows the shotcrete hose and the mixing nozzle above the miner's head. Figure 14 shows the completed seal 4. The compressive strength of the shotcrete used in this seal was 41 MPa after 7 days and 60 MPa after 28 days. Figure 15 shows the reinforcing bolts and Meshblock formwork during the construction of the 325-mm-thick by 2.7-m-high seal in crosscut 3. The engineer in the figure is standing on a wood plank scaffold used to reach the upper parts of this 2.7-m-high seal. Figure 16 shows a miner attaching another row of Meshblock formwork during the construction of the seal. Figure 17 shows the completed seal in crosscut 3. The compressive strength of the shotcrete used in this seal was 41 MPa after 1 day, which was the time of the first explosion test on this seal.

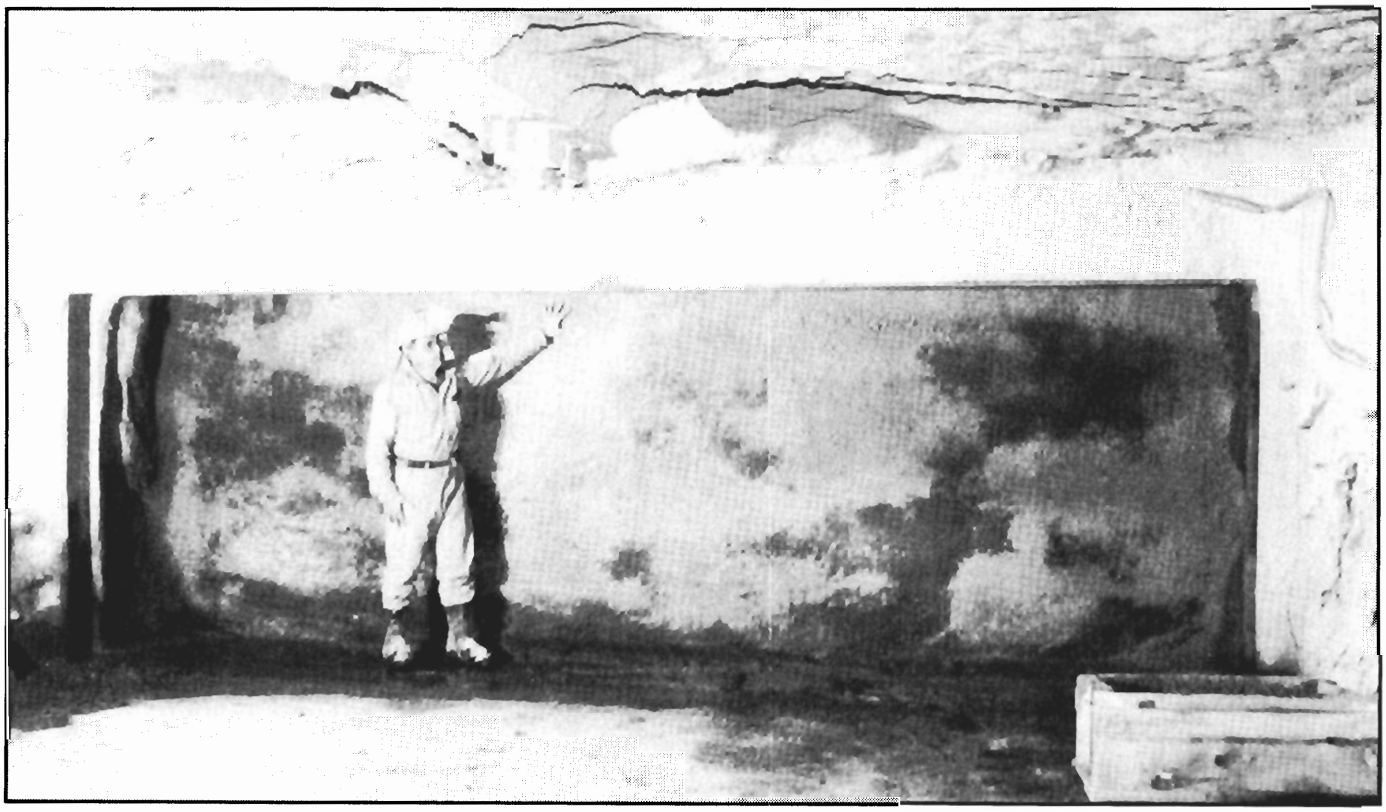

Figure 10.—Completed Meshblock seal in crosscut 2.

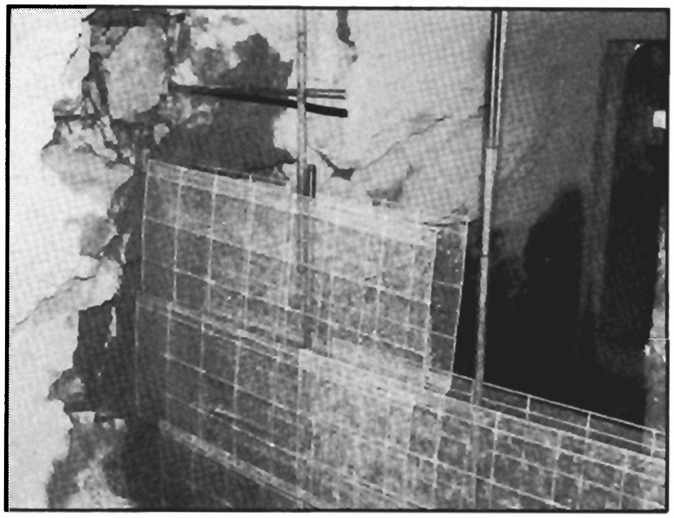

Figure 11.—Construction of Meshblock seal in crosscut 4, showing reinforcing bars anchoring it to the ribs and roof.

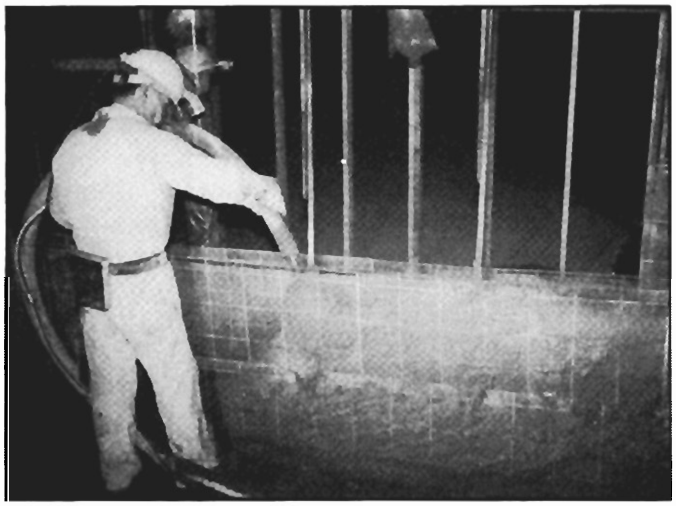

Figure 12.—Construction of Meshblock seal in crosscut 4.

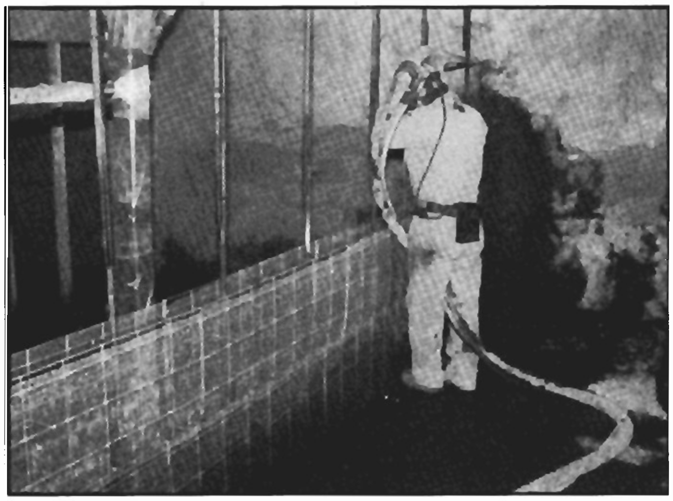

Figure 13.—Construction of Meshblock seal in crosscut 4.

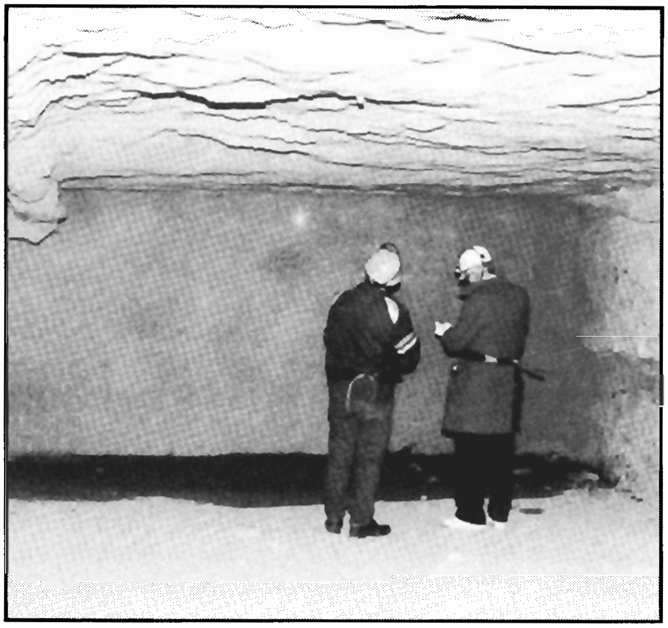

Figure 14.—Completed Meshblock seal in crosscut 4.

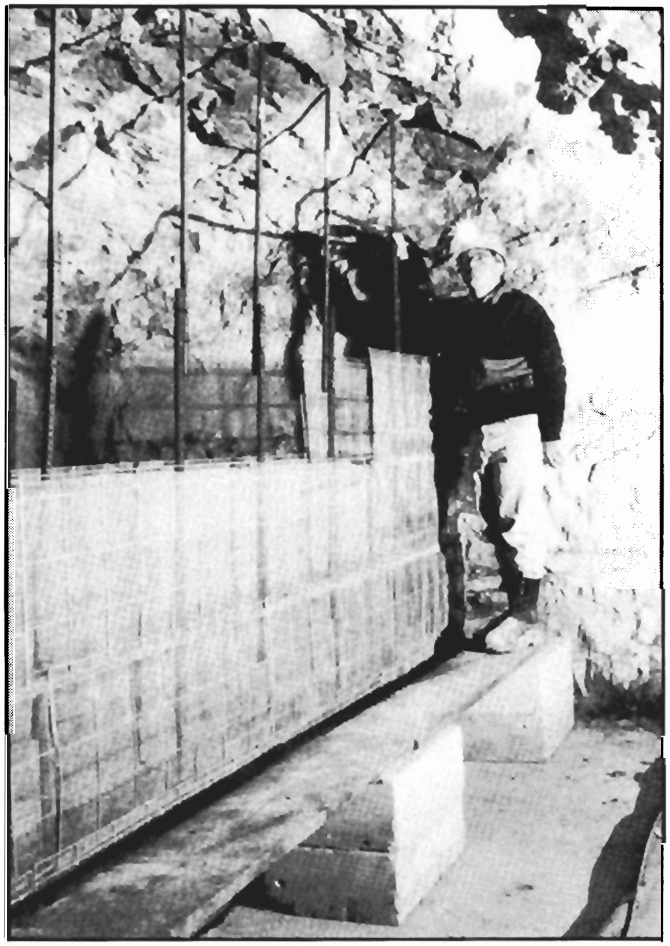

Figure 15.—Construction of Meshblock seal in crosscut 3, showing reinforcing bars anchoring it to the ribs and roof.

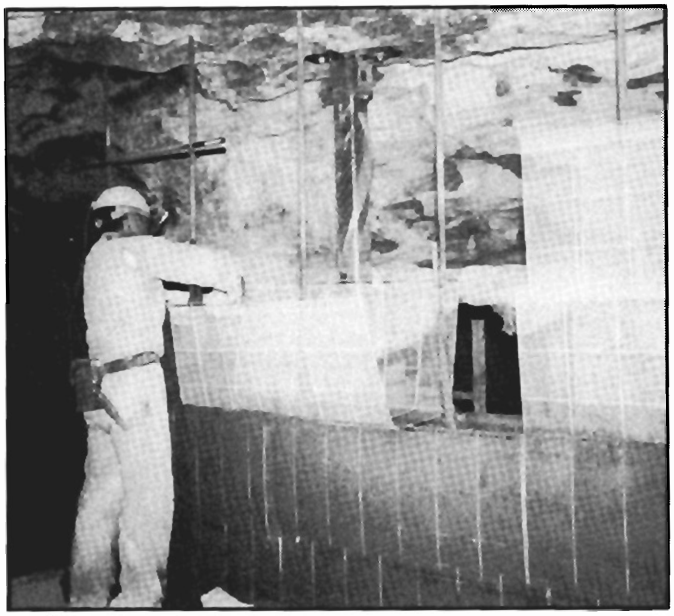

Figure 16.—Construction of Meshblock seal in crosscut 3.

Figure 17.—Completed Meshblock seal in crosscut 3.

GUNMESH STOPPINGS

Two stopping designs were constructed in the crosscuts between B- and C-drift in the LLEM using Gunmesh formwork that was erected and then in-filled with sprayed shotcrete. The construction is similar to that of the walls constructed for the plug seal in crosscut 1 (figure 7). In the stopping erected in crosscut 5, both formwork and shotcrete were supplied by Tecrete Industries. The Tecrete MB500 (similar to the Quikrete MB500) is a mixture of cement and minus 5-mm aggregate shotcrete supplied in 25-kg bags and applied with the REED Lova 215 gunite machine. As for the seals, the roof, ribs, and floor were cleaned of loose debris back to solid material. The concrete floor was keyed approximately 20 mm to form a level base. The bolt pattern in the Gunmesh stoppings required 24-mm-diam by 1,200-mm-long bolts in the roof, ribs, and floor spaced at 1-m centers. The bolts were fully encapsulated 600 mm into solid rock, forming a vertical plane.

The Gunmesh formwork consisted of a 4-mm-diam galvanized wire framework (square grid pattern on 150-mm centers) sheet in 1.2- by 3-m sections. A galvanized steel mesh with 3-mm apertures was welded integral with this heavier wire framework. This composite sheet was attached to an additional square grid pattern of welded 4-mm-diam galvanized wire bars held apart from the composite sheet by cross braces of the same material, thus forming a lattice of ~50-mm thickness open at one side. This sheet was tied to the roof and floor bolts. The Gunmesh sheet edges were overlapped 100 mm and secured together with plastic cable ties. Once the formwork was in place and attached to the peripheral bolts, it was in-filled from the open side with the shotcrete. The vertical roof and floor bolts were linked by attaching steel bolts of the same diameter. The bolt sections were overlapped 0.5 m with the extended sections of the grouted roof and floor bolts. Plastic cable ties were used to secure these bolt sections. Care must be taken that there is total coverage of the steel bolts with no shadows of dry or overspray shotcrete material and that the Gunmesh cage is attached to and envelops the steel bolts. The Gunmesh stopping was spray shotcreted with no delays until the specified nominal thickness was achieved.

The first stopping to be constructed was the 75-mm-thick Gunmesh stopping within crosscut 5. The Gunmesh formwork was cut using bolt cutters to fit the contours of the entry. The mine strata on both sides of the stopping were sealed with shotcrete. The formwork had a depth/thickness of 50 mm, which meant that an additional 25-mm thickness of shotcrete was sprayed to provide the total stopping thickness of 75 mm. At the stopping, crosscut 5 was 5.79 m wide by 2.22 m high. The compressive strength of the shotcrete used in this stopping was 37 MPa after 7 days and 50 MPa after 28 days.

As part of a low-pressure explosion test program, a second Gunmesh stopping was erected in crosscut 3 on March 4, 1997 (after the seal in crosscut 3 was destroyed during LLEM explosion test 349), using the Gunmesh formwork. Due to a shortage of shotcrete, no additional coating was applied to this stopping beyond the ~40-mm thickness of the Gunmesh formwork (figure 18). The size of crosscut 3 at this stopping location was 5.88 m wide by 2.10 m high. Generally, to satisfy the requirements of the Queensland Department of Minerals and Energy "Approved Standard for Ventilation Control Devices," Gunmesh construction techniques are used in applications that require explosion overpressure ratings of 14, 35, and 70 kPa (2, 5, and 10 psi). Totals of 5,239 kg and 1,948 kg of shotcrete were sprayed on the 75-mm-thick and 40-mm-thick stoppings, respectively. A significant fraction of this material was lost by passing through the Gunmesh formwork or as rebound.

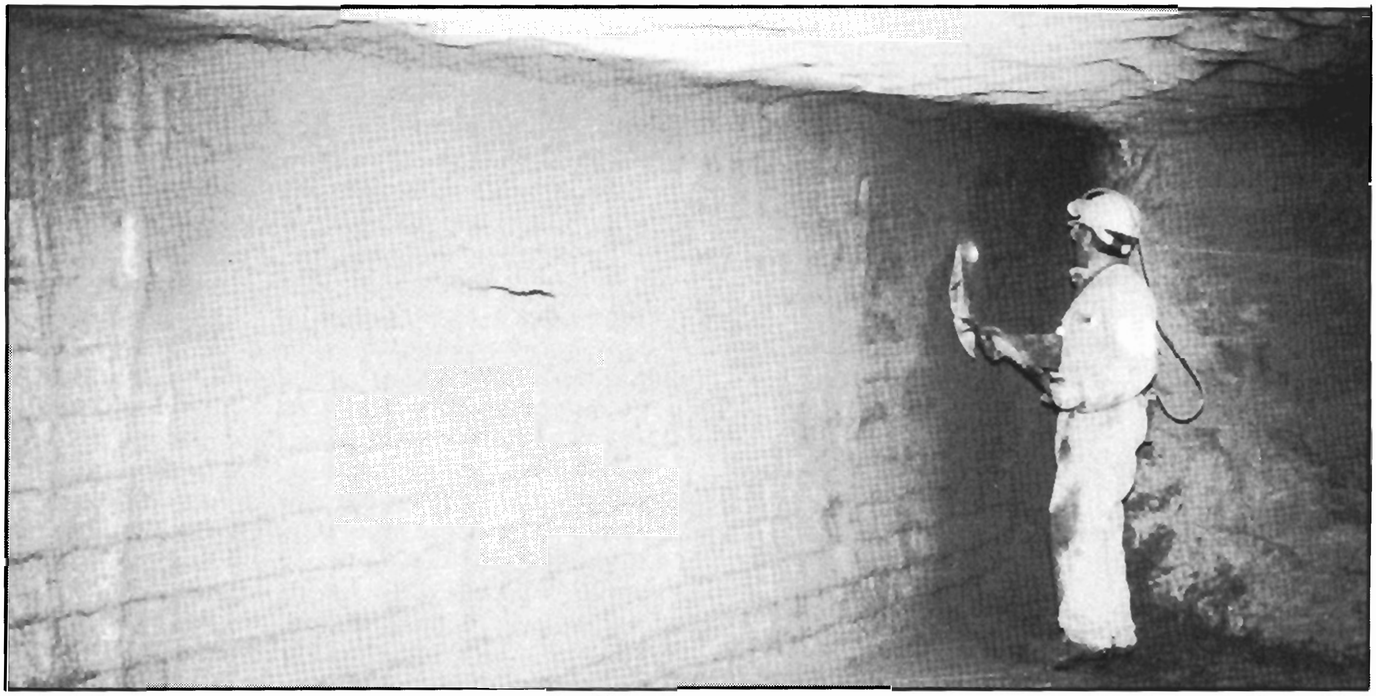

Figure 18.—Completed stopping in crosscut 3.

EXPLOSION AND AIR LEAKAGE TEST RESULTS

A summary of the five explosion tests in the LLEM is presented in table 1, which lists average maximum explosion pressures and flame speeds for each test. More detailed data for the explosion tests are found in the appendices. Summary tables of static pressure data are in appendix A. The table for each explosion test lists the static pressures at the various station locations and the interpolated static pressures at the seals. A summary table of flame arrival times at the various stations for each explosion is in appendix B. These flame arrival times were used to calculate the average flame speeds in table 1. Summary tables of LVDT data are in appendix C. Examples of the accelerometer data for LLEM test 348 are shown in appendix D. The plots on the left side of figure D-1 show the raw accelerometer data on a greatly expanded time scale. On the right side of the figure are the corresponding Fourier transforms of the data. Analyses of the failure/destruction of the seals and stoppings are in appendix E. The LLEM explosion tests are individually discussed in detail in the following sections.

Before the first explosion test, the four seal designs (in crosscuts 1 through 4) and the one stopping design (in crosscut 5) were evaluated for air leakage resistance. The four differential pressures listed in table 4 correspond to the four speeds of the main ventilation fan in the LLEM. As table 4 indicates, virtually no air leakage could be detected through any of the four seal designs for pressure differentials up to nearly 1 kPa. The 75-mm-thick Gunmesh stopping design in crosscut 5 exhibited no air leakage up to 0.28-kPa pressure differential and only very minimal leakages to pressure differentials of up to 1 kPa.

Table 4.—Air leakage measurements before the first LLEM explosion test

Location	Air leakage rate, m^3/min, at pressure differential of—			
	0.03 kPa	0.28 kPa	0.53 kPa	0.93 kPa
Seal in crosscut 1	0.0	0.0	0.0	0.0
Seal in crosscut 2	0.0	0.0	0.0	0.8
Seal in crosscut 3	0.0	0.0	0.0	0.0
Seal in crosscut 4	0.0	0.0	0.0	0.0
Stopping in crosscut 5 . .	0.0	0.0	1.2	1.8

FIRST EXPLOSION TEST

On February 11, 1997, the first explosion test (LLEM test 347) was conducted in C-drift of the LLEM approximately 27 hr after the completion of the 2.74-m-high by 325-mm-thick Meshblock seal in crosscut 3. The ignition of the 210 m^3 of ~9.0% methane-air zone at the closed end of C-drift generated peak static overpressures at the seal and stopping locations ranging from 160 kPa at the 325-mm-thick Meshblock seal in crosscut 2 to 115 kPa at the Gunmesh stopping in crosscut 5. These pressure values are based on a 10-ms time average (15-point smoothing) of the raw pressure signals from the PC-DAS. Figure 19 shows the pressure traces at various distances down the entry for explosion test 347. These pressure

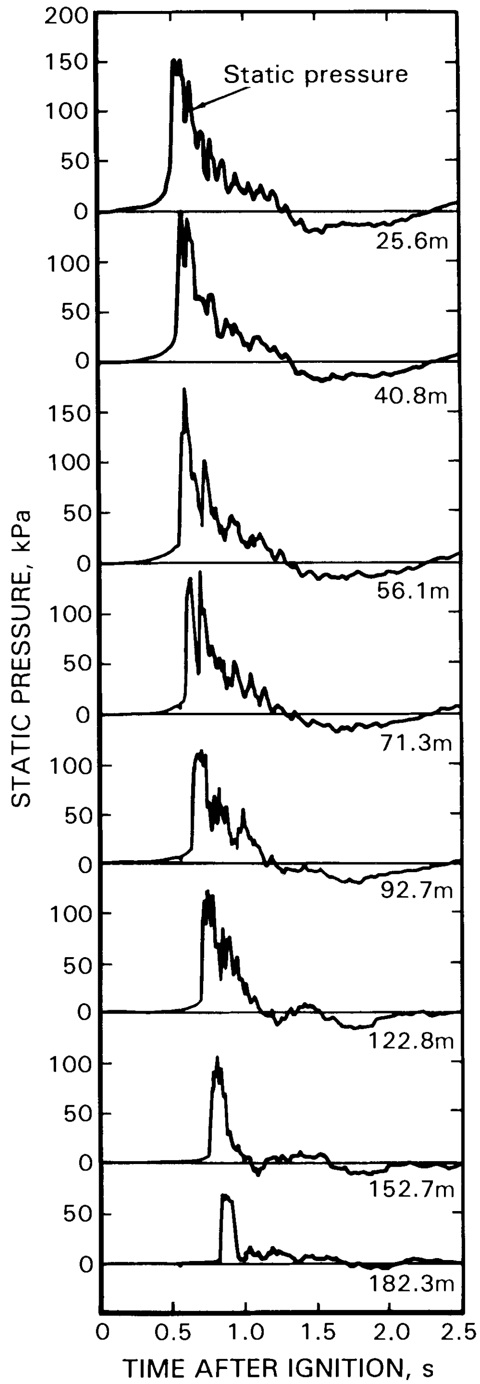

Figure 19.—Pressure traces as a function of distance in C-drift for LLEM test 347.

traces in figure 19 and in subsequent figures have also been averaged over 10 ms. The complete listings of the peak pressures (P_{max}) at the various transducer locations for LLEM test 347 are in table A-1 for both 10- and 20-ms averaging. Also listed in table A-1 are the interpolated static peak pressures at each of the seals and the stopping for this test. The 10- and 20-ms time-averaged pressure data, the pressure-time integrals ($\int$Pdt), and the P_{max} times are from the PC-DAS using LabView, Excel, and PSI-Plot software. This PC data analysis system allows the data traces to be expanded in time and pressure so that the peak values can be read precisely. Additionally, table A-1 lists the visual pressure readings from the VAX computer plots, which are at a similar scale to the plots in figure 19 and thus cannot be read as precisely. The PC and VAX pressure readings, however, show good agreement within measurement error.

Postexplosion observations following the first explosion test revealed that the four seal designs withstood the explosion pressure pulse with little or no outward damage except for a few vertical and/or horizontal hairline cracks on each of the Meshblock seal designs. A 1.6-mm-wide center vertical crack extending from the mine roof to the floor was observed on the front wall of the 325-mm-thick Meshblock seal in crosscut 3 after the explosion. The depth of this crack was unknown. It was also uncertain if this crack was due to the explosion pressure pulse or to shrinkage of the shotcrete material, because this seal was tested after only a 27-hr cure period. A similar crack had developed on the 325-mm-thick Meshblock seal in crosscut 2 approximately 2 days after the seal was completed and well before the first explosion test. The crack in the crosscut 2 seal was observed on both sides of the seal and was attributed to the not uncommon problem of shrinkage sometimes associated with cementitious-based products.

The 75-mm-thick Gunmesh stopping design in crosscut 5 also withstood the pressure pulse, but exhibited two horizontal cracks that extended across the entire front face (C-drift, or explosion side) of the stopping—one across the top section of the stopping about 150 mm down from the roof and the second across the center portion of the stopping. A chipped-out section of the center of this stopping on the C-drift wall indicated localized compression failure of the shotcrete, with the entire structure very close to failure. No cracking was evident on the back side of this stopping. The data from the LVDTs (see appendix C) on the Gunmesh stopping recorded a maximum displacement of about 25 mm during the explosion. The maximum displacement (see appendix C) of the thicker Meshblock seals for LLEM test 347 was only 1.8 mm for the 325-mm-thick seal in crosscut 2 (160-kPa peak pressure); 2.7 mm for the similarly thick, but larger cross-section Meshblock seal in the 2.7-m-high crosscut 3 (135-kPa peak pressure); and 8.4 mm for the 175-mm-thick Meshblock seal in crosscut 4 (120-kPa peak pressure). The 1,200-mm-thick plug seal in crosscut 1 revealed only negligible displacement (~0.1 mm) when subjected to a peak pressure pulse of approximately 150 kPa. These LVDT data show that, as expected, the displacements were greater for the thinner seals or larger cross-section seals. The more detailed LVDT data for test 347 (table C-1) show that the largest displacement (within experimental error) for each individual seal occurred at the middle LVDT; similar or smaller displacements occurred at the other LVDTs. Postexplosion air leakage rates (table 5) across each of the seal and stopping designs following the first explosion test were well within the established guidelines (table 2) for the LLEM seal evaluations.

Table 5.—Air leakage measurements between the first (No. 347) and second (No. 348) LLEM explosion tests

Location	Air leakage rates, m³/min, at pressure differential of—			
	0.14 kPa	0.34 kPa	0.51 kPa	0.90 kPa
Seal in crosscut 1	0.0	0.0	0.0	0.0
Seal in crosscut 2	0.0	0.0	≤0.7	1.0
Seal in crosscut 3	0.0	0.0	0.0	1.0
Seal in crosscut 4	0.0	≤0.7	0.8	1.3
Stopping in crosscut 5	≤0.7	1.0	1.2	1.8

An important measure of the damaging potential of the explosion pressure pulse is the total pressure impulse, which is the time integral of the pressure trace ($\int Pdt$) multiplied by the surface area of the seal. Therefore, the total impulse is $\int PAdt$, where P is pressure, A is the area of the seal, and t is time. The $\int Pdt$ data are listed in table A-1, along with the pressure data. The destructive forces of the explosion blast wave depend on both the maximum peak overpressure and the impulse [Sapko et al. 1987]. Under the current U.S. evaluation criterion, a seal design need only withstand a minimum static pressure pulse of 138 kPa while maintaining acceptable air leakage resistance (table 2); impulse requirements have yet to be defined. For this reason, seal designs in previous research programs were frequently subjected to higher level explosion pulses in the LLEM as a means to evaluate them against higher impulse loadings. The calculated pressure-time integral for the plug seal in crosscut 1 was approximately 41 kPa-s, giving a total impulse of 435 kN-s.

In order to more fully evaluate the strengths of the seals and the stopping and to generate data to assist in the development of a numerically based design tool for explosion seals, successive and more intense explosions were required.

SECOND EXPLOSION TEST

On February 18, 1997, a second explosion test (LLEM test 348) was conducted against the seal and stopping designs. The ignition of the methane zone (same as for the first explosion) with the addition of the 64-m-long zone of suspended pulverized coal dust (100 g/m³) generated a static pressure pulse throughout the test zone that ranged from a high of 385 kPa at the 175-mm-thick Meshblock seal in crosscut 4 to a low of 300 kPa at the 2.7-m-high, 325-mm-thick Meshblock seal in crosscut 3. The pressure traces at various distances down the entry are shown in figure 20. The P_{max} and $\int Pdt$ data at the various transducer and seal locations for LLEM test 348 are listed in table A-2. Based on a previous seal evaluation program in the LLEM using a similar gas and dust zone, it was anticipated that the peak pressure pulse would not

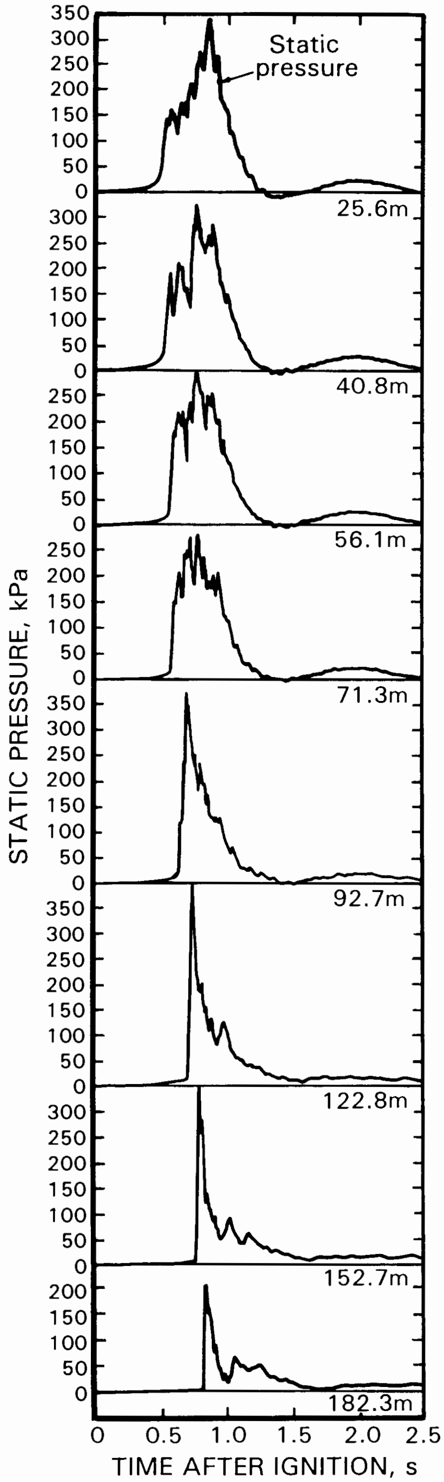

Figure 20.—Pressure traces as a function of distance in C-drift for LLEM test 348.

exceed the desired level of 240 kPa. The unexpectedly high pressure pulse generated during this second test may have been due to very low humidity conditions compared to the high humidity of the earlier evaluation program. Lower humidity may have allowed the coal dust to disperse more easily, resulting in higher airborne dust concentration and higher explosion overpressures.

There are some points of interest when comparing the arrival times of the pressure peaks at the various transducer locations for LLEM tests 347 and 348 (tables A-1 and A-2; figures 19 and 20). In test 347, the pressure pulse arrives first at the station closest to the face (closed end of the ignition zone) and progresses outward from the face, as expected. However, in test 348, the peak of the pressure pulse arrives first at the 93-m station and progresses from there both toward and away from the face. In reality, there was a pressure pulse propagating from the methane-air explosion at the face in this test, as in test 347. However, farther from the face, the coal dust contributed more energy to the explosion, and the highest P_{max} values were at the 93- and 123-m locations (table A-2). This coal dust explosion pressure pulse then propagated outward and also reflected back toward the face. At the locations closer than 93 m to the face, this reflected pressure pulse was higher than the earlier, outgoing pulse from the methane explosion. In table B-1, the flame arrival times show an explosion propagating outward from the face in both tests 347 and 348. In test 348, the flame travels much farther with the added coal dust, as expected. Additionally, the average flame speed was somewhat higher for test 348 than for test 347 (table 1).

Observations of the seal and stopping designs after LLEM test 348 revealed that both the 75-mm-thick Gunmesh stopping in crosscut 5 and the 175-mm-thick Meshblock seal in crosscut 4 were completely destroyed by the pressure pulse. The plug seal in crosscut 1 and the Meshblock seals in crosscuts 2 and 3 showed little or no apparent damage.

The LVDT data for the 75-mm-thick Gunmesh stopping in crosscut 5 showed a displacement of >60 mm prior to failure (table C-2). The time of failure was determined from the LVDT data (see table E-2). The pressure data (10-ms time average) from the two transducers on each side of this stopping are shown in figure 21. The two pressure traces were aligned by matching the positions of peak pressure at the two stations. The resulting time scale at the position of the stopping was

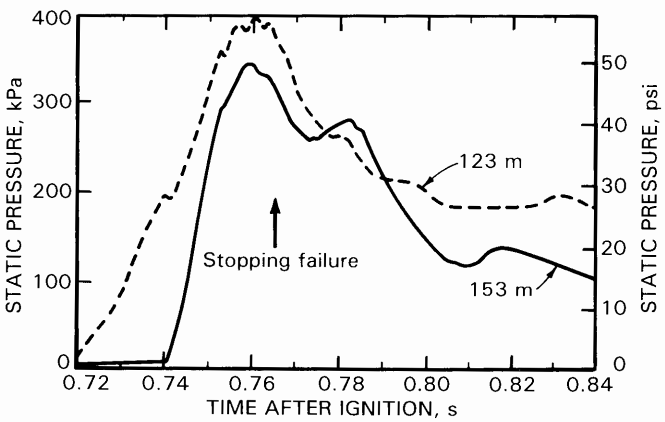

Figure 21.—Pressure data for stopping 5, showing time of stopping failure for LLEM test 348.

interpolated between the time scales at the two stations. The average peak pressure pulse on the stopping in crosscut 5 was ~370 kPa, based on the data from the two transducers. The stopping failed near peak pressure (figure 21). The total pressure-time integral to the time of stopping failure was ~9 kPa-s; the total impulse to the time of failure was ~116 kN-s. The remains of stopping 5 are shown in figure 22. Although the stopping itself was destroyed, the reinforcing bolts remained attached to the roof, ribs, and floor.

The LVDTs on the 175-mm-thick Meshblock seal in crosscut 4 recorded a movement of >15 mm prior to failure of the seal (table C-2). The time of seal failure was determined from the LVDT and accelerometer data (table E-1). The pressure and impulse data from the two transducers on either side of this seal are shown in figure 23. In the bottom of figure 23, the right ordinate shows the pressure-time integral ($\int Pdt$), which, when multiplied by the cross-sectional area of the seal, gives the impulse ($\int PAdt$) shown as the left ordinate. As in figure 21, the two pressure traces were aligned by matching the positions of peak pressure and interpolating the time scale. The maximum pressure was ~385 kPa at crosscut 4. This seal failed at ~40 ms after peak pressure, as shown in figure 23. The total impulse up to the time of failure was ~312 kN-s, which indicates that this seal was much stronger than the stopping in crosscut 5. Additional details of the seal failure analysis are presented in appendix E. The remains of seal 4 are shown in figures 24 and 25. The reinforcing bars remained embedded in the roof, ribs, and floor, but they have been bent by the force of the explosion. Part of the seal remained attached to the ribs.

The seals in crosscuts 1, 2, and 3 survived the second explosion (LLEM test 348). The 325-mm-thick Meshblock seals in crosscuts 2 and 3 were exposed to peak pressure pulses of 315 and 300 kPa, respectively. The plug seal in crosscut 1 was exposed to a 330-kPa peak pressure pulse. Maximum displacements of the three surviving seals were 6.6 mm for the crosscut 3 Meshblock seal in the high roof area, 2.4 mm for the crosscut 2 Meshblock seal, and 0.5 mm for the plug seal in crosscut 1 (table C-2). The pressure and impulse data from the two transducers on either side of the 2.7-m-high seal in crosscut 3 (75 m from the face) are shown in figure 26. As in the previous figures, the pressure peaks were aligned and the time scale was interpolated. The pressure-time integral data and the impulse data reported in appendix A were calculated from the main pressure pulse, up to 1.5 s in figure 26. The second, smaller reflection pressure pulse (1.5 to 2.6 s in figure 26) was not included. Therefore, the pressure-time integral for seal 3 was ~94 kPa-s and the impulse was ~1,500 kN-s based on an interpolation of the data from the two transducers. Summary pressure and impulse data for seal 3 and the other seals for LLEM test 348 are presented in table A-2.

The plug seal in crosscut 1 and the Meshblock seal in crosscut 2 survived LLEM explosion test 348 with little or no apparent damage, except for a few additional vertical and

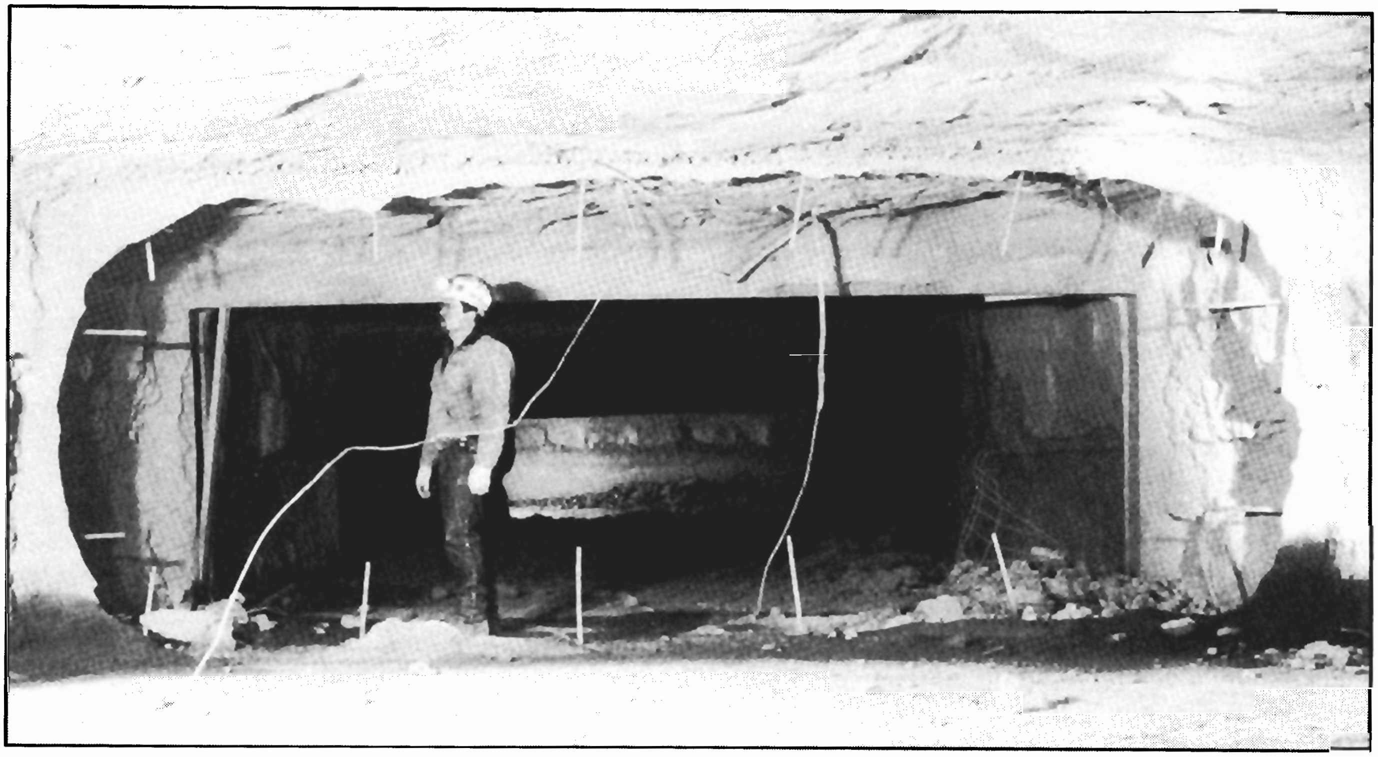

Figure 22.—Remains of stopping 5 after LLEM test 348.

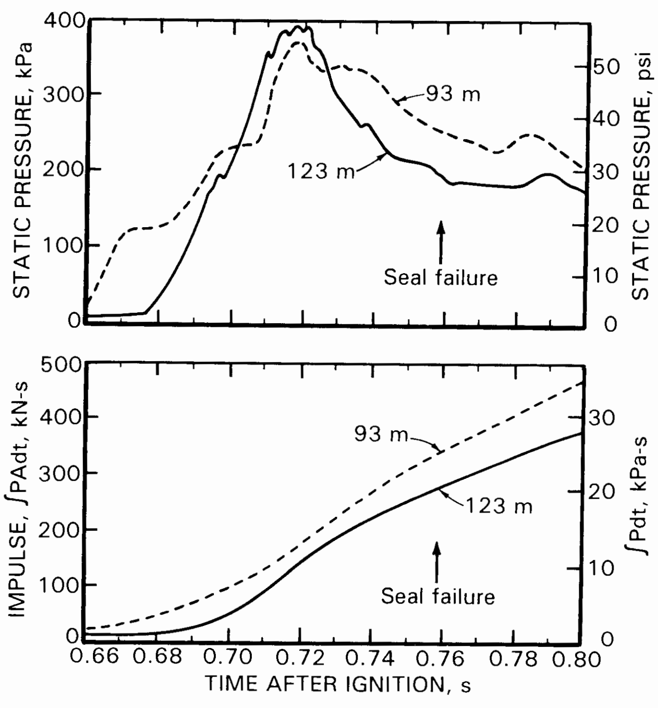

Figure 23.—Pressure and impulse data for seal 4, showing time of seal failure for LLEM test 348.

horizontal hairline cracks on both sides. The Meshblock seal in crosscut 3 evidenced a more extensive crack pattern, with wider and deeper cracks, indicating that it was close to failure. Figure 27 shows the front (C-drift) side of the Meshblock seal in crosscut 3 after the explosion. The vertical center crack observed on the front wall of the seal in crosscut 3 after the first explosion test was more pronounced following the second test. Figures 28 and 29 show the postexplosion back (B-drift) sides of the Meshblock seals in crosscuts 3 and 2, respectively. The patterns of small cracks on the two seals are outlined in white chalk. Figure 28 also shows the wood framework used to hold the brattice cloth for the air leakage tests. The minor tension cracks on the B-drift side of seals in crosscuts 2 and 3 show a yield line mechanism wherein the seal is divided into a series of elastic plates forming a roof-to-floor arch. The resistance to bending loads from the explosion is provided by the stiff surrounding rock, which provides a reaction to the arch formed in the wall. When the C-drift central portion of the seal can no longer sustain the high compressive load and the shotcrete crushes, failure is by snap-through of the seal and stopping; this occurred with the 175-mm-thick seal in crosscut 4 and the 75-mm-thick stopping in crosscut 5. Table 6 shows that the air leakage tests on the surviving Meshblock seals in crosscuts 2 and 3 were well within the established guidelines even up to

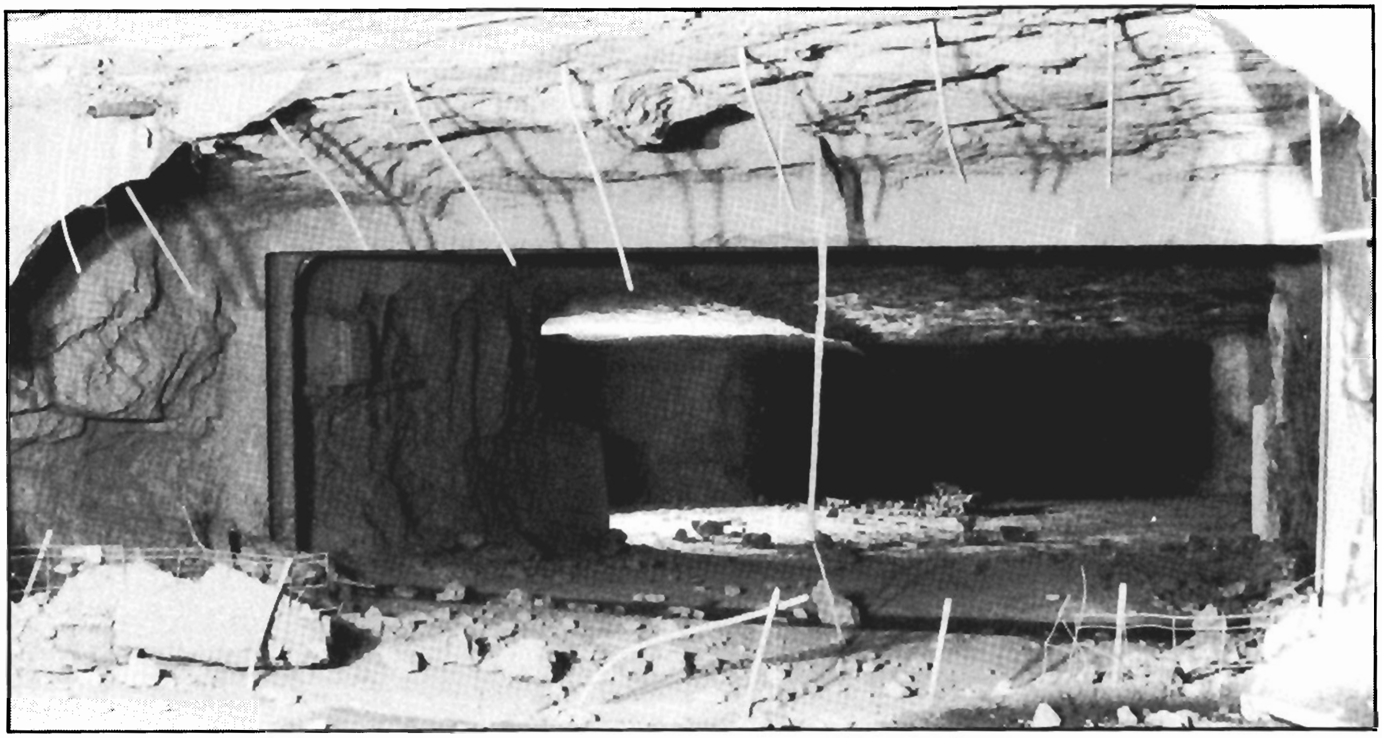

Figure 24.—Remains of seal 4 after LLEM test 348.

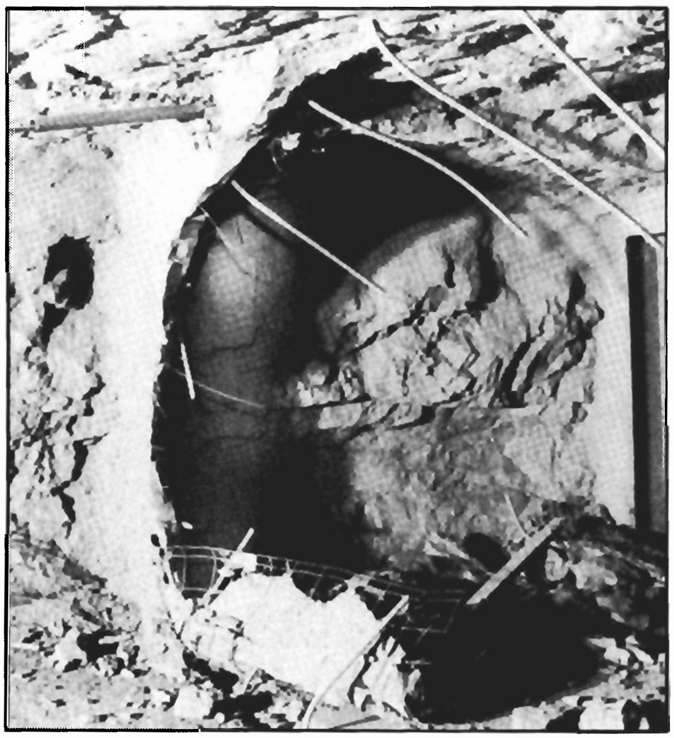

Figure 25.—Remains of seal 4 after LLEM test 348 (closeup view near wall).

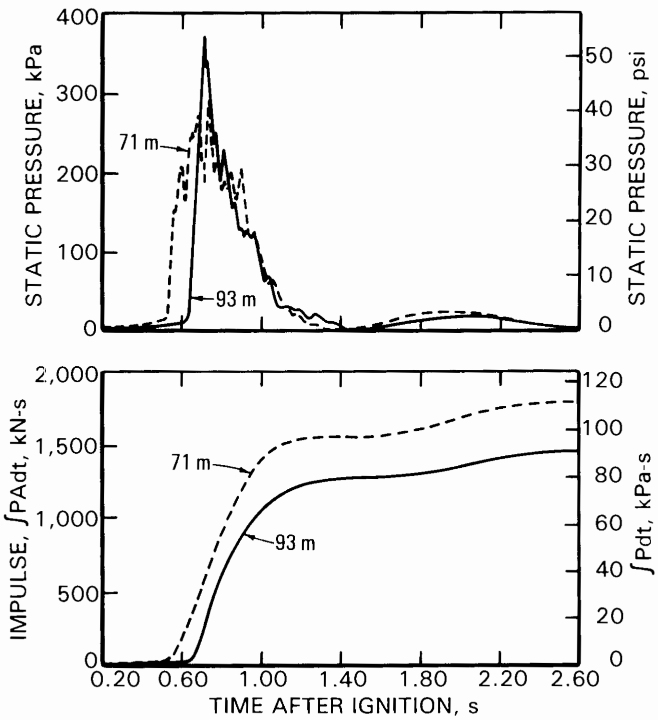

Figure 26.—Pressure and impulse data for seal 3 for LLEM test 348.

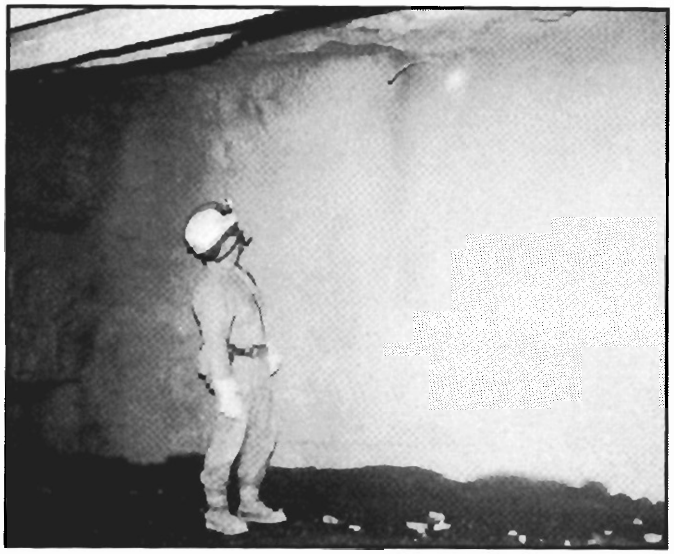

Figure 27.—Front (C-drift) side of seal 3 after LLEM test 348.

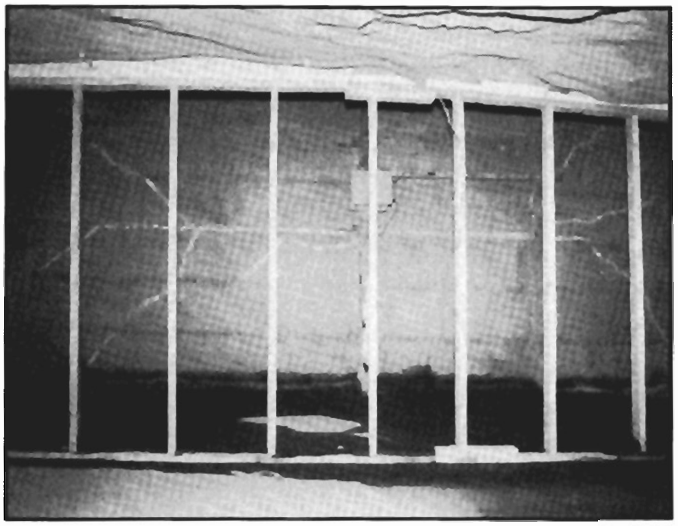

Figure 28.—Back (B-drift) side of seal 3 after LLEM test 348, showing crack pattern marked with white chalk.

pressure differentials of 0.9 kPa. The plug seal showed no evidence of any air leakage.

THIRD EXPLOSION TEST

On February 26, 1997, the third and largest explosion test (LLEM test 349) was conducted against the remaining seals in crosscuts 1, 2, and 3. The ignition of the methane and coal dust zone (same as for the second explosion test, except that the coal dust concentration was increased to 200 g/m^3) generated a peak static pressure pulse ranging from 595 kPa at the 2.7-m-high Meshblock seal in crosscut 3 to 430 kPa at the plug seal in crosscut 1. Figure 30 shows the pressure traces at the various instrument stations in C-drift for this third explosion test. Peak pressures and $\int Pdt$ data at the various transducer and seal locations for LLEM test 349 are listed in table A-3. For this test, there were significant differences in the pressure readings, depending on the amount of smoothing. This was especially true at the stations from 71 to 123 m, where the time at peak pressure was very short.

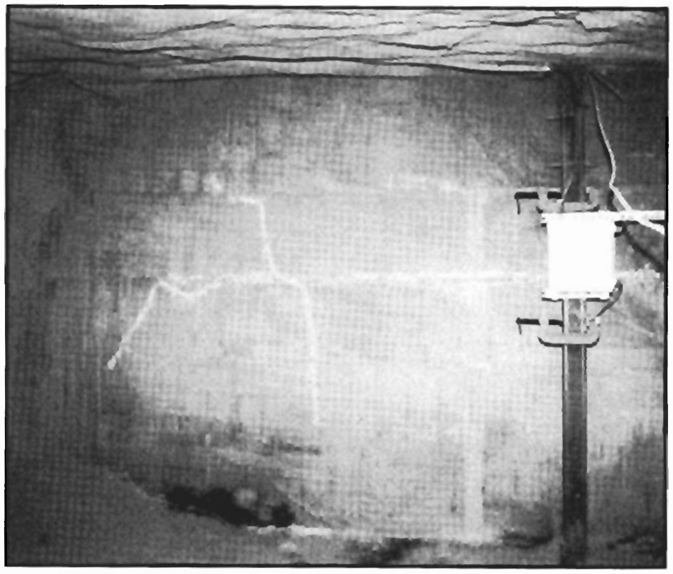

Figure 29.—Back (B-drift) side of seal 2 after LLEM test 348, showing crack pattern marked with white chalk.

Table 6.—Air leakage measurements between the second (No. 348) and third (No. 349) LLEM explosion tests

Location	Air leakage rates, m^3/min, at pressure differential of—			
	0.16 kPa	0.33 kPa	0.51 kPa	0.88 kPa
Seal in crosscut 1	0.0	0.0	0.0	0.0
Seal in crosscut 2	0.0	0.0	0.7	1.1
Seal in crosscut 3	0.0	0.0	0.7	1.1
Seal in crosscut 4	(1)	(1)	(1)	(1)
Stopping in crosscut 5	(1)	(1)	(1)	(1)

1Destroyed by pressure pulse.

Postexplosion observations revealed that the 2.74-m-high, 325-mm-thick Meshblock seal in crosscut 3 was completely destroyed by this higher pressure pulse generated during the third explosion test. This seal design withstood two previous explosion tests at pressures of 135 and 300 kPa. Prior to failure of seal 3 during this third explosion test, the LVDT data showed a maximum displacement of ≥ 15 mm (table C-3). The time of failure for this seal was determined from the LVDT data (table E-3). The pressure and impulse data from the two transducers on either side of this seal are shown in figure 31. The peak pressure pulse was ~595 kPa at crosscut 3. This seal failed at ~90 ms after peak pressure. The total impulse up to the time of failure was ~800 kN-s. The remains of seal 3 are shown in figures 32 and 33. The reinforcing bars remained

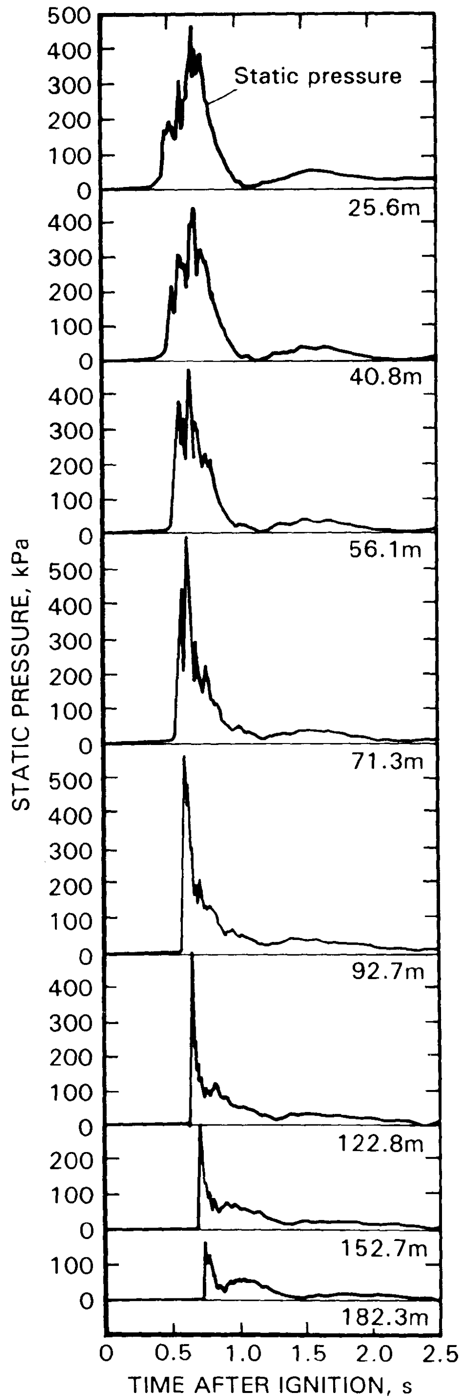

Figure 30.—Pressure traces as a function of distance in C-drift for LLEM test 349.

embedded in the roof, ribs, and floor, but they had been bent by the force of the explosion. Part of the seal remained attached to the ribs (figure 33). This indicates that failure occurred at the middle of the seal rather than at the interface with the mine ribs and roof.

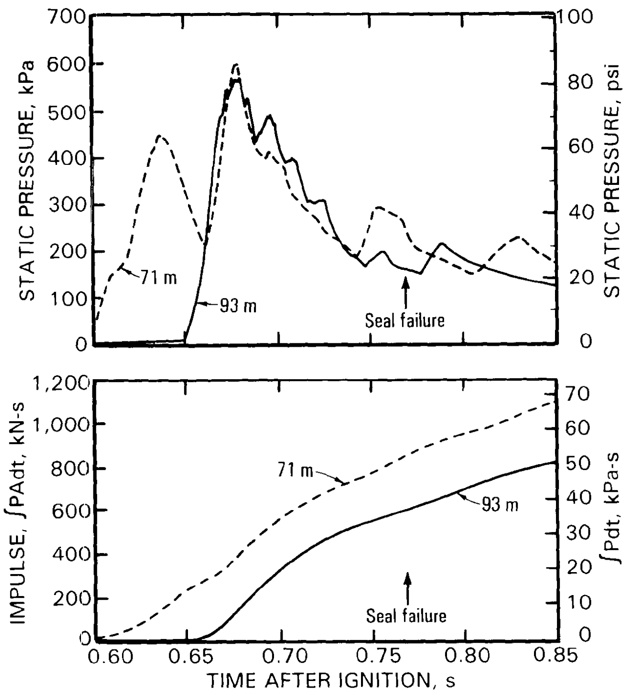

Figure 31.—Pressure and impulse data for seal 3, showing time of seal failure for LLEM test 349.

Very little outward damage was evident on the two surviving seals after LLEM explosion test 349, except for some additional minor horizontal yield line cracks. A maximum displacement of ~11 mm was recorded from the LVDT on the crosscut 2 Meshblock seal as it was subjected to a 455-kPa pressure pulse. As expected, the maximum displacement was at the middle LVDT, with smaller displacements for the upper and right LVDTs. The maximum displacement from the LVDTs was <1 mm for the plug seal that was subjected to a pressure pulse of 430 kPa. Figure 34 shows the crack pattern (outlined in white chalk) on the B-drift side of the seal in crosscut 2 after LLEM test 349. The horizontal yield line cracks observed after the second explosion test (figure 29) have now extended horizontally across the center of the seal and angled diagonally into the corners (figure 34). This is an expected pattern of yield lines for a confined vertical rectangular structure subject to horizontal load.

Due to scheduling limitations, the postexplosion air leakage evaluations were not conducted until after the last two low-level explosion tests were conducted. The air leakage evaluations after the fifth test showed that the plug seal in crosscut 1 had no detectable air leakage even at pressure differentials up to 0.9 kPa (table 7). The 325-mm-thick Meshblock seal in crosscut 2 also exhibited low air leakage rates that were well within the established guidelines.

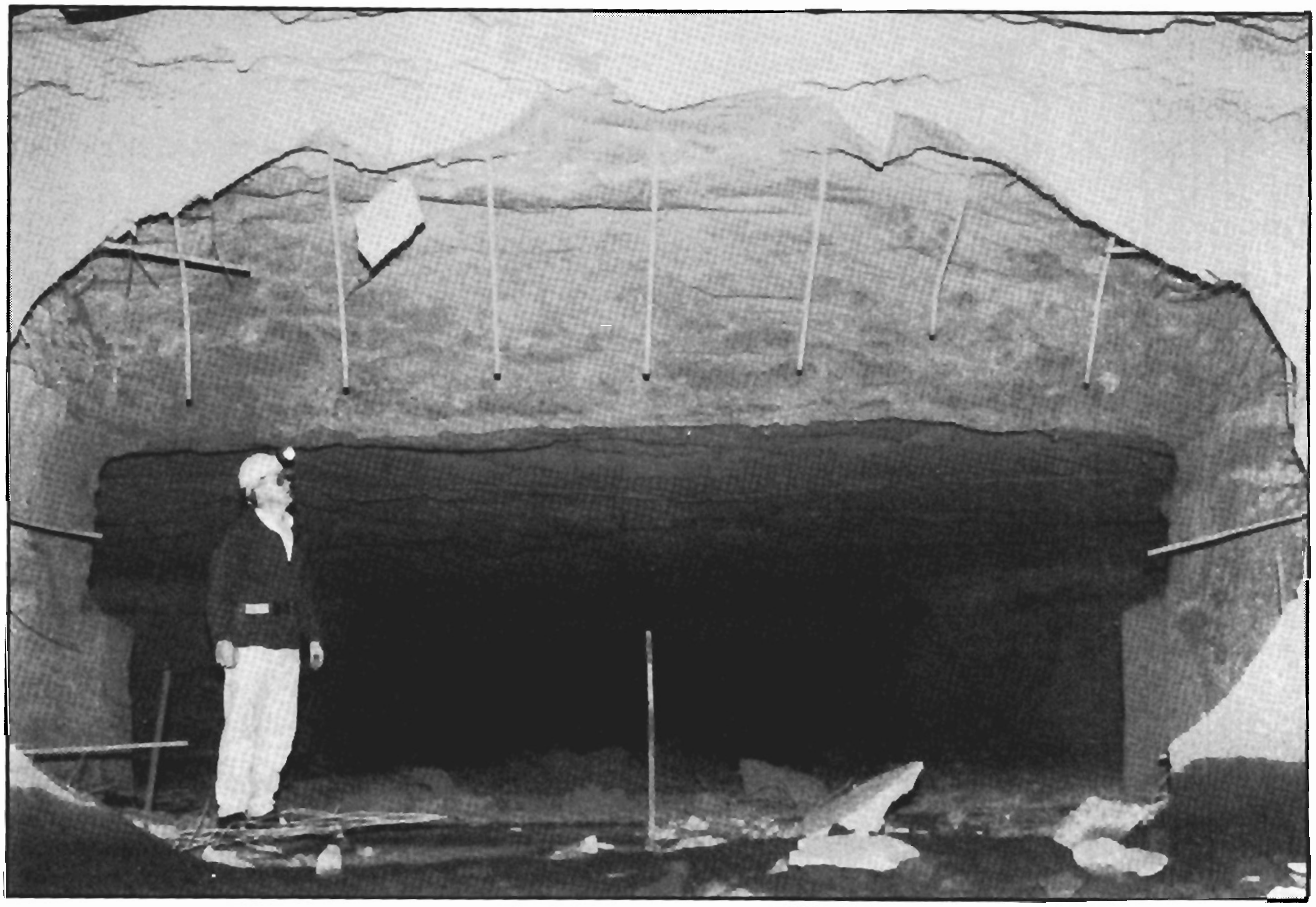

Figure 32.—Remains of seal 3 after LLEM test 349.

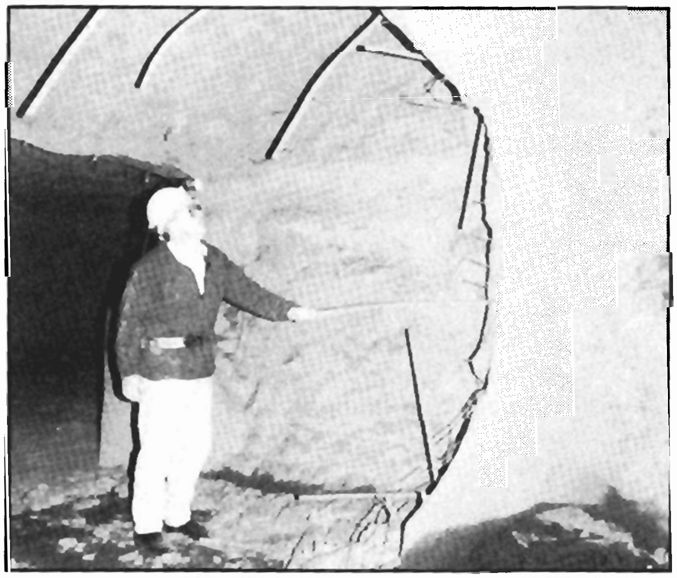

Figure 33.—Remains of seal 3 after LLEM test 349 (closeup view near wall).

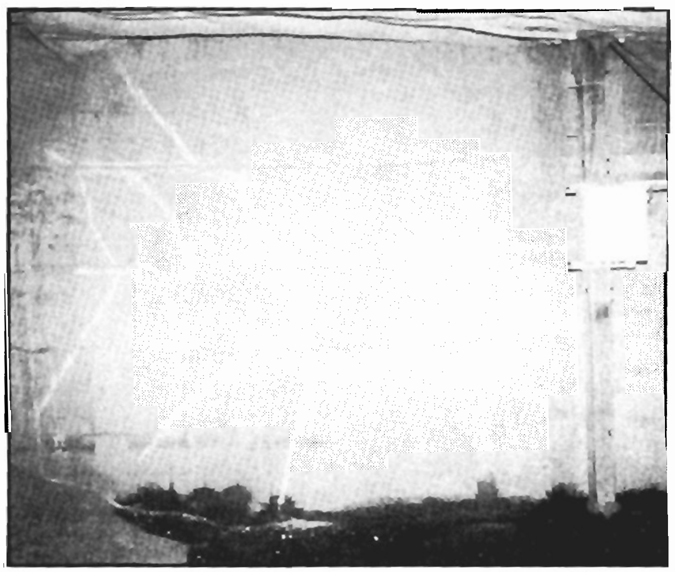

Figure 34.—Back (B-drift) side of seal 2 after LLEM test 349, showing crack pattern marked with white chalk.

Table 7.—Air leakage measurements after the fifth (No. 351) LLEM explosion test

Location	Air leakage rates, m^3/min, at pressure differential of—			
	0.14 kPa	0.35 kPa	0.51 kPa	0.90 kPa
Seal in crosscut 1	0.0	0.0	0.0	0.0
Seal in crosscut 2	0.0	0.7	0.8	1.2
Seal in crosscut 3	(1)	(1)	(1)	(1)

1Destroyed by pressure pulse.

FOURTH AND FIFTH EXPLOSION TESTS

The remaining two low-pressure explosion tests were conducted to evaluate a second Gunmesh stopping design that was constructed in crosscut 3 after seal 3 was destroyed during LLEM explosion test 349. This 40-mm-thick Gunmesh stopping was installed at a location in crosscut 3 with a mine roof height of approximately 2 m (closer to C-drift than the seal, which had been in an enlarged part of the crosscut). The fourth explosion test (LLEM test 350) was conducted on March 11, 1997. The ignition of the 115-m^3 zone of 7.1% methane-air generated a peak pressure pulse of 23 kPa at the Gunmesh stopping location in crosscut 3 during this fourth explosion test. Figure 35 shows the pressure traces at the various instrument stations in C-drift for the fourth test. Postexplosion observations following the fourth test revealed no outward damage to the stopping, except for a vertical hairline crack on the front wall (C-drift, or explosion side) of the stopping. The Gunmesh stopping experienced a maximum displacement of slightly over 13 mm as recorded by the LVDTs

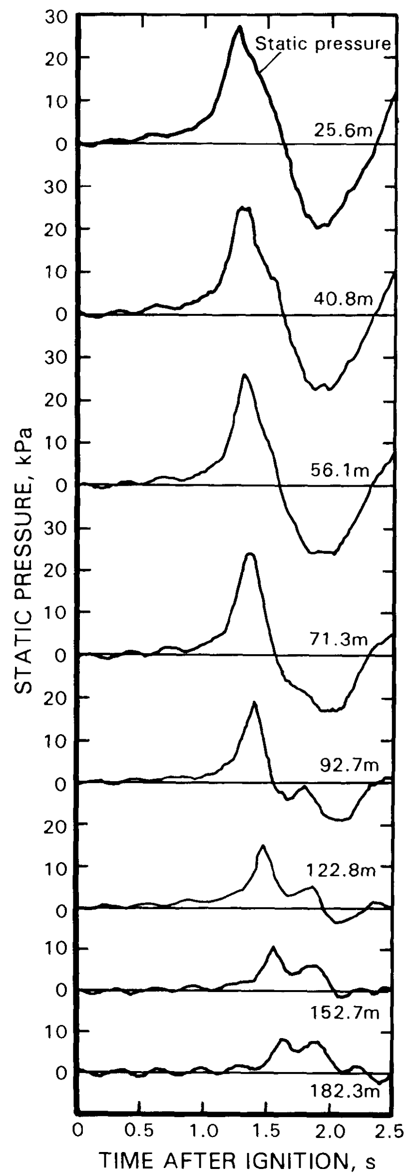

Figure 35.—Pressure traces as a function of distance in C-drift for LLEM test 350.

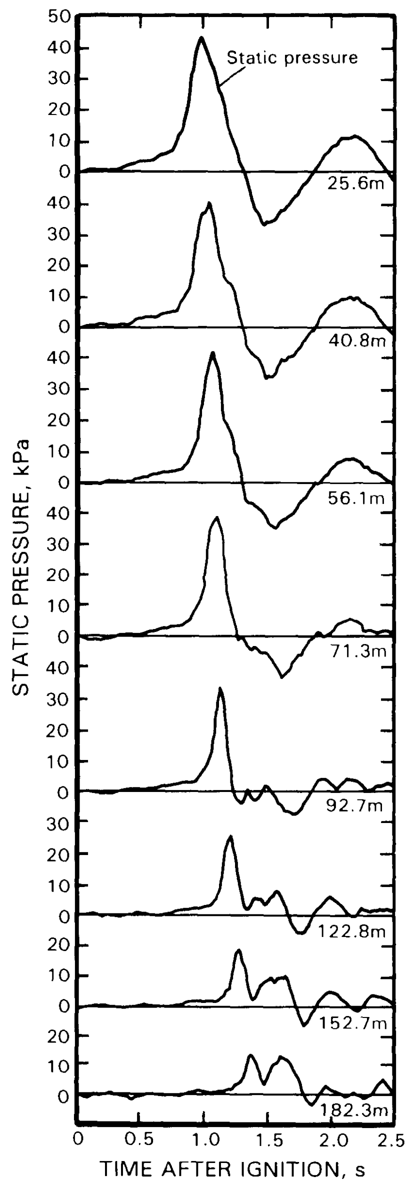

Figure 36.—Pressure traces as a function of distance in C-drift for LLEM test 351.

mounted on the back of the stopping. No air leakage evaluations were conducted after this fourth explosion test due to time limitations.

The fifth explosion test (LLEM test 351) was conducted on March 12, 1997. This was the final test of the Tecrete seal evaluation program. The gas ignition zone was 115-m^3 of 7.7% methane-air. Figure 36 shows the pressure traces at the various instrument stations in C-drift. The pressure and impulse data from the two transducers on either side of this stopping are shown in figure 37. This explosion generated a peak pressure pulse of ~39 kPa at the Gunmesh stopping location in crosscut 3 based on an interpolation of the data from the two transducers. This pressure pulse destroyed the 40-mm-thick Gunmesh stopping. A maximum displacement of about 28 mm was recorded by the LVDTs prior to the failure of the stopping (table C-5). Because the stopping was destroyed, no air leakage evaluations were possible.

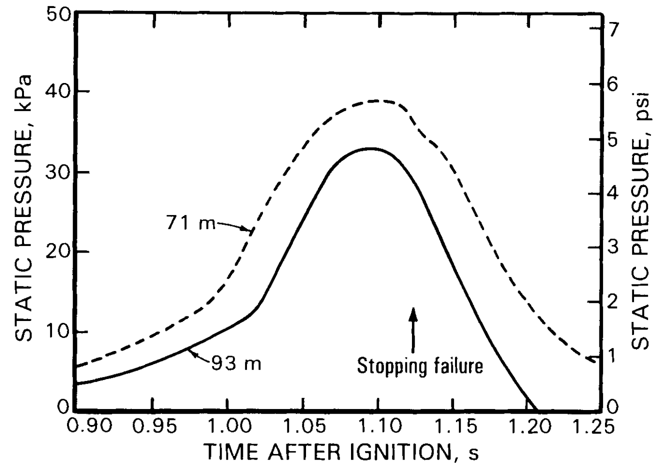

Figure 37.—Pressure data for stopping 3, showing time of stopping failure for LLEM test 351.

DISCUSSION

The LVDTs were very useful in evaluating the movement of the seals and stoppings caused by the explosion pressures. Examples of the displacement (deflection) data from the middle LVDT on the seal in crosscut 3 are shown in figure 38. In the first explosion test (LLEM test 347), there is only a small deflection (~3 mm) of the LVDT as the seal was exposed to a static pressure of 135 kPa. There is a peak deflection of ~7 mm measured by the LVDT as the seal was exposed to a pressure of 300 kPa during LLEM test 348. The middle LVDT measured a deflection of ≥15 mm before the seal was destroyed at just before 0.8 s during LLEM test 349, which had a maximum explosion pressure of 595 kPa. The other LVDTs on seal 3 showed similar deflection data, as listed in the tables in appendix C. By comparing the LVDT data in figure 38 with the pressure data in figures 26 and 31, the effects on the seal can be studied as a function of time. The seal started to deflect shortly after the arrival of the leading edge of the pressure pulse in both tests. Maximum deflection occurred at peak pressure. In LLEM test 348, the seal deflection gradually decreased as the pressure returned to ambient. In LLEM test 349, the seal and the LVDT were destroyed while still at maximum deflection; thus, any data after 0.8 s were meaningless.

Examples of the accelerometer data for LLEM test 348 are shown in figure D-1. The plots on the left side of the figure show the raw accelerometer data for the seals in crosscuts 2, 3, and 4 on a greatly expanded time scale. On the right side of the figure are the corresponding Fourier transforms of the data. The raw data show an oscillation that is mostly symmetric about zero, with only a slight net positive component. The Fourier transforms of the accelerometer data indicate the natural vibration frequencies of the seals. For example, the Fourier

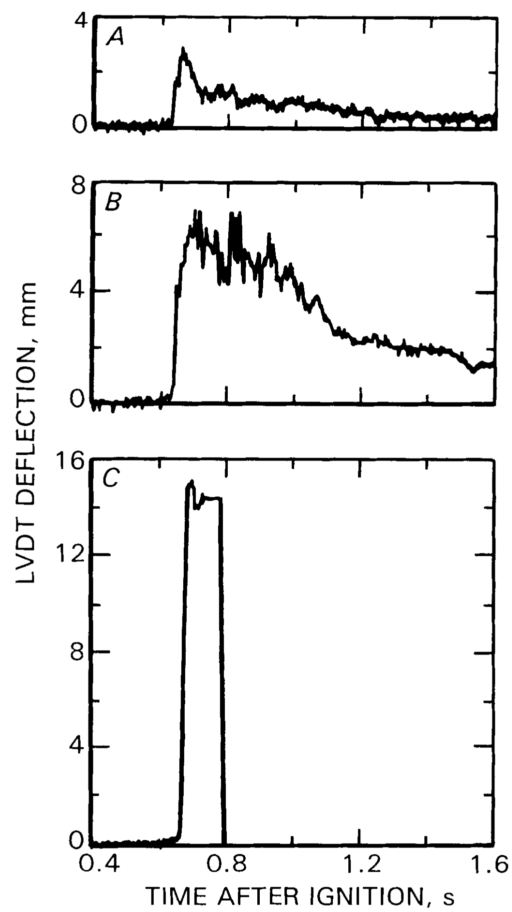

Figure 38.—Data for the middle LVDT on seal 3 for (*A*) LLEM test 347, (*B*) LLEM test 348, and (*C*) LLEM test 349.

transform of the data for the middle accelerometer on the seal in crosscut 2 for LLEM test 348 showed multiple strong peaks between 90 and 115 Hz. The Fourier transform of the data for the accelerometer on seal 3 showed multiple strong peaks between 50 and 80 Hz. The Fourier transform of the data for the accelerometer on seal 4 showed a strong peak at <20 Hz and another strong peak between 45 and 60 Hz. In general, the Fourier transforms of the accelerometer data showed that the stiffer seals (i.e., those that were thicker and/or had a smaller cross section) had higher natural frequencies. In principle, the data from the LVDTs and accelerometers are complementary. If the LVDT displacement data are differentiated twice with respect to time, the result should be the accelerometer data. This was tested for the middle LVDT on seal 3 for LLEM test 348. The LVDT displacement data were first smoothed at 15 points. Then, the resulting second derivative was qualitatively similar to the accelerometer data, except for some increased baseline noise due to the remaining intrinsic noise on the LVDT trace.

Prior to the completion of this report, a brief summary of the test program and results was reported at the Queensland Mining Industry Health and Safety Conference [Mutton and Downs 1997] in September 1997.

CONCLUSIONS

Explosion-resistant seals, such as those evaluated in this report, provide protection for underground coal miners by isolating them from the effects of explosions that might occur in the gob or other worked-out areas of the mine. Although this research project was funded by and conducted primarily for the Australian mining industry, the knowledge gained will also benefit the U.S. mining industry. The four reinforced cementitious seal and stopping designs developed by Tecrete Industries were evaluated by PRL in its Experimental Mine at Lake Lynn Laboratory for strength characteristics and air leakage resistance. These full-scale designs were air-leakage tested, then subjected to a series of explosions. One primary objective was to determine if the seal and stopping designs were of sufficient strength and leakage resistance to meet or exceed the requirements of the Queensland Department of Mines and Energy "Approved Standard for Ventilation Control Devices" and the requirements of U.S. mining regulations. The second objective was to gather data for use in the development of a model that will be used to optimize future seal designs in terms of strength and economics based on roadway conditions and required pressure rating. Both of these objectives were successfully achieved during this program.

All seal and stopping designs withstood the first explosion test. The static pressure exerted on the two 325-mm-thick Meshblock seals and the 1,200-mm-thick plug seal ranged from 135 to 160 kPa (with the values rounded to the nearest 5 kPa, as noted in appendix A). The 175-mm-thick Meshblock seal (located farther from the face) was subjected to a lower pressure of ~120 kPa. Air leakage resistance data were also well within the guidelines established for this program. The special requirement of this program to design a seal capable of withstanding a 138-kPa explosion overpressure within ~24 hr after construction was also satisfied. The 2.74-m-high, 325-mm-thick Meshblock seal design was tested 27 hr after construction and withstood the ~138-kPa explosion pressure while maintaining negligible leakage rates.

Successively higher level explosion tests were then conducted. The 175-mm-thick Meshblock seal failed during an explosion with a peak pressure of ~385 kPa (~56 psi). The 325-mm-thick, 2.74-m-high Meshblock seal design survived a peak pressure of ~300 kPa (~43 psi) and failed during a stronger explosion with a peak pressure of ~595 kPa (~86 psi). The 1,200-mm-thick plug seal and the 325-mm-thick, 2.26-m-high Meshblock seal withstood the most intense explosion test, which generated peak pressures at the seal locations of ~430 kPa (~62.5 psi) and ~455 kPa (~66 psi), respectively.

Results from the testing of the Gunmesh stoppings showed that the 75-mm-thick structure withstood an explosion overpressure of ~115 kPa (~17 psi) while maintaining air leakage resistances well within the established guidelines for this program. This stopping later failed during an explosion with a peak pressure of ~385 kPa (~55 psi). The 40-mm-thick stopping withstood an explosion overpressure of ~23 kPa (~3.4 psi) and later failed during an explosion with a peak pressure of ~39 kPa (~5.6 psi).

The development of the high-explosion resistance in the seal and stopping designs can be attributed to the lateral restraint provided by the surrounding strata, the high strength of the shotcrete material, and the reinforcing "roofbolts" and Meshblock. The use of fully encapsulated 24-mm-diam steel bolts embedded 600 mm into the roof, ribs, and floor and extending into the seal and stopping designs provided increased restraint at the seal-to-strata interface. An important aspect demonstrated by these tests is that seal height is of major importance to the seal's ability to resist explosion overpressure. This was evident during the testing of the two 325-mm-thick Meshblock seal designs wherein one was constructed in an entry enlarged to a height of 2.74 m and the other in an area 2.26 m high. The 2.74-m-high seal was close to failure at ~300 kPa (~43 psi) as shown by the crack patterns (figures 27 and 28); the 2.26-m-high seal withstood ~455 kPa (~66 psi) with only minor yield line cracking apparent (figure 34).

The data provided by the LVDTs and accelerometers will aid in the development of numerical models to assist in seal design to meet current requirements and to enable future improvements to these structures. Further study, however, is needed to address the impact of man doors and other cast-in fittings, such as water traps, on seal integrity.

The National Institute for Occupational Safety and Health will continue to develop and/or evaluate, through programs similar to the one discussed in this report, new and innovative seal designs that will provide increased protection for U.S. miners. These new seal designs will reduce materials handling, thereby reducing personnel injuries; reduce overall seal installation time, resulting in reduced mine personnel exposure when installing seals under hazardous conditions; and/or enhance seal performance in terms of strength characteristics, air leakage resistance, and better durability in high-convergence areas.

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Reg Merriman of Sydney, Australia, contributed to the installation of the Gunmesh and Meshblock formworks and provided invaluable expertise as the shotcrete nozzleman for seal construction. R. David Pearson, Scientific Officer in Fires and Explosions of the WorkCover Authority in Londonderry, New South Wales, Australia, provided significant contributions to the calibration, installation, and preliminary data analyses of the LVDT and accelerometer sensors.

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APPENDIX A.—SUMMARY TABLES OF STATIC PRESSURE DATA FOR LLEM EXPLOSION TESTS

Table A-1.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: pressure data, test 347 (February 11, 1997)

Distance, ft (m)	Time of P_{max}, s	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
TRANSDUCER								
13 (4.0)	—	~35	—	—	~34	(235)	—	—
59 (18.0)	—	—	—	—	—	—	—	—
84 (25.6)	2.725	22.0	22.0	(150)	21.5	(150)	6.20	(43.0)
134 (40.8)	2.757	22.0	22.0	(150)	21.5	(150)	5.50	(38.0)
184 (56.1)	2.798	24.5	25.0	(175)	22.5	(155)	5.00	(34.0)
234 (71.3)	2.820	19.0	20.0	(135)	19.0	(130)	4.50	(31.0)
304 (92.7)	~2.885	17.0	16.5	(115)	15.5	(105)	3.60	(25.0)
403 (122.8)	2.943	18.5	18.0	(125)	16.5	(115)	3.15	(22.0)
501 (152.7)	3.008	~16	15.5	(105)	14.5	(100)	1.65	(11.5)
598 (182.3)	—	10.0	—	—	9.0	(60)	—	—
757 (230.7)	—	7.5	—	—	7.0	(50)	—	—

Location and distance, ft (m)	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
SEAL/STOPPING							
Seal in crosscut 1: 59 (18.0)	~22	~22	(150)	~22	(150)	~6	(~41)
Seal in crosscut 2: 156 (47.7)	23.0	23.5	(160)	22.0	(150)	5.3	(36)
Seal in crosscut 3: 246 (75.0)	18.5	19.5	(135)	18.5	(130)	4.3	(30)
Seal in crosscut 4: 355 (108.2)	18.0	17.0	(120)	16.0	(110)	3.4	(23)
Stopping in crosscut 5: 452 (137.8)	17.0	17.0	(115)	15.5	(105)	2.4	(17)

NOTE.—Visual pressure readings from VAX plots are ±1 psi; PC LabView pressures are to nearest 0.5 psi (5 kPa). Pressure-time integral is calculated up to the time that the pressure trace returns to ~0 psi; it does not include the second (reflected) pressure pulse.

Table A-2.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: pressure data, test 348 (February 18, 1997)

TRANSDUCER							
Distance, ft (m)	Time of P_{max}, s	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
13 (4.0)	—	—	—	—	—	—	—
59 (18.0)	3.055	48.0	(330)	47.5	(330)	16.6	(115)
84 (25.6)	3.040	49.5	(340)	48.0	(335)	17.4	(120)
134 (40.8)	2.960	47.0	(325)	45.0	(310)	16.5	(114)
184 (56.1)	2.960	44.0	(300)	43.0	(295)	15.4	(106)
234 (71.3)	{[1]2.940, [1]2.990}	41.0	(285)	40.0	(275)	14.0	(97)
304 (92.7)	2.900	54.0	(375)	52.0	(355)	11.5	(79)
403 (122.8)	2.944	57.0	(395)	54.5	(375)	9.6	(66)
501 (152.7)	2.984	50.0	(345)	45.5	(315)	7.4	(51)
598 (182.3)	3.030	31.0	(215)	28.5	(195)	—	—
757 (230.7)	3.118	19.0	(130)	18.0	(125)	—	—

SEAL/STOPPING						
Location and distance, ft (m)	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
Seal in crosscut 1: 59 (18.0)	48.0	(330)	47.5	(330)	16.6	(115)
Seal in crosscut 2: 156 (47.7)	45.5	(315)	44.0	(305)	16.0	(110)
Seal in crosscut 3: 246 (75.0)	43.0	(300)	42.0	(290)	13.6	(94)
Seal in crosscut 4: 355 (108.2)	[2]55.5	(385)	[2]53.0	(365)	[3]3.3	[3](23)
Stopping in crosscut 5: 452 (137.8)	[2]53.5	(370)	[2]50.0	(345)	[3]1.3	[3](9)

[1]Two peaks of equal height.
[2]Destroyed.
[3]Integral up to time of failure.

NOTE.—PC LabView pressures are to nearest 0.5 psi (5 kPa).

Table A-3.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: pressure data, test 349 (February 26, 1997)

TRANSDUCER							
Distance, ft (m)	Time of P_{max}, s	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
13 (4.0)	2.990	86.5	(595)	85.0	(585)	—	—
59 (18.0)	2.975	62.5	(430)	57.0	(390)	16.0	(110)
84 (25.6)	2.940	68.0	(465)	61.0	(420)	17.0	(117)
134 (40.8)	2.945	64.0	(440)	62.0	(425)	16.0	(110)
184 (56.1)	2.910	68.5	(470)	62.0	(430)	14.1	(97)
234 (71.3)	2.894	87.0	(600)	74.0	(510)	13.4	(92)
304 (92.7)	2.884	83.0	(570)	76.0	(525)	11.4	(79)
403 (122.8)	2.924	73.0	(500)	62.5	(430)	—	—
501 (152.7)	2.965	44.0	(300)	39.0	(270)	—	—
598 (182.3)	3.015	25.0	(170)	22.5	(155)	—	—
757 (230.7)	3.110	15.0	(100)	14.0	(95)	—	—

SEAL/STOPPING						
Location and distance, ft (m)	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
Seal in crosscut 1: 59 (18.0)	62.5	(430)	57.0	(390)	16.0	(110)
Seal in crosscut 2: 156 (47.7)	66.0	(455)	62.0	(425)	15.2	(105)
Seal in crosscut 3: 246 (75.0)	[1]86.0	(595)	[1]74.5	(510)	[2]7.3	[2](50)

[1]Destroyed.
[2]Integral up to time of failure.

NOTE.—PC LabView pressures are to nearest 0.5 psi (5 kPa).

Table A-4.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: pressure data, test 350 (March 11, 1997)

TRANSDUCER								
Distance, ft (m)	Time of P_{max}, s	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
13 (4.0)	3.57	11.5	11.6	(80)	11.5	(79)	—	—
59 (18.0)	3.51	—	3.9	(27)	3.8	(26)	1.54	(10.6)
84 (25.6)	3.52	4.0	4.0	(28)	3.9	(27)	1.55	(10.7)
134 (40.8)	3.54	4.0	3.7	(26)	3.6	(25)	1.35	(9.3)
184 (56.1)	3.59	3.5	3.8	(26)	3.7	(26)	1.19	(8.2)
234 (71.3)	3.63	3.0	3.5	(24)	3.4	(24)	1.02	(7.0)
304 (92.7)	3.67	3.0	2.8	(19)	2.7	(18)	0.66	(4.6)
403 (122.8)	3.75	2.0	2.1	(15)	2.0	(14)	—	—
501 (152.7)	3.83	1.5	1.6	(11)	1.5	(10)	—	—
598 (182.3)	3.90	1.0	1.2	(9)	1.2	(8)	—	—
757 (230.7)	4.22	1.0	1.3	(9)	1.2	(8)	—	—

SEAL/STOPPING							
Location and distance, ft (m)	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
Seal in crosscut 1: 59 (18.0)	4	3.9	(27)	3.8	(26)	1.54	(10.6)
Seal in crosscut 2: 156 (47.7)	4	3.7	(26)	3.6	(25)	1.28	(8.8)
New stopping in crosscut 3: 246 (75.0)	3	3.4	(23)	3.3	(23)	0.96	(6.6)

NOTE.—Visual pressure readings from VAX plots are ±1 psi; PC LabView pressures are to nearest 0.1 psi (1 kPa), but uncertainty is approximately ±0.2 psi.

Table A-5.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: pressure data, test 351 (March 12, 1997)

TRANSDUCER								
Distance, ft (m)	Time of P_{max}, s	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
13 (4.0)	3.450	10.5	10.7	(74)	10.7	(74)	—	—
59 (18.0)	3.230	—	6.2	(43)	6.0	(42)	2.06	(14.2)
84 (25.6)	3.250	6.0	6.3	(44)	6.3	(43)	2.07	(14.3)
134 (40.8)	3.310	6.0	5.9	(41)	5.8	(40)	1.73	(11.9)
184 (56.1)	3.330	6.0	6.1	(42)	6.0	(41)	1.55	(10.7)
234 (71.3)	3.370	6.0	5.8	(40)	5.7	(39)	1.28	(8.8)
304 (92.7)	3.395	5.0	4.9	(34)	4.8	(33)	0.82	(5.7)
403 (122.8)	3.470	3.5	3.7	(26)	3.6	(25)	—	—
501 (152.7)	3.550	2.5	2.7	(19)	2.6	(18)	—	—
598 (182.3)	3.620	2.0	2.0	(14)	1.9	(13)	—	—
757 (230.7)	3.940	2.0	1.8	(12)	1.7	(12)	—	—

SEAL/STOPPING							
Location and distance, ft (m)	P_{max} visual reading, psi	P_{max} 10-ms (15-pt) avg, psi	(kPa)	P_{max} 20-ms (31-pt) avg, psi	(kPa)	Pressure-time integral ∫Pdt, psi-s	(kPa-s)
Seal in crosscut 1: 59 (18.0)	6	6.2	(43)	6.0	(42)	2.06	(14.2)
Seal in crosscut 2: 156 (47.7)	6	6.0	(41)	5.9	(41)	1.65	(11.4)
New stopping in crosscut 3: 246 (75.0)	6	[1]5.6	(39)	[1]5.5	(38)	[2]0.88	[2](6.0)

[1]Destroyed.
[2]Integral up to time of failure.

NOTE.—Visual pressure readings from VAX plots are ±1 psi; PC LabView pressures are to nearest 0.1 psi (1 kPa), but uncertainty is approximately ±0.2 psi.

APPENDIX B.—SUMMARY TABLE OF FLAME ARRIVAL TIMES FOR LLEM EXPLOSION TESTS

Table B-1.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: flame arrival time data

Flame sensor distance, ft (m)	Flame arrival time, s				
	Test 347	Test 348	Test 349	Test 350	Test 351
13 (4.0)	0.286	0.261	0.308	~0.74	0.52
84 (25.6)	0.495	~0.52	0.524	1.24	0.96
134 (40.8)	0.531	0.563	0.569	ND	([1])
184 (56.1)	0.573	0.610	0.615	ND	ND
234 (71.3)	([1])	0.652	0.630	ND	ND
304 (92.7)	([1])	0.694	0.664	ND	ND
403 (122.8)	ND	0.759	0.77	ND	ND
598 (182.3)	ND	([1])	1.18	ND	ND

ND No detectable signal.
[1]Signal was <1 V.

NOTE.—Flame arrival time corresponds to ≥1-V signal on flame sensor; data are relative to ignition time.

APPENDIX C.—SUMMARY TABLES OF LVDT DISPLACEMENT DATA FOR LLEM EXPLOSION TESTS

Table C-1.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: LVDT data, test 347 (February 11, 1997)

Location and instrument	Maximum displacement, mm
Seal in crosscut 1:	
LVDT Upper	0.1
LVDT Right	0.1
LVDT Middle	0.1
Seal in crosscut 2:	
LVDT Upper	1.8
LVDT Right	1.5
LVDT Middle	1.8
Seal in crosscut 3:	
LVDT Upper	1.5
LVDT Right	2.1
LVDT Middle	2.7
Seal in crosscut 4:	
LVDT Upper	5.7
LVDT Right	7.2
LVDT Middle	8.4
Stopping in crosscut 5:	
LVDT Upper	12
LVDT Middle	25

Table C-2.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: LVDT data, test 348 (February 18, 1997)

Location and instrument	Maximum displacement, mm
Seal in crosscut 1:	
LVDT Upper	0.5
LVDT Right	0.3
LVDT Middle	0.4
Seal in crosscut 2:	
LVDT Upper	1.8
LVDT Right	2.4
LVDT Middle	2.4
Seal in crosscut 3:	
LVDT Upper	3.6
LVDT Right	4.2
LVDT Middle	6.6
Seal in crosscut 4:[1]	
LVDT Upper	>15
LVDT Right	>15
LVDT Middle	>15
Stopping in crosscut 5:[1]	
LVDT Middle	>60

[1]Destroyed.

Table C-3.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: LVDT data, test 349 (February 26, 1997)

Location and instrument	Maximum displacement, mm
Seal in crosscut 1:	
LVDT Upper	0.7
LVDT Right	0.5
LVDT Middle	0.5
Seal in crosscut 2:	
LVDT Upper	3.0
LVDT Right	6.6
LVDT Middle	10.8
Seal in crosscut 3:[1]	
LVDT Upper	≥15
LVDT Middle	≥15

[1]Destroyed.

Table C-4.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: LVDT data, test 350 (March 11, 1997)

Location and instrument	Maximum displacement, mm
New stopping in crosscut 3:	
LVDT Upper	10.8
LVDT Middle	13.2

Table C-5.—Tecrete seals evaluation in the Lake Lynn Experimental Mine: LVDT data, test 351 (March 12, 1997)

Location and instrument	Maximum displacement, mm
New stopping in crosscut 3:[1]	
LVDT Upper	25
LVDT Middle	28

[1]Destroyed.

APPENDIX D.—EXAMPLES OF ACCELEROMETER DATA FOR LLEM EXPLOSION TEST 348

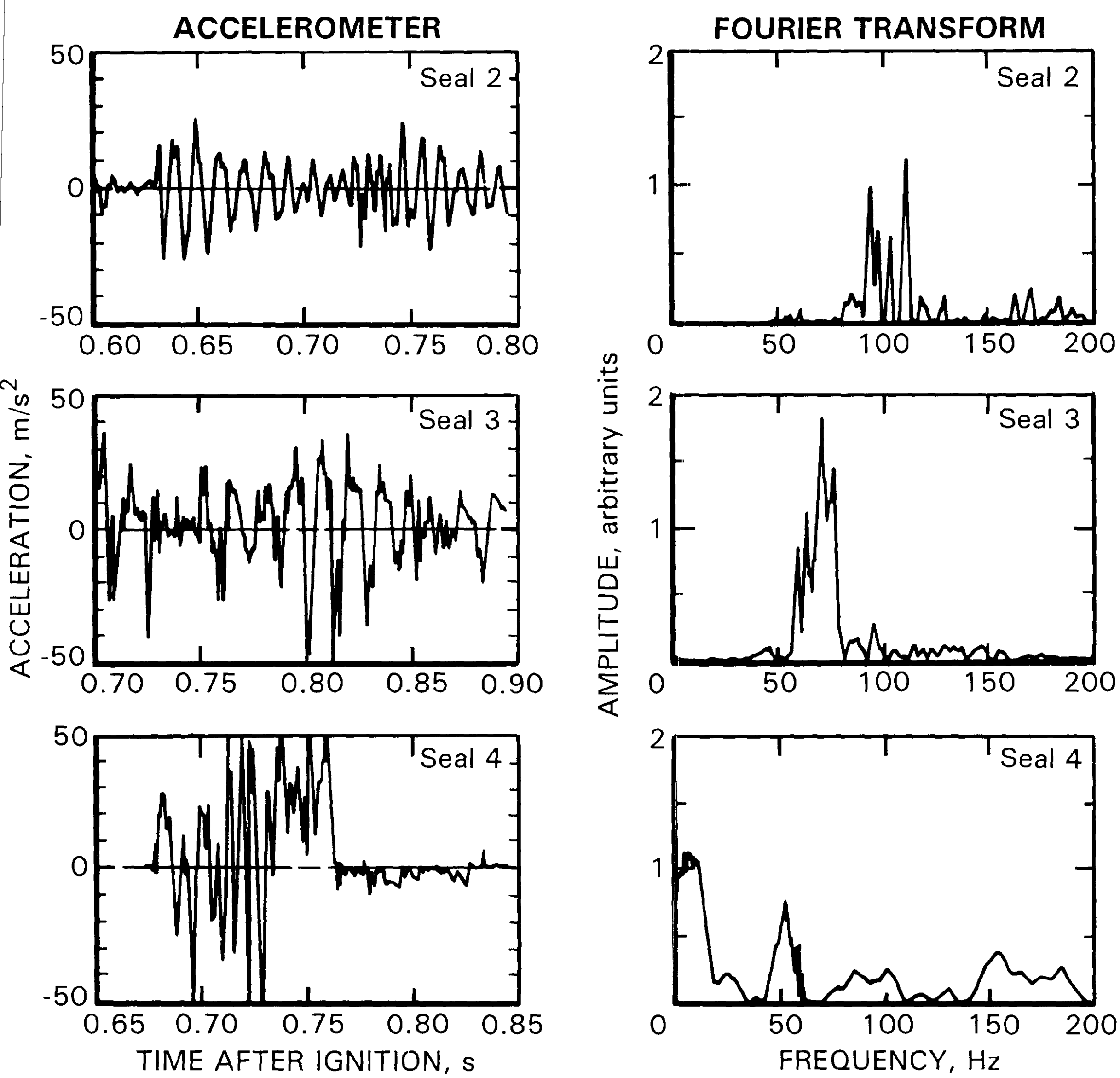

Figure D-1.—Data from middle accelerometers on seals 2, 3, and 4 for LLEM test 348, along with their Fourier transforms.

APPENDIX E.—SUMMARY TABLES OF SEAL AND STOPPING FAILURE ANALYSIS DATA

Seal in Crosscut 4

Table E-1.—Failure data for seal in crosscut 4, test 348 (February 18, 1997)

Position	Maximum displacement LVDT, mm	Time of seal failure, s[1]	
		LVDT	Accelerometer
Upper	≥15	0.784	—
Middle	15	0.759	0.760
Right	≤15	~0.80	0.757

[1]Time after ignition.

The peak pressure experienced by the seal in crosscut 4 was 55.5 psi (385 kPa) at ~0.718 s. The pressure at failure of the seal was ~32 psi (~224 kPa) at ~0.758 s. The pressure-time integral up to seal failure was ~3.3 psi-s (~23 kPa-s). The cross-sectional area of the seal in crosscut 4 was 145 ft^2 (13.5 m^2); therefore, the total impulse $\int PAdt$ up to seal failure was 312 kN-s.

Stopping in Crosscut 5

Table E-2.—Failure data for stopping in crosscut 5, test 348 (February 18, 1997)

Position	Maximum displacement LVDT, mm	Time of seal failure, s	
		LVDT	Accelerometer
Middle	>60	0.765	—

The peak pressure experienced by the stopping in crosscut 5 was 53.5 psi (370 kPa) at ~0.760 s. The pressure at failure of the stopping was ~51 psi (~352 kPa) at 0.765 s. The pressure-time integral up to seal failure was ~1.3 psi-s (~9 kPa-s). The cross-sectional area of the stopping in crosscut 5 was 139 ft^2 (12.9 m^2); therefore, the total impulse $\int PAdt$ up to seal failure was 116 kN-s.

Seal in Crosscut 3

Table E-3.—Failure data for seal in crosscut 3, test 349 (February 26, 1997)

Position	Maximum displacement LVDT, mm	Time of seal failure, s	
		LVDT	Accelerometer
Upper	>15	0.769	—
Middle	>15	0.769	—

The peak pressure experienced by the seal in crosscut 3 was 86 psi (595 kPa) at ~0.68 s. The pressure at failure of the seal was ~32 psi (~220 kPa) at 0.769 s. The pressure-time integral up to seal failure was ~7.3 psi-s (~50 kPa-s). The cross-sectional area of the seal in crosscut 3 was 172 ft^2 (16.0 m^2); therefore, the total impulse $\int PAdt$ up to seal failure was 800 kN-s.

New Stopping in Crosscut 3

Table E-4.—Failure data for new stopping in crosscut 3, test 351 (March 12, 1997)

Position	Maximum displacement LVDT, mm	Time of seal failure, s	
		LVDT	Accelerometer
Upper	≥25	1.123	—
Middle	≥28	1.123	—

The peak pressure experienced by the new stopping in crosscut 3 was 5.6 psi (39 kPa) at ~1.10 s. The pressure at failure of the new stopping was ~5.2 psi (~36 kPa) at 1.123 s. The pressure-time integral up to seal failure was ~0.88 psi-s (~6.0 kPa-s). The cross-sectional area of the new stopping in crosscut 3 was 133 ft^2 (12.4 m^2); therefore, the total impulse $\int PAdt$ up to seal failure was 75 kN-s.

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