RI 9477

REPORT OF INVESTIGATIONS/1993

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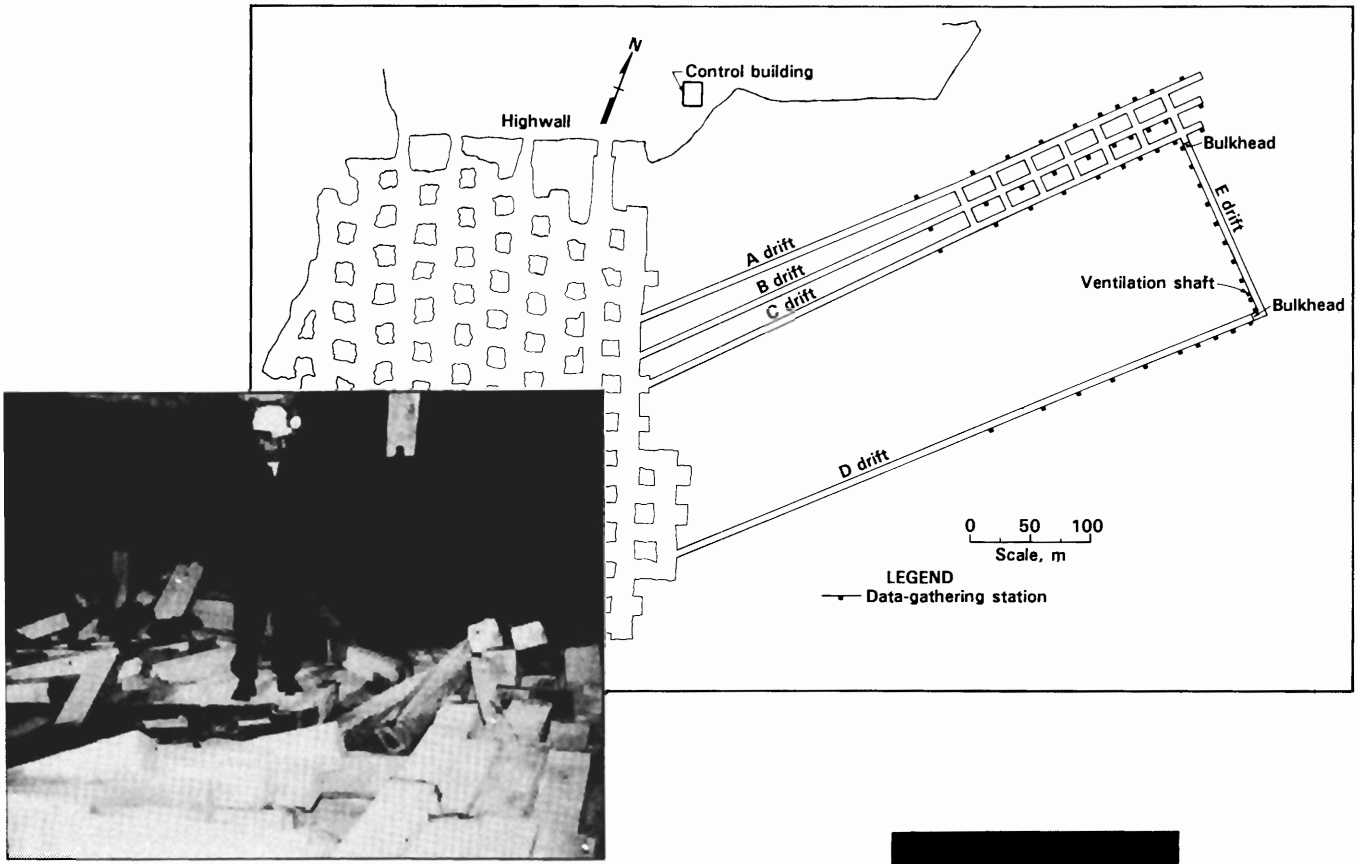

UNITED STATES DEPARTMENT OF THE INTERIOR

MARCH 3, 1849

BUREAU OF MINES

Cover Photographs: Top, U.S. Bureau of Mines Lake Lynn experimental mine. Mine seals constructed in the crosscuts between B and C drifts; Bottom, Damage to typical wood-block seal when subjected to 20-psig pressure pulse.

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Bruce Babbitt, Secretary

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Library of Congress Cataloging in Publication Data:

Strength characteristics and air-leakage determinations for alternative mine seal designs / by E.S. Weiss ... [et al.].

p. cm. — (Report of investigations; 9477)

Supt. of Docs. no.: I 28.23: 199:9477.

1. Concrete mine stoppings (Mining)—Airtightness—Testing. 2. Cement composites—Testing. 3. Foamed materials—Testing. 4. Wood—Testing. 5. Strength of materials. 6. Coal mines and mining. I. Series: Report of investigations (United States. Bureau of Mines); 9477.

TN23.U43 [TN304] 622 s—dc20 [622'.4] 93-25429 CIP

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°F	degree Fahrenheit	lb	pound
ft	foot	lb/ft^3	pound per cubic foot
ft^2	square foot	pct	percent
ft^3/min	cubic foot per minute	psi	pound (force) per square inch
h	hour	psig	pound (force) per square inch, gauge
in	inch	s	second
in H_2O	inch of water (pressure)		

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STRENGTH CHARACTERISTICS AND AIR-LEAKAGE DETERMINATIONS FOR ALTERNATIVE MINE SEAL DESIGNS

By E. S. Weiss,[1] N. B. Greninger,[2] C. R. Stephan,[3] and J. R. Lipscomb[4]

ABSTRACT

The U.S. Bureau of Mines and the U.S. Mine Safety and Health Administration (MSHA) are participating jointly in a research program to evaluate the strength characteristics and air-leakage resistance of various proposed seal designs for use in underground coal mines. The full-scale seals were constructed in the USBM's experimental mine at the Lake Lynn Laboratory, air-leakage tested, then subjected to pressure pulses of 20 psig or greater.

In experiments prior to this study, seven seal designs using solid-concrete blocks were tested. Only the standard-type seal passed the explosion and air-leakage criteria. Tests also were performed on four seals constructed with low-density foam blocks. All four of these seal designs withstood the pressure pulse. In more recent studies, nine cementitious foam seal designs of varying thicknesses and densities were investigated. Six of the nine designs successfully survived the explosion overpressures. Six wood-block convergence seals also have been tested. The typical 3-ft-thick, wood-block seal design currently used in many coal mines did not maintain its integrity, in the absence of convergence forces, following the explosion test. Five modified wood-block seals successfully withstood the 20-psig pressure pulse.

Based on these tests, three alternative seal construction materials, cementitious foam, low-density foam block, and wood, have been approved by MSHA for use in underground coal mines.

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INTRODUCTION

BACKGROUND

During the normal course of underground coal mining, it sometimes becomes necessary to seal off abandoned areas to eliminate the need to ventilate them. Seals also are used to isolate fire zones or areas susceptible to spontaneous combustion. Therefore, the mine seals must be capable of isolating these areas of the mine from the active workings. To isolate areas within a mine effectively, a seal should

- control the gas-air exchanges between the sealed and open areas to prevent toxic and/or flammable gases from entering 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 h when subjected to a fire test incorporating a specific (ASTM E119-88) time-temperature heat input, or its equivalent (*1*).[5]

Title 30, Part 75.335 of the U.S. Code of Federal Regulations (CFR) requires a seal to "... withstand a static horizontal pressure of 20 pounds per square inch ... ." If a seal includes "... the use of timbers, the timbers also shall be coated on all accessible surfaces with flame-retardant material having a flame spread index of 25 or less, as tested under ASTM E162-87." These revised regulations, effective November 16, 1992, were based, in part, on the results of the research presented in this report. Cementitious foams, like concrete, are incombustible and consist entirely of inorganic material that does not burn. Heavy timber of 4-in or greater thickness provides 2 h of fire resistance.

The U.S. Bureau of Mines and MSHA jointly are investigating the ability of various existing and new alternative seal materials and designs to meet or exceed the requirements of the CFR. This research is part of the USBM's overall mission to reduce mine accidents and improve working conditions in mines. Early USBM research (*2*) indicated that it would be unlikely for overpressures exceeding 20 psig to occur very far from the origin of the explosion provided that the area on either side of the seal contained sufficient incombustible, and minimal coal dust, accumulations. This is the first full-scale test program to evaluate seal designs in entry geometries similar to those of current U.S. coal mines.

The seal research program previously has addressed, through testing at the USBM's Lake Lynn Experimental Mine (LLEM), the integrity of solid-concrete-block seals (*3*), low-density foam-block seals (*4*), and an initial test series with cementitious foam seals (*3*, *5*). A brief summary of these published data on the construction techniques, preexplosion and postexplosion leakage measurements, and the effects of the explosion on these seals is presented in this paper.

At the request of MSHA, several additional seal designs have been constructed and tested under the USBM's seal-development investigation. This effort included a second series of cementitious foam seals and three series of tests on wood-block convergence seals. The cementitious foam seals, in this second test series, were all 4 ft thick with compressive strength designs varying from 100 to 200 psi. In addition to evaluating the strength characteristics of the cementitious foam seals, the effect of longer pumping distances for the cementitious foam slurries also was evaluated.

Wood-block seals are used commonly in deeper mining operations to offset the problems associated with roof, floor, and/or rib convergence and movement resulting from overburden stresses. When this strata movement is exerted on the standard-type, concrete-block seal, the seal fails because of the stiffness characteristics of the block. Wood-block seals are less stiff with better deformation characteristics and they will yield or compress in response to strata movement. Experimental mine tests were conducted to evaluate the ability of wood-block seals to withstand the 20-psig pressure pulse while maintaining acceptable air-leakage rates. The wood-block seals were not subjected to any convergence forces other than those obtained from the use of wooden wedges at the roof and ribs prior to the explosion tests. The installation methods, leakage determinations, and explosion results associated with the cementitious foam and wood-block seals are presented in this report.

PURPOSE

The objective of this research is to determine whether seals constructed from various materials and designs can withstand a 20-psig methane-air explosion without losing their structural integrity. Not only must the seal be physically strong, but it also must effectively control gas-air exchanges between sealed and open areas. A safety and cost benefit also may result from these evaluations in that some of these new seal designs require fewer worker-hours and less materials handling to install than the standard-type, solid-concrete-block seal.

Full-scale explosion-proof seal research provides input to MSHA for setting adequate standards and useful information to industry for the improvement of mining safety

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[5] Italic numbers in parentheses refer to items in the list of references at the end of this report.

and economics. The Mine Safety and Health Administration has issued new safety standards for underground coal mine ventilation that became enforceable regulations in November 1992. These new regulations address the construction of seals. As new seal construction materials and designs become available, MSHA needs performance data from full-scale dynamic tests to evaluate the strength characteristics and air-leakage determinations with these new seal types. The LLEM can be used to provide this data, and MSHA has requested USBM assistance in this area.

ACKNOWLEDGMENTS

Kenneth Jackson, electronics technician, and William Slivensky, physical science technician, both with the Pittsburgh Research Center, U.S. Bureau of Mines, Pittsburgh, PA, who assisted in the arrangement of the instrumentation for the tests, monitored the construction of the seals, assisted in conducting the tests, and performed the initial evaluation of the conditions of the seals following the explosion. The research support work required in the construction and leakage testing of the seals was coordinated through John Perry, supervisor of SSI Services, Inc., at the Lake Lynn Laboratory, Fairchance, PA. The authors also acknowledge the following MSHA personnel for their involvement in the design of the seals and in the monitoring of the construction of these seals: Stephen Sawyer, chief, Industrial Safety Division; Steven Luzik, supervisory chemical engineer; and William Hoffman, physical scientist, of the Industrial Safety Division, Bruceton, PA.

EXPERIMENTAL PROCEDURE

MINE EXPLOSION TESTS

All of the explosion and air-leakage determination tests on the various seal designs were conducted at the USBM's LLEM (*6-7*) located near Fairchance, PA. The LLEM is unique in that it is the only research facility in the world that 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 workings originally were used to extract limestone. In the late 1970's, the Bureau developed the experimental mine adjacent to these old workings. Drifts A, B, C, and D are 1,700 ft long and closed at the inby end. Drift E is 500 ft long and connects C and D drifts. The dimensions of the drifts and crosscuts are typical of modern U.S. geometries for mine entries and range from 18 to 20 ft wide and approximately 6 to 7 ft high. Each drift has 10 environmentally controlled data-gathering stations housing the instruments. Each data-gathering station houses a pressure transducer to measure the static pressure generated by the explosion, and an optical sensor to detect the flame travel.

Figure 2 shows an expanded view of the seal test area. Methane gas was injected into the closed end of C drift. A plastic diaphragm was used to contain the 10-pct methane-air mixture within the first 47 ft of the entry. Electric matches located at the face in three locations were used to ignite the flammable methane-air mixture. Prior to the ignition of the methane gas, a concrete-steel bulkhead was positioned across E drift to contain the explosion pressures in C drift. Barrels filled with water were located in the gas zone to act as turbulence generators to achieve the 20-psig pressure pulse. To generate higher pressures, pulverized coal dust was placed on foam shelves that were located at 10-ft intervals outby the gas zone along the mine roof. To achieve pressures of 25, 30, and +35 psi, the number of shelf locations was increased to extend the coal dust loading to 70, 100, and 260 ft, respectively, from the face.

All of the seals were constructed in the crosscuts between the B and C drifts. These crosscuts are approximately 6 to 7 ft high by 20 ft wide. The average cross-sectional area of the crosscuts is 125 ft^2. Generally, the seals were located in these crosscuts at a distance of approximately 5 to 8 ft from C drift. The pressure pulses exerted on each seal were measured by interpolation of the data from the nearest pressure transducers both inby and outby the crosscut position. Figure 3 shows a typical pressure trace generated from the LLEM computers.

AIR-LEAKAGE DETERMINATIONS

An important factor to be considered for any seal design is its impermeability, or its ability to prevent or reduce the exchange of gases from one side of the seal to the other. Measurements of the air leakages across the seals were conducted before and after each of the explosion tests. For these air-leakage tests, the D-drift bulkhead door (see figure 1) was closed to direct all of the ventilation flow to the seal locations in C drift. A stopping of double-brattice curtain was erected across C drift outby

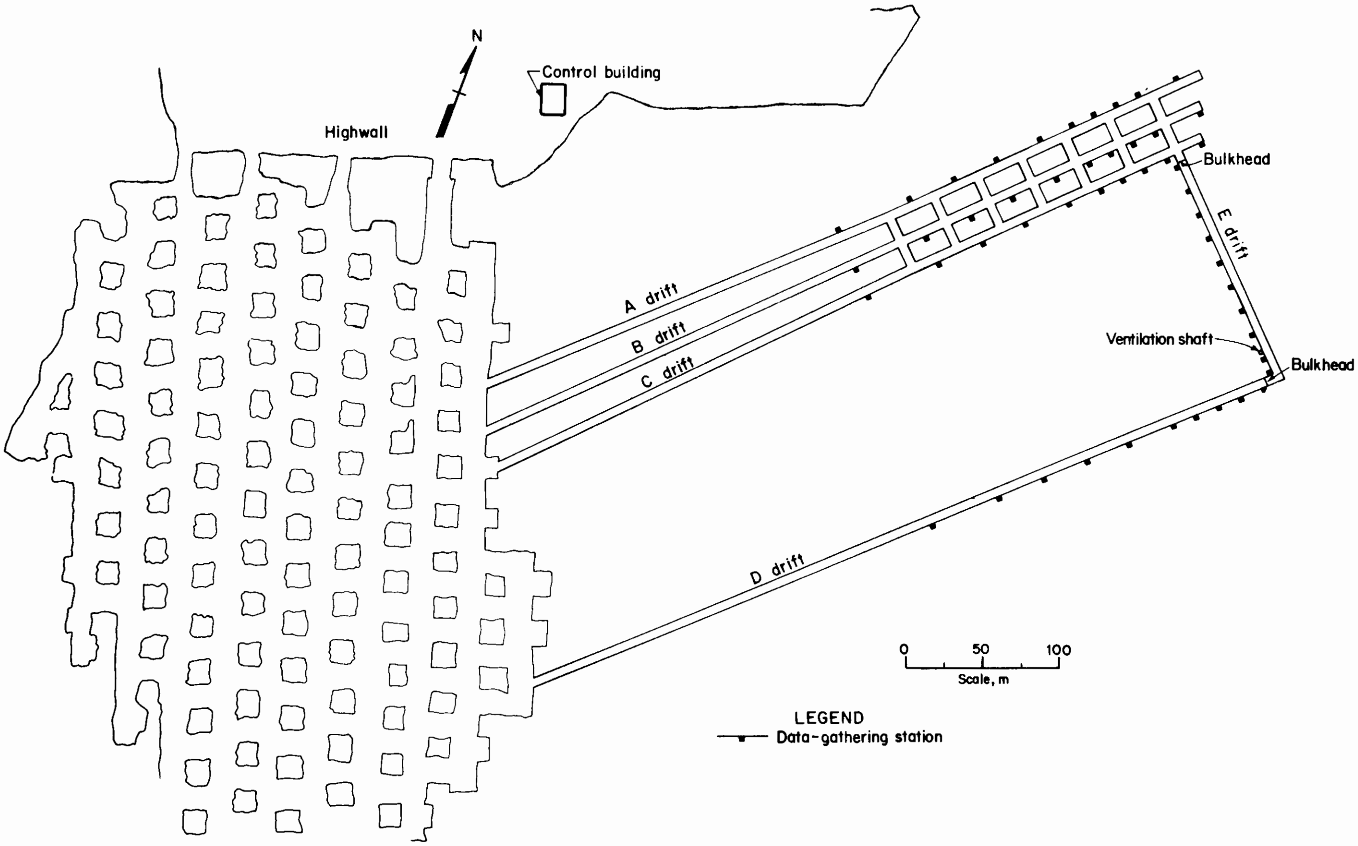

Figure 1.—Lake Lynn experimental mine.

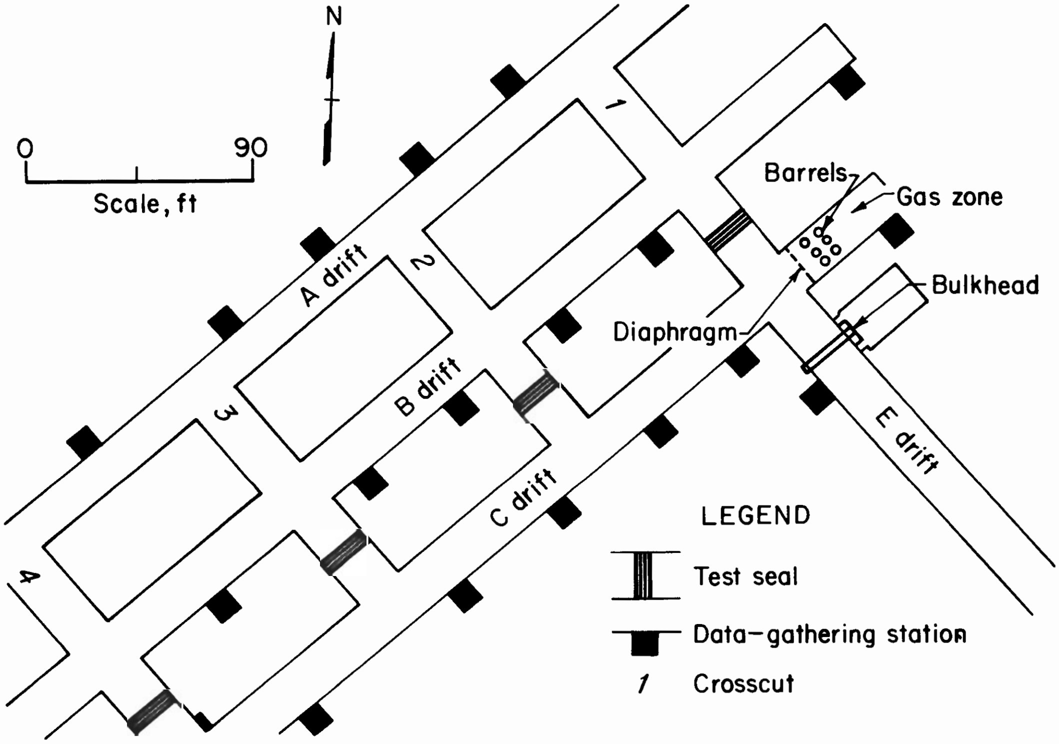

Figure 2.—Seal test area in the LLEM.

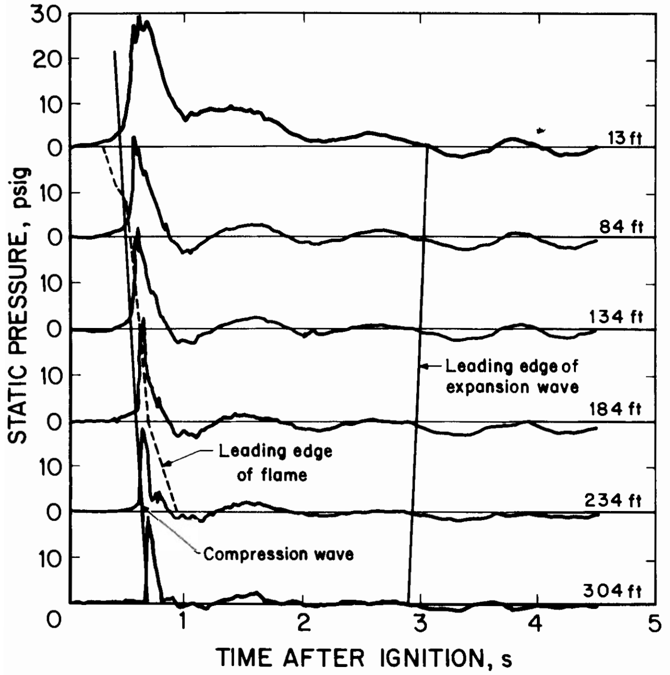

Figure 3.—Computer data from 20-psig pressure pulse in C drift.

the last seal position (fig. 4). This curtain effectively blocked the ventilation flow, which resulted in a pressurized area on the C-drift side of the seals. By increasing the fan speed, the resulting pressure exerted on the seals increased from approximately 1 in H_2O for the lowest fan speed setting to slightly over 4 in H_2O for the highest fan speed setting.

On the B-drift side of each of the seals, a diaphragm of brattice cloth was installed across the crosscut (fig. 5) with a 0.5 ft^2 opening near the center. An anemometer was used to monitor the air flow through this opening.

During the construction of the seals, a copper tube was positioned through each of the seals with one end of the tube extending out on either side. This tube served to measure the pressure exerted on the seal, and in mining applications, can be used as a means to collect gas samples from the sealed atmosphere. During these leakage determination tests, a pressure gauge was attached to the copper tube on the B-drift side to monitor the differential water pressure across the seal.

As the ventilation fan speed was increased, the pressures and the air flows through each seal were recorded (fig. 6). Based on data collected during the testing program (*3*, *4*) with solid-concrete-block and cementitious

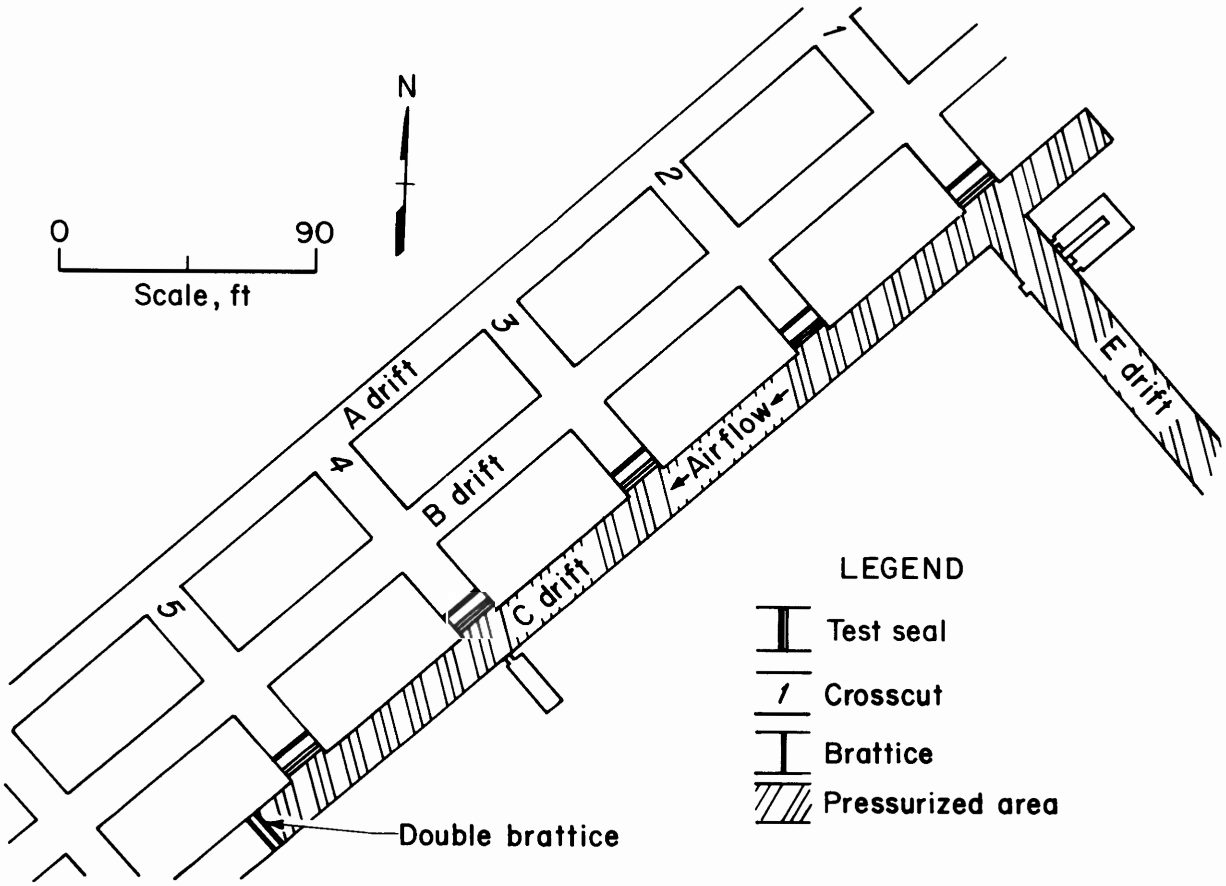

Figure 4.—Pressurized entry for leakage-determination rates across the seals.

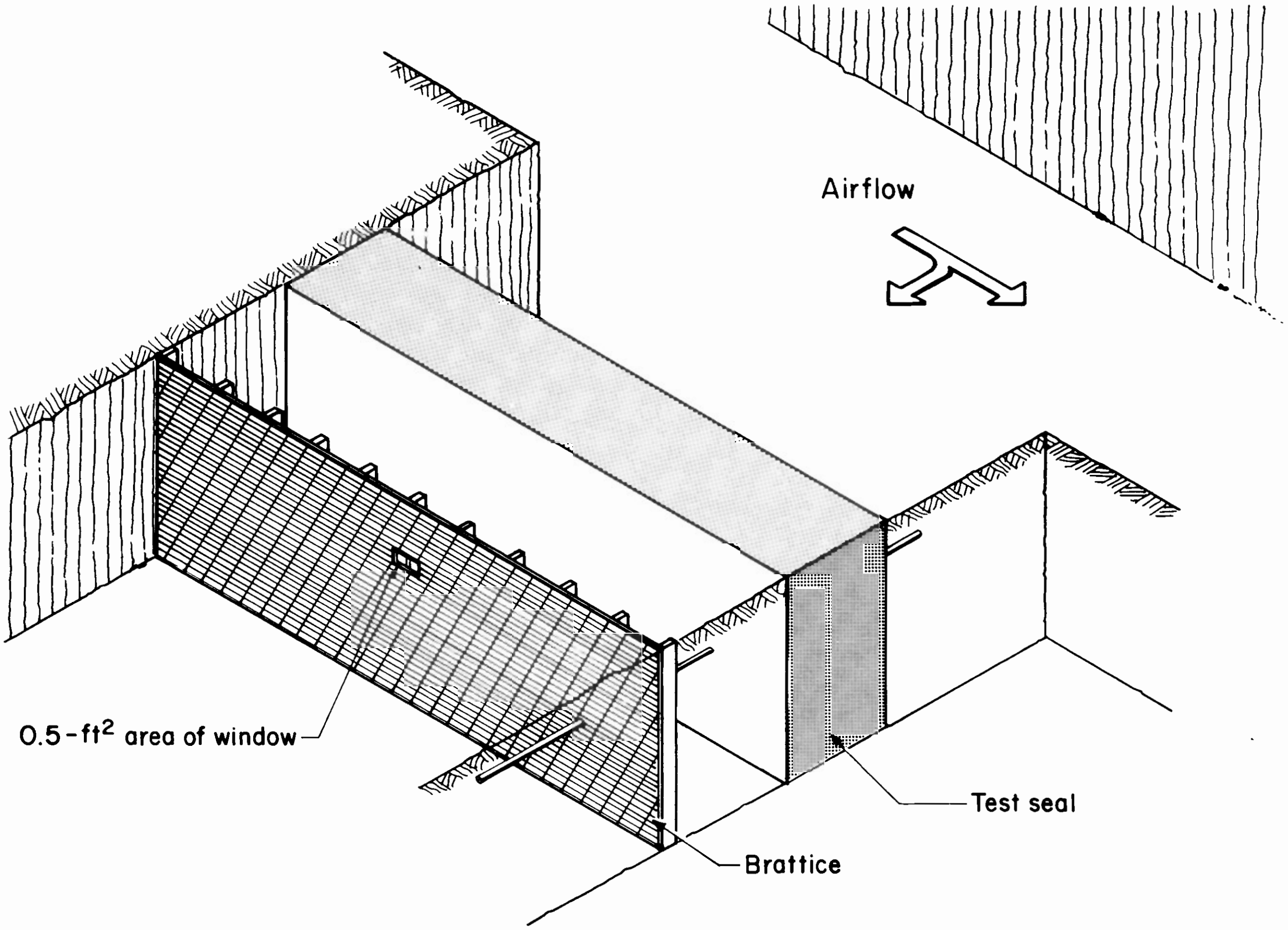

Figure 5.—Curtain configuration for leakage tests through test seal.

Figure 6.—Monitoring of air flow through test seal.

foam seals, MSHA personnel have developed tentative guidelines for acceptable air-leakage rates through a seal for this seal-testing program. The air-leakage rates through the subsequent seals during both preexplosion and postexplosion leakage tests were judged against these MSHA-established tentative guidelines. Table 1 shows these maximum acceptable air leakage rates, in cubic foot per minute, as a function of pressure differential, in inch of water. For pressure differentials up to 2 in H_2O, air leakage through the seal should not exceed 150 ft^3/min. For pressure differentials over 3 in H_2O, air leakage should be less than 250 ft^3/min.

Table 1.—MSHA-established tentative guidelines for air leakage through a seal

Pressure differential, in H_2O	*Air leakage through seals, ft^3/min*
Up to 1.0	≤100
Up to 2.0	≤150
Up to 3.0	≤200
More than 3.0	≤250

A seal that did not withstand the 20-psig pressure pulse (a postexplosion inspection of that seal revealed structural damage) was considered not to have met the CFR 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 cracks and/or block removal. The seals that withstood the pressure pulse with little or no outward damage were then tested for air-leakage resistance.

SUMMARY OF PREVIOUS TEST RESULTS

SOLID-CONCRETE-BLOCK SEALS

Seven solid-concrete-block seal designs were first tested in the crosscuts between B and C drifts of the LLEM (*3*, *5*). All of the seals tested in the LLEM were evaluated relative to the explosion and air-leakage resistance obtained with the standard-type seal. The standard-type seal, shown in figure 7, is a 16-in-thick, solid-concrete-block design with a 32-in pilaster and a cross-sectional area of about 125 ft^2. The center pilaster imparts additional support and strength characteristics to the seal. Approximately 450 solid-concrete blocks (nominal size of 6 by 8 by 16-in, and density of 128.1 lb/ft^3) were used to construct the standard-type seal, and mortar (*8*) was applied at all of the block interfaces. Keying was simulated (to protect the concrete floors in the LLEM) by bolting a 6- by 6- by 1/2-in-thick steel angle to the floor and ribs using 24-in long, 1-in-diam case-hardened steel bolts (embedded 18 in) on 18-in spacings on the floor and ribs. The bolts were grouted into the ribs and floor. In operating mines, keying of the seal is achieved by hitching or trenching, to a depth of at least 4 in, into the solid ribs and floor before erecting the seal. The other concrete-block designs were either modified standard-type seals or thin-wall (8-in thickness) seals (*3*).

Following the explosion and leakage-determination tests, only the standard-type seal maintained its integrity. A standard-type seal without floor keying incurred significant damage in terms of block removal near the roof and large cracks. A standard-type seal with no pilaster, but

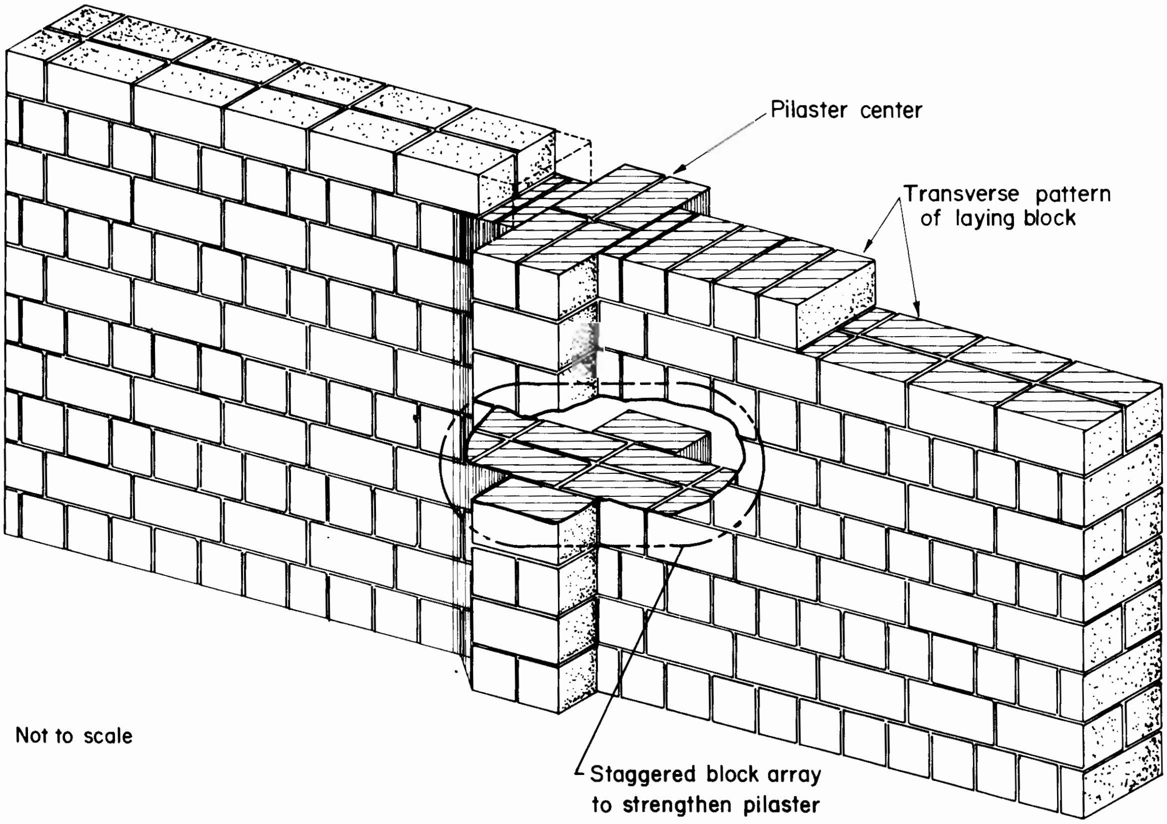

Figure 7.—Standard-type, solid-concrete-block seal.

with floor keying, also failed structurally. All of the thin-wall, mortared seals failed structurally, even when constructed with a pilaster and floor keying. Table 2 summarizes the test conditions and results for these solid-concrete-block seal designs. The use of coatings (1/8-in-thick coatings of Austin and Associates' Fibercoat) on the seals did not strengthen the seals significantly; however, coating did help to minimize leakage through high-strength seals. The standard-type seal, keyed into both floor and ribs, withstood overpressures up to 42 psig without signs of failure. After five tests with explosion pressures >20 psig, the leakage through the standard-type seal was measured at only 87 ft^3/min at a pressure differential of 1 in H_2O, an acceptable leakage rate.

CEMENTITIOUS FOAM SEALS—TEST SERIES 1

Five cementitious foam seal designs were constructed in the crosscuts between B and C drifts of the LLEM to evaluate their strength characteristics and air-leakage resistance when subjected to a pressure pulse of 20 psig (*3, 5*). Tekseal cementitious foam (manufactured by Celtite Corp.,) was the material used in the construction of these seals. A simple wooden lattice structure, consisting of upright posts wedged to the roof and floor and horizontal crossboards with brattice material attached to the inside, was used as a form and liner to contain the cementitious foam slurry for each of the seals.[6] No simulated keying was used with the cementitious foam seal designs. The slurry, consisting of the Tekseal powder, water, and air, was injected into the forms by means of a pump and hose assembly. A multiple-point injection technique was adopted that permitted the final slurry mixture to be injected, under slight pressure, near the top of the structure at three ports to ensure complete filling to the mine roof.

The cementitious foam seals varied in thickness and design compressive strength. The compressive strength of the seal material varied according to its density, which was affected by the amount of Tekseal powder used per cubic yard of seal. Two of the seals had design compressive strengths of approximately 200 psi (density of about 46 lb/ft^3), with thicknesses of 8 ft (crosscut 2) and 4 ft (crosscut 3). Another seal with a design compressive strength of 100 psi (density of approximately 30 lb/ft^3) was 4 ft thick (crosscut 4). The final two seals had compressive strengths of 50 psi (density of about 23 lb/ft^3) with thicknesses of 8 ft (crosscut 5) and 4 ft (crosscut 6). A standard-type, solid-concrete-block seal remained in crosscut 1 from the previous test series.

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[6] Additional bracing is needed on both sides of the seal to prevent collapse from the lateral forces exerted on the form during the injection of the cementitious foam slurry.

Table 2.—Summary of test conditions and results for previously tested solid-concrete-block seal designs in the LLEM

Design	Thickness, ft	Crosscut	Maximum overpressure, psig	Postexplosion air-leakage rates,[1] ft^3/min		20-psig test outcome[2]
				1.0 in H_2O	4.0 in H_2O	
Standard-type seal, wet-wall, plaster, rib and floor keying.	1.3	1	22	87	94	Passed.
Standard-type seal except no floor keying.	1.3	2	21	NAp	NAp	Failed.
Wetwall, plaster, rib and floor keying, coating on inby side.	.7	3	19	NAp	NAp	Do.
Wetwall, plaster, rib and floor keying, coating on outby side.	.7	4	[3]15	NAp	NAp	Do.
Standard-type seal except no pilaster.	1.3	2	17	NAp	NAp	Marginal at <20-psig pressure.
Drywall, pilaster, rib and floor keying, coating on both sides.	.7	3	18	NAp	NAp	Failed.
Standard-type seal except dry wall.	1.3	2	20	NAp	NAp	Do.

NAp Not applicable.

[1] Preexplosion air-leakage tests were not conducted. Postexplosion leakage tests were not performed against seals that exhibited significant damage in terms of block removal and/or large gaping cracks.

[2] Refer to reference 3 for detailed information.

[3] Approximate pressure lower because of the venting through the opening formed when the seal in crosscut 3 failed.

Following a curing period that exceeded 30 days, the cementitious foam seals were subjected to a nominal 20-psig explosion pulse on the C-drift side. The pressure was approximately 29 psig at the first cementitious foam seal near crosscut 2 and 21 to 22 psig at the seals in crosscuts 3, 4, and 5; and decreased to about 13 psig at the farthest outby seal in crosscut 6. Both of the 200-psi-strength seals survived the explosion and exhibited insignificant air-leakage rates at pressure differentials up to 4.25 in H_2O after the explosion. The 4-ft thick, 100-psi-strength seal displayed a series of cracks on both sides of the seal. Subsequent air-leakage tests showed that the seal was still maintaining acceptable air-leakage values, but because of the size and number of cracks, MSHA personnel considered the seal's performance marginal. Additional testing on the 100-psi-strength seal design needed to be conducted for final determination. The two 50-psi-strength seals failed under the explosion pressures. The 8-ft-thick, 50-psi seal displayed severe fractures that extended through the entire seal. The 4-ft-thick, 50-psi seal was totally destroyed by the explosion. Table 3 summarizes the test conditions and results for these cementitious foam seal designs.

Explosion tests have shown that 200-psi compressive strength, 4- and 8-ft-thick cementitious foam seals erected in a 125-ft² crosscut can structurally withstand a 20-psig pressure pulse, and subsequently, maintain acceptable air-leakage resistance based on postexplosion air-leakage measurements. Cementitious seal designs, regardless of the cementitious foam's manufacturer, have been approved by MSHA for use in underground coal mines if the seals have compressive strength equal to or greater than 200 psi, and if they are constructed like those tested in the LLEM.

OMEGA 384 FOAM-BLOCK SEALS

Four seal designs were constructed in the crosscuts between B and C drift at the LLEM using Omega 384 low-density block, as manufactured by Burrell Mining Products, Inc. (*4*). Omega 384 is a glass-fiber, reinforced, lightweight block (16 by 24 by 8 in with a density of 23.9 lb/ft³) that is impervious to water and air leakage to pressure differentials of up to 8.0 in H_2O. A cementitious, fiberglass-reinforced bonding agent, Burrell Bond, was used in conjunction with the Omega 384 block (for mortar at block joints and for surface coatings) and was allowed to cure for at least 28 days.

Table 3.—Summary of test conditions and results for previously tested cementitious foam and low-density foam-block seal designs in the LLEM

Design	Thickness, ft	Crosscut	Maximum overpressure, psig	Postexplosion air-leakage rates,[1] ft³/min		20-psig test outcome[2]
				1.0 in H_2O	4.0 in H_2O	
			CEMENTITIOUS FOAM			
Compressive strength, psi:						
200	8	2	29	0	31	Passed.
	4	3	22	52	114	Do.
100	4	4	22	47	114	Marginal.
50	8	5	21	180	420	Failed.
	4	6	13	NAp	NAp	Do.
			LOW-DENSITY FOAM BLOCK[4]			
Pilaster:						
2	2.7	2	20	21	52	Passed.
	2	3	21	140	294	Marginal.
1	2	4	20	39	87	Passed.
	2	5	19	63	139	Do.

NAp Not applicable.

[1] Preexplosion air-leakage tests were not conducted. Postexplosion leakage tests were not performed against seals that exhibited significant damage in terms of block removal and/or large gaping cracks.

[2] Refer to references 3 and 4 for detailed information.

[3] Design compressive strengths were slightly different than actual strengths; for example, the seal in crosscut 4 was designed for 100 psi, but sample testing indicated an actual strength of 78 psi.

[4] All of these seals utilized mortared joints (wetwall), coating on both sides, keying at the ribs and floor, and staggered block design.

Simulated keying (hitching) on the floor and ribs using a 6- by 6- by 1/2-in-thick steel angle secured with 24-in-long by 1-in-diam case-hardened steel bolts on 18-in centers was applied to all of the seal designs. These bolts were grouted into the floor and ribs. All of the block joints were staggered and mortared in each design. A surface bonding mortar of at least 0.25-in thickness was applied to the inby and outby faces of each seal. Each seal was wedged approximately 0.5 to 1 ft on top against the mine roof. Three of the seals were 24 in thick and one (located in crosscut 2) was 32 in thick. The seals located in crosscuts 2 and 3 each had two pilasters (48 in thick by 48 in wide and located approximately one-third of the distance in from each rib); the seal in crosscut 5 had only one pilaster (centered) of similar dimensions. The seal in crosscut 4 had one large pilaster 56 in thick by 72 in wide located at the center of the seal. A standard-type, solid-concrete-block seal, installed previously, was in crosscut 1 (*4*).

The four Omega 384 block designs were subjected to an explosion that exerted a pressure pulse of approximately 20 psig on each seal. Each of the four seal designs survived the test. Air-leakage measurements were then taken across each of the seals to determine the seals' air-leakage resistance characteristic. The air-leakage rates across the seals in crosscuts 2, 4, and 5 fell well within the MSHA-established tentative guidelines (less than 250 ft^3/min) for pressure differentials up to 4.0 in H_2O. The leakage across the seal located in crosscut 3 exceeded these guidelines. Table 3 summarizes the test conditions and results for these low-density foam-block designs.

Testing has confirmed that the Omega 384 seal designs meet the requirements of 30 CFR Part 75.335 (2) if constructed in the same manner as the seals in the LLEM (*4*).

DISCUSSION OF RECENT TEST RESULTS

CEMENTITIOUS FOAM SEALS—TEST SERIES 2

Five additional seals were installed in the crosscuts between B and C drifts of the LLEM as part of a second test series to evaluate cementitious foam as a seal construction material. All of the seals were 4 ft thick and installed in the crosscuts with an average cross-sectional area of approximately 125 ft^2. The designed strengths and thicknesses of two of the five seals, constructed with Celtite Tekseal, were based on the successful test results from the first test series (*3, 5*). Celtite also had improved on its cementitious foam dry-powder formulation, and the remaining three designs incorporated the Tekseal II material.

The wooden framework with attached brattice cloth used to contain the cementitious slurry was similar to that used during the first test series (*3*). No simulated keying with a steel angle was used with these seal designs. Figures 8 and 9 show two phases of the lumber and brattice framework construction. A copper tube was positioned through the middle of each seal (fig. 9), prior to the slurry injection, for monitoring the pressure differential across each seal during the leakage tests. Thermocouples were attached to the tubing to monitor the reaction temperatures of the cementitious slurry during the curing period.

The seals installed in the first two outby crosscuts were constructed with the original Tekseal material. The dry Tekseal powder (packaged in 45-lb bags) was added to the hopper, auger-fed into a bin where it was mixed with water, aerated, and pumped into the seal forms. The LLEM's water supply at the time of construction ranged in temperature from 45° to 50° F. The design compressive strengths of the seals located in crosscut 1 and crosscut 2 were 200 and 140 psi, respectively. The slurry used for these seals was pumped through 400 ft of hose.

The other three seals were constructed with Tekseal II with designed compressive strengths of 200 psi (crosscut 3), 150 psi (crosscut 4), and 100 psi (crosscut 5). The water used in the slurries for these seals was heated to a temperature range of 60° to 64° F. The increased water temperature was achieved by heating the mine's water supply. The water was passed through a bank of large electric heaters prior to going into the mixing pump. The elevated water temperature hastened the initial curing period required of the Tekseal II slurry, and served to harden and improve the compressive strengths of the seals. The improved characteristics of the Tekseal II formulation resulted in a reduction in the amount of dry powder (fewer bags per cubic yard of seal) required to obtain the desired compressive strengths as compared with that of the original Tekseal powder (approximate density of 30 to 38 lb/ft^3 for Tekseal II as compared with 46 lb/ft^3 for the original Tekseal to achieve comparable 200-psi-design compressive strength seals). The slurry was pumped through 850 ft of hose during the construction of the 100-psi-designed compressive strength seal in crosscut 5. This distance would be typical of actual underground seal installation.

Compressive strength measurements were made on 90 samples, 3 in diam by 6 in long, that were collected during the slurry injection period from the five cementitious foam seals. Personnel from MSHA collected and tested the samples. Eighteen samples were collected from

Figure 8.—Wooden framework for cementitious foam seal.

Figure 9.—Brattice liner attached to framework used to contain the cementitious foam slurry. Note copper tubing through the middle of the seal.

each seal; six each from the bottom, middle, and top sections of the seal. Half of the samples were allowed to cure underground under the same temperature and humidity conditions as that for the seals; the rest were removed to a surface laboratory. Compressive strength tests were conducted on the samples at three time increments; 2, 4, and 6 weeks after seal completion. The compressive strength test results show, as expected, that the strengths increase as the curing time increases. The tests conducted on the samples after 6 weeks of curing, which corresponds to the time of the first explosion test conducted on the seals, generally resulted in average compressive strengths (table 4) well above the design strengths for both the samples cured in and out of the mine for all of the seals.

Thermocouples were installed in the first three outby seals to measure the exothermic reaction temperatures of the curing Tekseal and Tekseal II materials. The temperatures, as recorded from the thermocouples imbedded in the center of the seals, for the first two outby seals (constructed with the original Tekseal) peaked at about 145° F approximately 1.5 days after the slurry injection. The temperature for the seals constructed with the Tekseal II peaked at 140° F after 7 days. The temperature from thermocouples imbedded 6 in inside each face of each seal ranged from 5° to 20° F lower than the center temperatures.

Air-leakage rates were measured at various pressure differentials for each seal before the explosion tests. With a pressure differential of approximately 4.4 in H_2O, the leakage rates across each of the seals starting from the face were 21, 35, 99, 80, and 83 ft^3/min, respectively. All of these values were well within the MSHA-established tentative guidelines shown in table 1.

Four explosion tests were conducted in C drift to evaluate the performance of the five cementitious foam seals. The explosion pressures generated at the seal locations during each of the mine tests increased, respectively, as follows: 16 to 19, 21 to 26, 26 to 30, and 30 to 35 psi during the final test. Following each of the first three explosion tests, minor damage was noted on several of the seals. This damage consisted of burned brattice cloth and removal of some of the upright wooden posts that had been part of the original form designed to hold the cementitious foam slurry. All five of the seals withstood the pressures exerted on them during the first three explosion tests. Air-leakage tests following each of these explosions showed that the air leakages were still within the established tentative guidelines (*4*). During the final explosion test, which generated pressures up to 35 psi, the seal in crosscut 5 (Tekseal II, 100-psi strength) was completely destroyed. Upon testing, the seal in crosscut 4 (Tekseal II, 150-psi strength) exhibited excessive air-leakage rates; at a pressure differential of 4.3 in H_2O, its leakage was 618 ft^3/min. The seals in the first three crosscuts essentially were undamaged and had acceptable air-leakage rates. At a differential pressure of 4.3 in H_2O the leakage was 21 ft^3/min for the crosscut 1 seal, 90 ft^3/min for the crosscut 2 seal, and 92 ft^3/min for the crosscut 3 seal. Table 4 summarizes the test conditions and results for these cementitious foam seal designs.

All five of the cementitious foam seals, as constructed in the 125 ft^2 crosscuts during this second test series, survived the 20-psi explosion test, and subsequently, maintained negligible air-leakage rates. It must be noted, however, that the seals described in this report were approved by MSHA for use in underground coal mines only if constructed in a similar size and manner as in this study. Seals erected in larger than 125 ft^2 crosscuts may need to be either thicker and/or have greater compressive strength.

Table 4.—Summary of test conditions and results for recent 4-ft-thick cementitious foam seal designs

Crosscut	Design compressive strength, psi	Actual compressive strength,[1] psi	Maximum overpressure, psig	Air-leakage rates, ft^3/min: Preexplosion 1.0 in H_2O	Air-leakage rates, ft^3/min: Preexplosion 4.0 in H_2O	Air-leakage rates, ft^3/min: Postexplosion 1.0 in H_2O	Air-leakage rates, ft^3/min: Postexplosion 4.0 in H_2O	20-psig test outcome
1	200	208	26	21	21	21	21	Passed.[3]
2	140	157	25	21	35	21	60	Do.
3	[2]200	376	22	37	99	31	85	Do.
4	[2]150	219	22	26	80	52	152	Do.
5	[2]100	168	21	30	83	61	154	Marginal.[4]

[1] Actual compressive strength values were based on an average value for 18 samples collected and laboratory tested for each seal.

[2] Tekseal II used for this seal.

[3] Degree of damage - none.

[4] Degree of damage - marginal. Minor damage, hairline cracks appearing to extend through seal.

The seals were constructed in the LLEM under conditions analogous to those that may be encountered during seal construction in actual underground coal mining operations. However, measures must be taken to prepare the seal site, and additional bracing of the framework is recommended. All of the manufacturer's specifications on site preparation, form installation, and slurry injection must be carefully followed. As with the installation of any seal design, all loose material on the roof, ribs, and floor must be removed down to competent strata. All accumulated water in the seal area must be removed or absorbed with cement powder prior to the injection of the foamed slurry. In one mine there was difficulty in maintaining the framework in that the upright posts were kicking out at the bottom during the slurry injection period. To overcome this problem, it is recommended that roof bolts or tie wires be secured near the floor, at half height, and at the roof between two upright posts on opposite sides of the seal to reduce the tendency of those posts to move. This method should be used, if necessary, at a minimum of three locations across the width of the seal. Additional angle braces also can be installed laterally across the seal to strengthen the framework. To maximize closure at the roof and ribs, the framework-brattice must be erected in such a manner as to eliminate slurry leakages during the injection process. This may require stuffing brattice material or rags in the gaps between the roof and framework. When the gaps are plugged, the slurry can be injected within the framework through the injection ports near the roof under a slightly positive pressure. When injecting the final slurry material into the form under pressure, complete closure to the ribs and roof can be obtained.

The proximity of cribbing and other obstructions near the area being sealed could result in injury to personnel in the event of a form collapse. For additional safety protection for the personnel injecting the slurry, it is recommended that extension pipes be attached to the injection hose to remove the personnel from the immediate vicinity of the seal.

After the cementitious foam has cured, it is advisable that the wood framework and brattice be removed on the outby side to enable inspections of the seal. Observations can be made as to the integrity of the final seal with respect to complete contact with the ribs and roof. Any gaps should be filled immediately with additional cementitious foam or its equivalent. A suitable sealant (*8*) should be applied to the accessible surfaces of the seal to reduce drying. The seal then can be checked periodically for structural integrity (stress cracks) and impermeability (resistance to air leakages) and sealant can be reapplied if necessary.

WOOD-BLOCK SEALS

Wood-block seals currently are used in many mines that experience high convergence forces. These high convergence forces exceed the compressive strength of the standard-type, concrete-block seals, rendering these seals ineffective. Various wood-block (also referred to as crib-block) seal designs have been evaluated during this program. These tests determined strength and air-leakage resistance characteristics of the seals relative to the established guidelines of Title 30, Part 75.335 of the CFR. This research also focused on methods to strengthen existing wood-block seals to minimize the labor and costs associated with replacing inadequate seal designs. Once constructed, each seal was subjected to a 20-psig explosion pressure pulse. All of the seals were tested without any convergence forces (except that from wedging) that may be exerted on the seals from the roof, floor, and/or ribs under actual mine conditions. The tests with the wood-block seal designs were conducted in the absence of convergence forces since the extent and magnitude of these forces can not be predicted or guaranteed at every sealing location. These convergence forces also may take a while to build up and act on a newly erected seal. Furthermore, there is a compelling need to know the strength of an explosion that a newly installed crib-block seal can withstand.

Standard crib blocks with nominal dimensions of 6 by 6 by 36 in long were used during construction. These hardwood crib blocks weigh, on average, 30 lb each (density of about 44 lb/ft^3). Approximately 38 crib blocks were used per row per seal. Approximately 15 rows of crib blocks were required to complete each of the seals. Therefore, 570 to 590 crib blocks were needed for each seal. As was the case with the solid-concrete-block (*3*, *5*) and Omega block (*4*) seal designs, keying was simulated by bolting a 6- by 6- by 1/2-in-thick steel angle to the floor and ribs. The bolts were grouted into the ribs and floor. Inadvertently, 3/4-in-diam steel bolts were used instead of the required 1-in-diam case-hardened steel bolts to secure the steel angle for all of the wood-block seal designs. This resulted in the failure of the restraint mechanism designed to simulate hitching.

Test Series 1

A wooden crib-block and rock-dust seal design typically used now in many underground coal mines was tested. This crib-block seal was installed in crosscut 2 between B and C drifts (fig. 10). In this design, the mine floor was first leveled, and then a layer of rock dust was placed on the mine floor to start construction. Wooden crib blocks (6 by 6 by 36 in long) were installed lengthwise, parallel to the crosscut ribs, with the square ends facing out toward B and C drifts. A 0.25- to 0.5-in-thick layer of rock dust was placed between the timber rows (or courses) to level and fill void spaces between crib blocks and to reduce air leakage through the seal (fig. 11). The seal was constructed to make solid contact with the roof, floor, and ribs. Voids around the perimeter of the seal were filled with wood pieces and the timber rows then were wedged solidly against both ribs. This procedure was followed for each row until the last full row reached the mine roof. Once the mine roof height was reached, any space remaining that was too small for a full timber was filled with a taper-cut timber. The top course of these crib blocks was installed solidly against the mine roof using wood wedges on both sides of the seal (fig. 12).

On the explosion side of the seal (C-drift face), a full-face, 1/2-in-thick coating of MSHA-approved sealant (*8*), Celtite 10-14 Airtight, was applied. On the other face, the sealant was applied only around the perimeter at the seal-mine surface interface.

The seal constructed in crosscut 1 was designed to have increased strength characteristics. As shown in figure 13, the crib blocks were installed lengthwise, parallel to the crosscut ribs. Each timber in the design was toenailed to the timber in the lower course using three 20-penny common nails on 9-in centers. No rock dust was used; instead, 5/8-in-thick plywood sheeting was used on both sides to reduce the air leakage through the seal and to provide additional design strength to the seal. This plywood was secured to the timbers using 16-penny common nails on 6-in centers. For this seal, the plywood sheeting abutted the steel angle used for keying and was not set in behind the angle. The sealant, Celtite 10-14 Airtight, was applied to both faces of the seal, but only at the perimeters and at the plywood sheet joints.

Air-leakage measurements were conducted on both seals following the final sealant applications. Initially, both seals exhibited excessive leakages due to the improper application of the sealant material. At a differential pressure of 4.8 in H_2O, the leakage was 500 ft^3/min on the seal in crosscut 1 and 340 ft^3/min on the seal in crosscut 2. Experience has shown that the Celtite 10-14 Airtight sealant must be applied in two thinner coatings instead of one thick coating. After applying a thin recoating, both seals had air leakages that fell well within acceptable rates (see table 1) at each of the differential pressure levels. At pressure differentials up to 4.5 in H_2O, the nailed-crib-block seal in crosscut 1 had a negligible air leakage of 27 ft^3/min and the crib-block and rock-dust seal in crosscut 2 had a leakage of only 58 ft^3/min. The sealant was allowed a 7-day curing period before the seals were explosion tested.

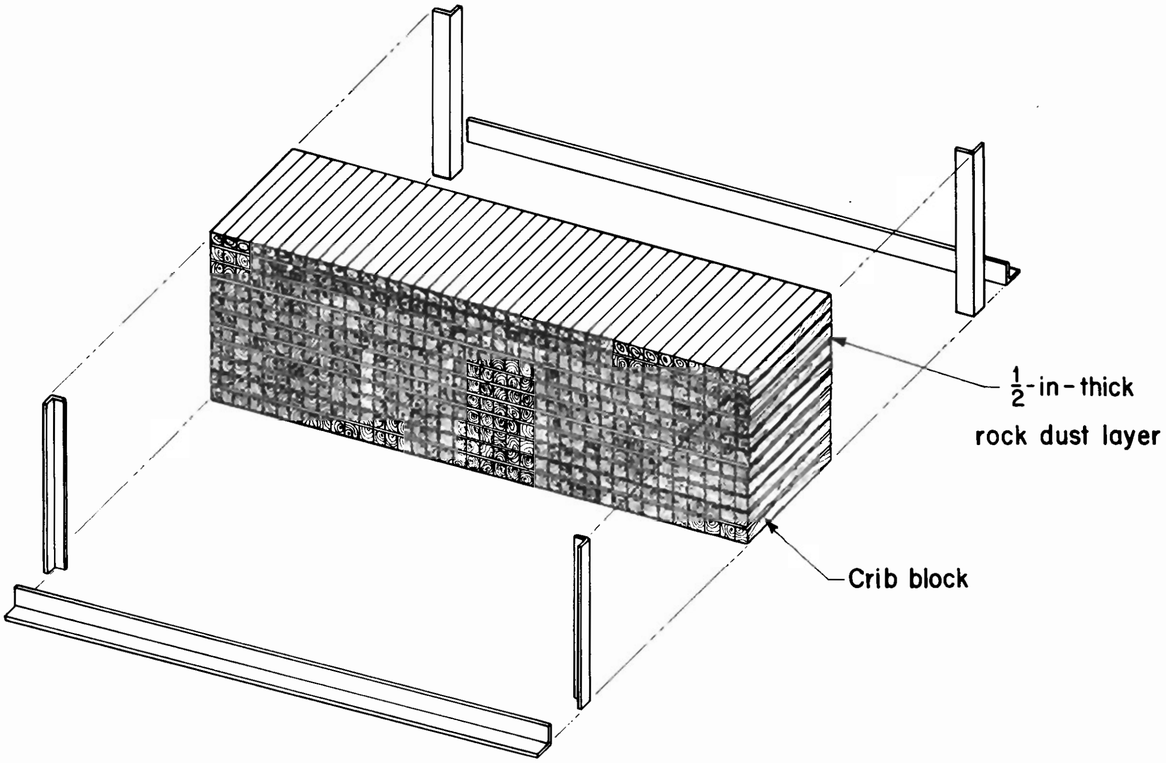

Figure 10.—Typical wood-block and rock-dust seal design.

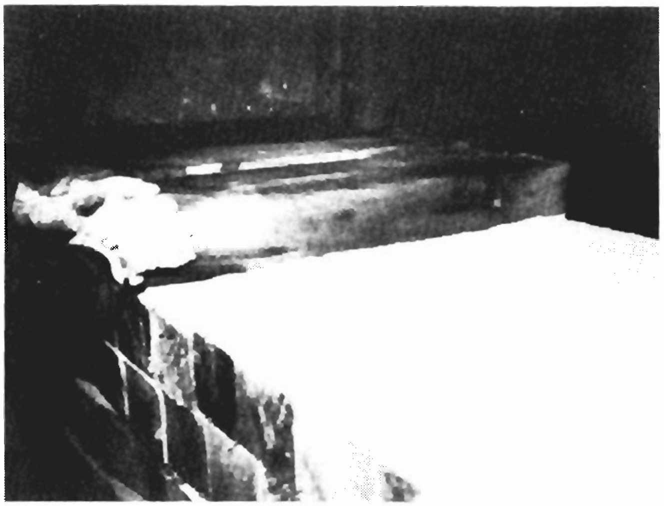

Figure 11.—Rock dust between timber rows.

Figure 12.—Wedging of wood blocks to mine roof.

Following the curing period and the second leak test, the seals were subjected to a gas explosion generated at the face of C drift. A postexplosion inspection of the nailed-crib-block seal in crosscut 1 revealed that the seal was displaced en masse approximately 1 ft in the direction of B drift. Note that it was later determined that the 3/4-in-diam steel bolts were not of adequate strength to secure the steel-angle simulated hitching. The seal had been subjected to a pressure wave of 23 psi, as measured with nearby static pressure transducers. The plywood facings on this seal received minor damage along their peripheries. The leakage test on this seal showed, as expected, that excessive amounts of air were passing through the damaged seal. At 2.2 in H_2O, the air leaking through the seal was measured at 1,650 ft^3/min. This value is well above the MSHA-established tentative guidelines of 200 ft^3/min for a pressure differential up to 3.0 in H_2O.

The crib-block and rock-dust seal in crosscut 2 was demolished totally by the 22-psi level pressure wave (fig. 14). Note that the 3/4-in-diam bolts used to secure the steel-angle simulated hitching were not damaged and were of sufficient strength, in this instance, to hold the angle in place. Crib-block and rock-dust seals, as currently constructed in operating mines, will not withstand a 20-psig explosion prior to being subjected to mine convergence.

Test Series 2

Test series 1 has shown that the typical crib-block and rock-dust seal currently used in operating mines will not withstand a 20-psig level explosion in the absence of any mine convergence forces. In the second series with crib-block designs, the research focused on design modifications that will strengthen sufficiently the typical crib-block and rock-dust seal externally so as to withstand the explosion and subsequent air-leakage tests. Such a design will allow for the strengthening of existing seals in operating mines in order to meet the standards required in Title 30 of the CFR without the need for their removal.

The modified nailed-crib-block seal design in crosscut 1 was improved by installing crib blocks lengthwise, perpendicular to the ribs, for approximately one-third of the seal's length adjacent to each rib, as shown in figure 15. As can be seen in figure 16, each of these crib blocks was positioned so that all of the block joints were staggered. The center crib blocks were installed lengthwise, parallel to the crosscut ribs, in the same manner as was the entire original seal in the first test series. For this seal, the crib blocks were secured together using 20-penny screw-type nails. In addition to nailing the crib blocks vertically to the lower course, each block also was nailed horizontally to the adjacent block. In the staggered block sections of the seal, this generally resulted in a full block being secured with nails to the surrounding blocks at eight locations. The blocks in the top row near the roof were all positioned lengthwise, parallel to the ribs, to facilitate nailing. Plywood sheeting (5/8 in thick) was inserted behind the steel angle keying on the floor and ribs and attached to both faces of the seal using 16-penny common nails. These nails were installed on 6-in centers. The Celtite 10-14 Airtight sealant was applied to the perimeter and plywood joints on both sides of the seal.

The crib-block and rock-dust seal in crosscut 2 was erected in the same manner as it was during the first test series except that 3/4-in-thick plywood sheeting was inserted behind the floor and rib keying and secured to both faces of the seal with 16-penny screw-type nails on 6-in

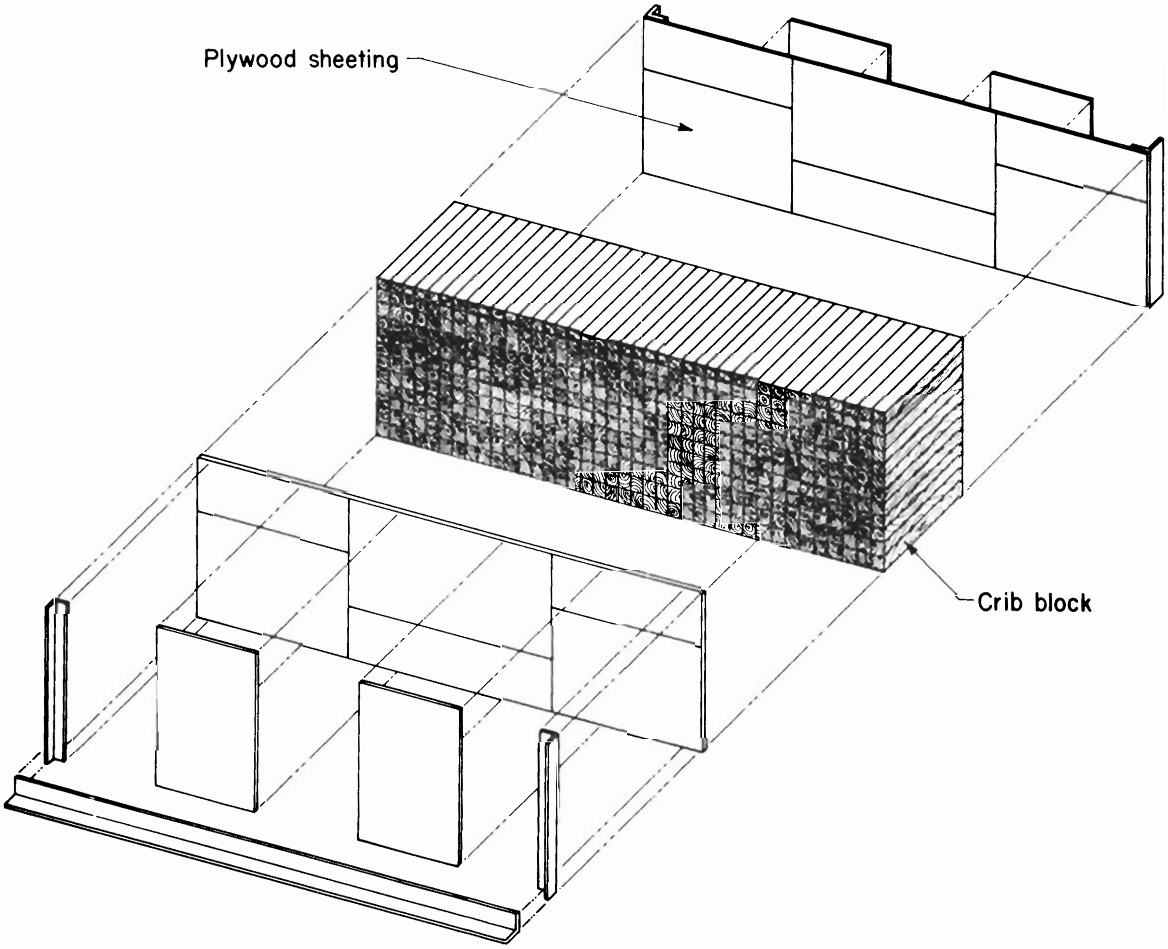

Figure 13.—Nailed-wood-block seal design 1.

Figure 14.—Damage to typical wood-block seal when subjected to 20-psig pressure pulse.

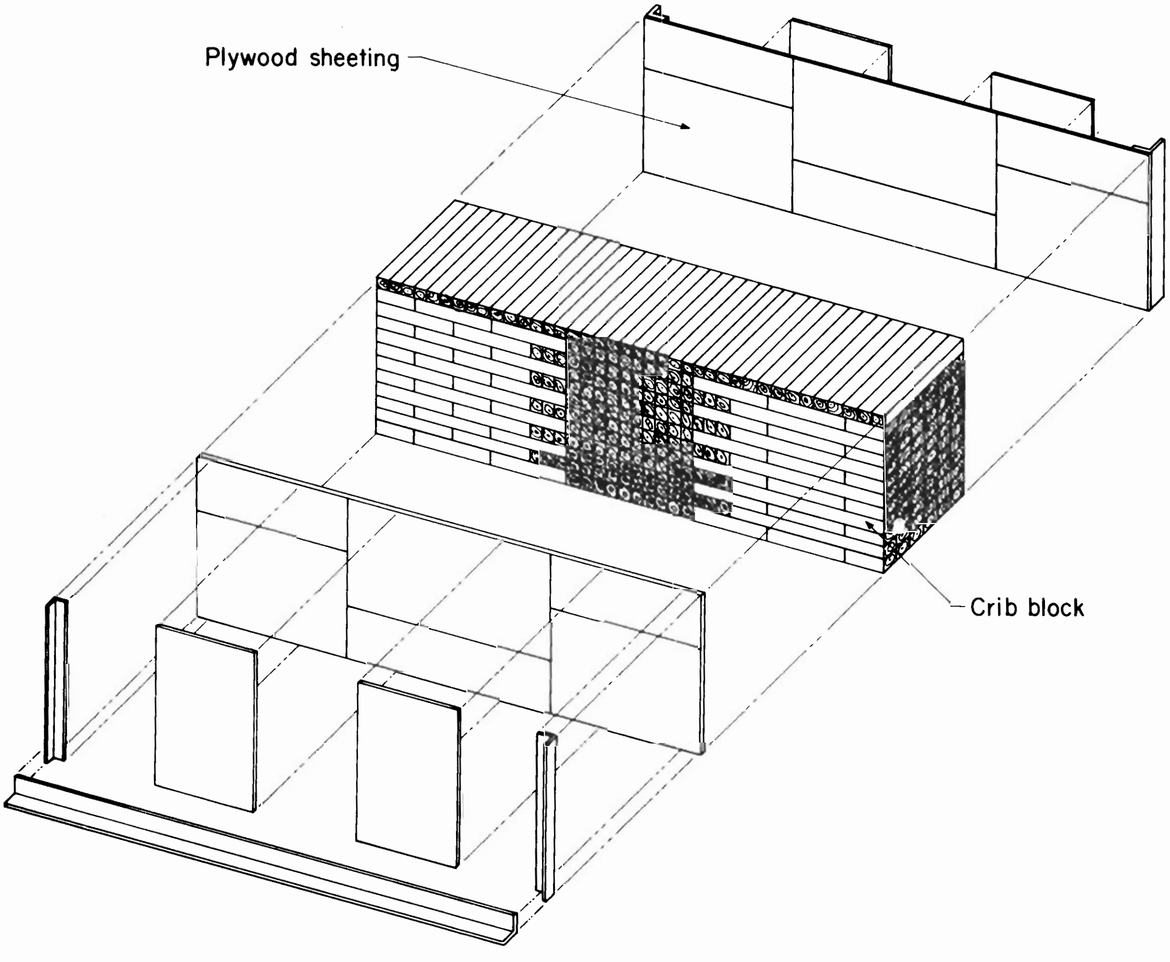

Figure 15.—Nailed-wood-block seal design 2.

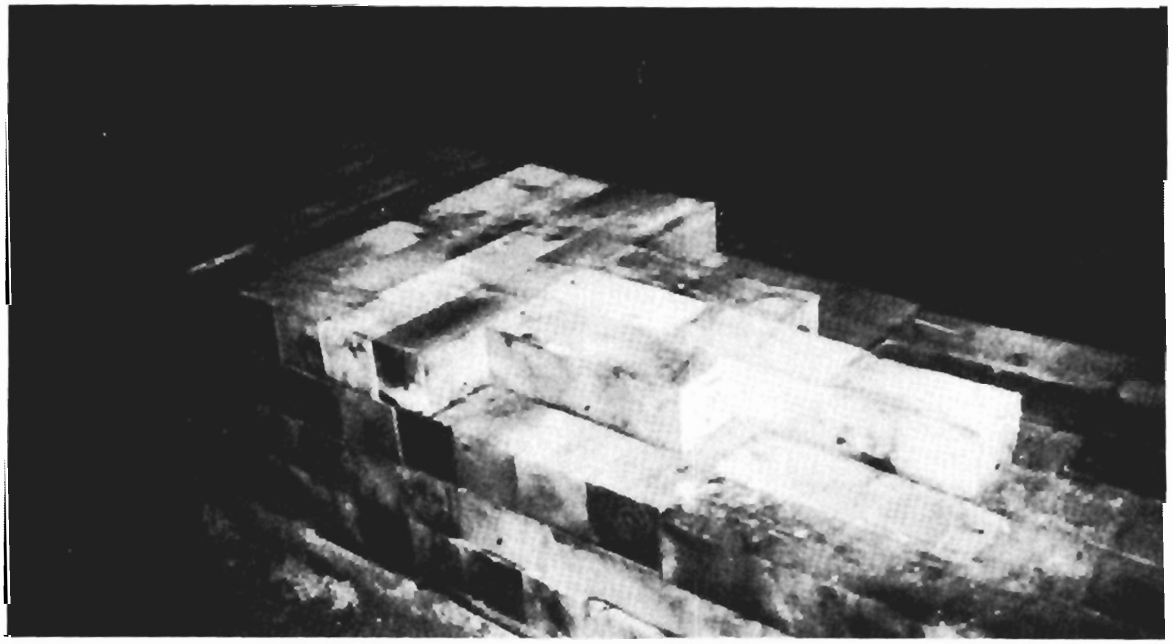

Figure 16.—Staggered wood-block joints.

centers (fig. 17). No nails were used to attach the individual blocks in the seal together. A 1/4-in- to 1/2-in-thick layer of rock dust (approximately 150 lb) was used between timber rows. A full-face coating of the Celtite 10-14 Airtight sealant was applied twice to the explosion side of the seal (C-drift side) and resulted in a 1/2-in-thick coating. The B-drift side of the seal was sealed along its perimeter and at the plywood joints.

To strengthen the steel angle used to simulate floor and rib keying, four steel-angle braces were attached to the existing steel angles. Four braces were secured into the concrete floor and two braces to each rib angle using 1/2-in-diam by 12-in-long bolts. It was not realized then that the 3/4-in-diam steel bolts were being used instead of the required 1-in-diam case-hardened steel bolts.

Air-leakage determinations on the two seals then were conducted following a 7-day curing period for the sealant. The modified nailed-crib-block seal design exhibited negligible air leakage across the seal at pressure differentials up to 4.5 in H_2O. At a pressure differential of 2.2 in H_2O, the air leakage across the seal was 18 ft^3/min, and at a pressure differential of 4.5 in H_2O, the leakage across the seal was only 45 ft^3/min; both values were well within the acceptable limits. The crib-block and rock-dust seal design erected in crosscut 2 also passed the preexplosion air-leakage test. At a pressure differential of 2.1 in H_2O across the seal, the air-leakage rate was measured at 113 ft^3/min, and at a pressure differential of 4.5 in H_2O, the air leakage across the seal averaged 167 ft^3/min; both acceptable leakage rates.

Following the successful results from the air-leakage tests, the seals were subjected to the pressures generated from the ignition of a 47-ft long, 10-pct methane-air mixture at the closed end of C drift (fig. 2). A pressure force of approximately 23 psig was exerted on the modified nailed-crib-block seal located in crosscut 1. The crib-block and rock-dust seal design in crosscut 2 was subjected to a slightly lower explosion pressure pulse of about 21 psig.

A postexplosion inspection of the seals revealed that the seals withstood the overpressures with relatively minor damage. From scrape marks on the roof, it was evident that the seals flexed away from the explosion side toward B drift. Three of the four 1/2-in-diam bolts used to

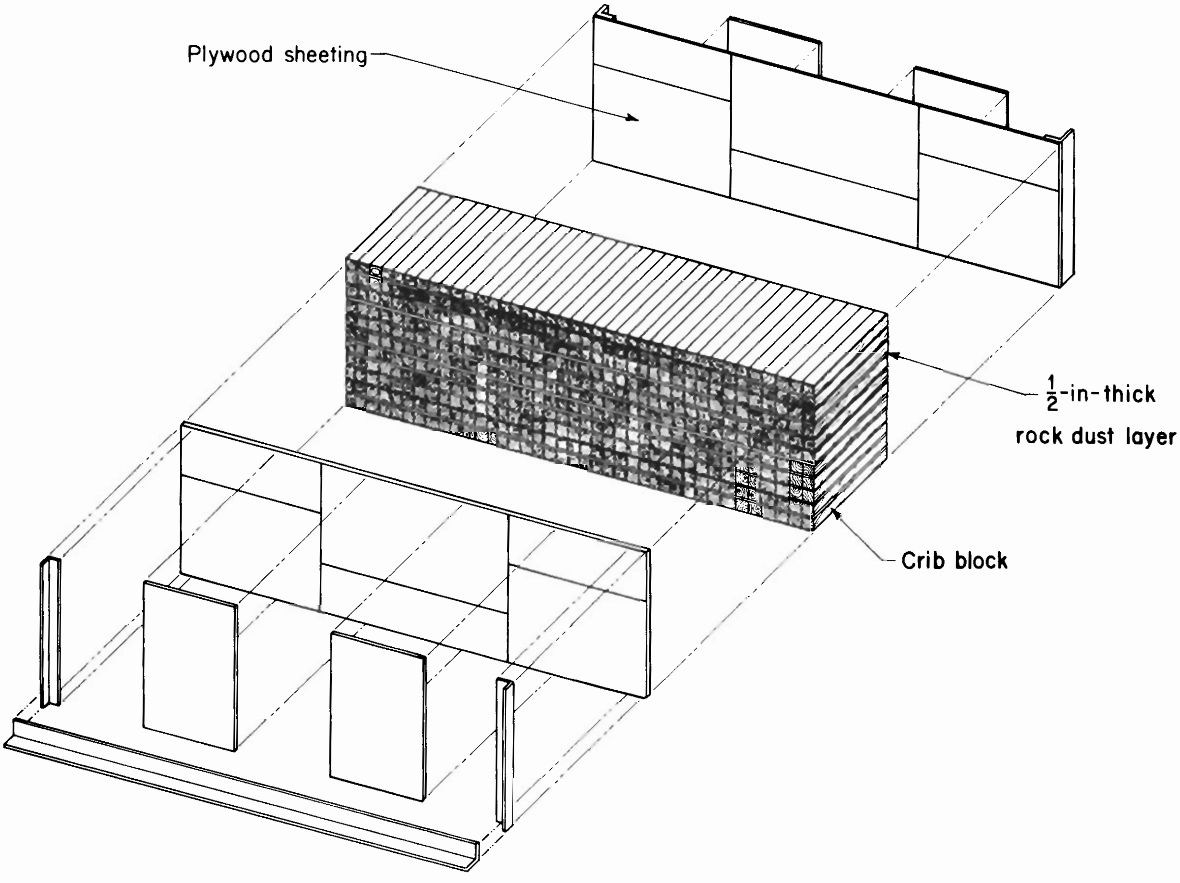

Figure 17.—Wood-block and rock-dust seal design 2.

anchor the extra bracing to the floor angle were sheared off on the modified nailed-crib-block seal, and all four of these bolts were sheared off on the crib-block and rock-dust seal in crosscut 2. The plywood sheets, in some areas, pulled slightly away from the crib block, as evidenced by the fact that the nails were extracted from the block and that there were scrape marks on the mine roof. The modified nailed-crib-block seal in crosscut 1 flexed approximately 8 in at the top center of the seal on the B-drift side. On the C-drift side, the seal moved en masse about 1.5 in toward B drift. The crib-block and rock-dust seal in crosscut 2 showed very little evidence of movement of the plywood. On the B-drift side, the plywood flexed away from the explosion approximately 3 in at the top center of the seal; no evidence of seal movement was evident on the explosion side of the seal (C drift). All of the nails used to attach the plywood to the crib block appeared to have held tightly. Note that this seal utilized 16-penny screw-type nails to secure the plywood to the crib block; whereas, the modified nailed-crib-block seal in crosscut 1 used 16-penny common nails to attach the plywood. Both seal designs survived a greater than 20-psi explosion force.

Both seal designs failed to pass the postexplosion air-leakage tests. For the modified nailed-crib-block seal in crosscut 1, an average of 1,370 ft^3/min of air was passing through the seal at a pressure differential of 1.3 in H_2O. For the crib-block and rock-dust seal design in crosscut 2, an average of 1,005 ft^3/min of air was leaking across the seal at a pressure differential of 1.3 in H_2O. Excessive quantities of air were passing through the seals; therefore, the seals no longer met the MSHA-established tentative guidelines for air-leakage resistance. However, it was later the judgement of MSHA that this excessive leakage was due primarily to the failure of the restraint mechanism (inadequacy of the 3/4-in-diam bolts used to hold the steel-angle simulated hitching).

Test Series 3

The seals from the second test series were judged to be of adequate strength to withstand the 20-psig pressure pulse. During the third test series, emphasis was placed on developing a method of applying sealant to the seal designs to meet or exceed air-leakage requirements following an explosion.

The seal design constructed in crosscut 1 was very similar to the original nailed-crib-block seal design in crosscut 1 from the first test series (fig. 13). All of the crib blocks were installed lengthwise, parallel to the ribs and wedged tightly to the roof and ribs. Two 20-penny screw-type nails were used to secure each block to the adjacent block. One important difference was that for the new seal design the crib blocks were nailed both horizontally and vertically to the adjacent block, instead of just in the vertical plane as was the case in the first test series. Another change was that the plywood sheeting was inset behind the steel-angle keying for the new seal design. Plywood sheeting was not placed in this manner for the seal in the first test series. Both sides of the seal were covered with 5/8-in-thick plywood sheets. Another change for this design was the manner in which the sealant was applied to the seal. Both sides of the seal were given a 1/2-in-thick coating using the Celtite 10-14 sealant prior to the installation of the plywood sheeting. It was believed that a more cohesive bond could be achieved between the block and the block-mine interfaces to limit sufficiently the amount of air leakage across the seal following the 20-psig explosion. The plywood sheeting was set behind the simulated hitching and attached to the crib block using 16-penny screw-type nails on 6-in centers.

The seal design constructed in crosscut 2 (fig. 17) was similar to the crib-block and rock-dust seal that was tested in the same crosscut in the second test series. However, in this case the sealant was applied fully to both faces prior to attaching the 3/4-in-thick plywood sheets. Four days after the application of the sealant, the plywood facings were set behind the steel angle keying and attached to the crib block using 16-penny screw-type nails on 6-in centers.

Measurements of the air leakage through the two seals were conducted prior to the 20-psig level explosion test. The modified nailed-crib-block seal design in crosscut 1 exhibited negligible air leakage across the seal. At 4.5 in H_2O, the air leakage was 86 ft^3/min. The crib-block and rock-dust seal design in crosscut 2 displayed an air leakage of only 67 ft^3/min at 4.5 in H_2O. Both of these values are well below the MSHA-established tentative guideline of a maximum air-leakage rate of 250 ft^3/min for water gauges exceeding 3.0 in H_2O.

The ignition of the 47-ft long, 10-pct methane-air zone at the closed end of C drift generated a pressure pulse of approximately 20 psig on each seal. A post-test inspection of the seals revealed some structural damage. Crib-block, plywood-facing, and steel-angle (simulated keying) displacements occurred in both seals. A subsequent air-leakage test showed that both seals exhibited significant air-leakage rates. At 0.9 in H_2O, each seal exhibited air leakage in excess of 1,000 ft^3/min. For water gauges up to 1 in H_2O, the maximum allowable air leakage should be 100 ft^3/min. Table 5 summarizes the test conditions and results for the wood-block convergence seal designs in this third test series, as well as those tested in the previous two series.

Table 5.—Summary of test conditions and results for the wood-block convergence seal designs

Seal type	Crosscut	Maximum overpressure, psig	Air-leakage rates,[1] ft^3/min Preexplosion 1.0 in H_2O	Preexplosion 4.0 in H_2O	Postexplosion[1] 1.0 in H_2O	Postexplosion[1] 4.0 in H_2O	20-psig test outcome
Test series 1:							
Nailed-wood-block seal[2] . .	1	23	0	27	1,066	NAp	Passed.[6]
Typical wood-block and rock-dust seal.[3]	2	22	0	58	NAp	NAp	Failed.[7]
Test series 2:							
Modified nailed-wood-block seal.[4]	1	23	7	45	1,370	NAp	Passed.[6]
Modified wood-block and rock-dust seal.[5]	2	21	72	167	1,005	NAp	Do.
Test series 3:							
Modified nailed-wood-block seal.[2]	1	20	40	86	1,155	NAp	Do.
Modified wood-block and rock-dust seal.[5]	2	19.5	24	67	1,039	NAp	Do.

NAp Not applicable.

[1] Postexplosion air-leakage tests were not performed against seals that exhibited significant damage or those that exceeded the MSHA-established tentative guidelines at the lower level pressure differentials.

[2] See figure 13.

[3] See figure 10.

[4] See figure 15.

[5] See figure 17.

[6] MSHA judged that the seal passed with minor damage and the excessive postexplosion air-leakage rates were due primarily to the failure of the restraint mechanism (simulated keying).

[7] Failed. Totally destroyed.

The results of the explosion tests against the wood-block designs have shown that the 3/4-in-diam bolts (thread-bolt) that were used were not adequate, in most cases, to prevent the movement of the steel angle. Case-hardened, solid-steel rods with 1 in diam were used successfully to secure the steel angle during the testing of the solid-concrete-block and Omega block seal designs. This bolting arrangement was of sufficient strength to secure the steel angle for all of the explosion tests with pressure pulses ranging up to 42 psig. Therefore, if this procedure is ever to be used in underground coal mines in place of hitching into the solid, 24-in long by 1-in-diam case-hardened steel rods (imbedded 18 in) on 18-in centers are to be used.

Without being subjected to convergence forces from the roof, ribs, and/or floor, all but one of the 6 tested crib-block seal designs were considered of adequate design strength to withstand a 20-psig pressure pulse. The one design that failed to withstand the pressure pulse was the typical crib-block and rock-dust seal design that is used currently in many mines. All of the wood-block seal designs failed to meet the tentative criteria for postexplosion impermeability in the absence of mine convergence forces. However, it is the judgement of MSHA that all of the modified wood-block convergence seal designs did meet the strength requirements of the CFR and would have exhibited acceptable postexplosion leakage rates if the restraint mechanism had not failed. Additional research is still needed to finalize a preexplosion and postexplosion air-leakage criteria. Research will also continue in the design and full-scale testing of convergence seals that can withstand a 20-psig pressure pulse in the absence of convergence forces from the roof and/or ribs.

CONCLUSIONS

Four types of seal construction materials were explosion and air-leakage tested in the LLEM. The tests were designed primarily to determine the strength characteristics of the seal designs. Each seal design was evaluated as to its ability to withstand a pressure pulse of at least 20 psig while still maintaining those features that provide resistance to air leakage.

As first noted in previous reports,. seven seal designs using solid-concrete blocks were tested in the LLEM. Only the standard-type seal passed the explosion and tentative air-leakage criteria. The standard-type seal is a 16-in-thick wall consisting of solid-concrete blocks staggered and mortared utilizing a center pilaster and keying at the floor and ribs. Eliminating any one of the above design parameters results in a seal design that fails the testing criteria. Four seal designs constructed with low-density foam blocks (Omega 384) were then tested. All four of the seal designs withstood the pressure pulse while three of the four maintained acceptable air-leakage rates. An additional materials handling benefit is realized in that the weight of the low-density foam block is significantly less than that of a similarly sized concrete block.

Nine cementitious foam seal designs of varying thicknesses and densities were tested in the LLEM. Six of the nine designs successfully survived the explosion overpressures and subsequent air-leakage evaluations. To avoid collapse of cementitious foam seals during installation and possible injury to workers, both sides of the seal need to be braced to offset lateral forces. Extension pipes should be attached to the injection hose to provide additional protection. Stuffing brattice material or rags along the ribs and roof aids in topping off the cementitious seals and in reducing air leakage through the cured seal. Seals constructed with cementitious foam, regardless of the cementitious foam's manufacturer, with a minimum compressive strength of 200 psi and a minimum thickness of 4 ft have been approved by MSHA for use in underground coal mines. Cementitious foam seals require significantly less worker-hours to install than conventional concrete block seals.

Six wood-block convergence seals also have been tested in the LLEM. The typical 3-ft-thick, wood-block seal design used currently in many coal mines did not maintain its integrity following the explosion test. Newly erected crib-block seals as currently used in mines offer little explosion protection. Convergence in actual underground coal mines may increase the strength characteristics of this wood-block seal. The five modified wood-block seal designs successfully withstood the 20-psig pressure pulse. It is the judgement of MSHA that all of these modified wood-block designs would have exhibited acceptable post-explosion air-leakage resistance given an adequate restraint system. Convergence may increase the air-leakage resistance of the wood block seal designs.

Based on the recent tests conducted in the LLEM, three alternative seal construction materials have been approved for use in underground coal mines by MSHA. In addition to the solid-concrete-block seals, mine operators can construct seals using cementitious foam, low-density foam block (Omega 384), or wood. These seals meet the CFR standards.

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*U.S.G.P.O.: 1993--709-008/80039

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