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Leakage and Performance Characteristics of Large Stoppings for Room-and-Pillar Mining

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UNITED STATES DEPARTMENT OF THE INTERIOR

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CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cfm	cubic foot per minute	in	inch
cfm/ft^2	cubic foot per minute per square foot	in w.g.	inch, water gauge
ft	foot	lb	pound
ft^2	square foot	pct	percent
ga	gauge	s	second

LEAKAGE AND PERFORMANCE CHARACTERISTICS OF LARGE STOPPINGS FOR ROOM-AND-PILLAR MINING

By Edward D. Thimons,[1] Carl E. Brechtel,[2] Marvin E. Adam,[3] and Joseph F. T. Agapito[4]

ABSTRACT

This report presents a Bureau of Mines study comparing the construction costs, leakage measurements, and predicted performance of different types of large stoppings built and tested in a room-and-pillar oil-shale mine. The six full-sized structures (30 ft high by 55 ft wide) included both permanent and temporary stoppings and were fabricated using materials ranging from structural steel to coated brattice cloth. Leakage across each stopping was measured at differential pressures ranging up to 1.0 in w.g., using both the brattice window method and sulfur hexafluoride (SF_6) tracer gas. Blast air pressures resulting from a full-scale face blast of approximately 1,800 lb of ammonium nitrate-fuel oil (ANFO) explosives were measured across two of the stoppings and the pre- and post-leakage rates were compared for all the stoppings.

Overall performance of the stoppings for production applications was evaluated using an operational model of a two-panel oil-shale mine. Different combinations of temporary and permanent stoppings were evaluated based upon ventilation performance and construction and operating costs.

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INTRODUCTION

Ventilation air requirements for large room-and-pillar mining operations in oil shale are projected to range up to 6 million cfm to provide effective dilution of diesel and blasting fumes and to handle potential methane liberated due to mining operations. The cost of ventilating the mine will be substantial, and optimization of the control of airflow by ventilation control structures (stoppings, overcasts, and doors) has been recognized by the industry as an important parameter in providing cost efficient and effective ventilation. Two characteristics of oil-shale mining operations combine to make underground ventilation control problems somewhat different from current industrial practice--

High mining rates in-panel lead to localized production of large quantities of air pollutants requiring sizable volumes of fresh air for effective dilution at the face.

Planned large openings complicate the construction of effective ventilation control structures.

Leakage across the ventilation control structures must be minimized so that optimum use of most of the ventilation air can be achieved.

The need for cost-effective and reliable construction techniques for stoppings, doors, and overcasts led members of the industry to sponsor an engineering study involving cooperation among the Colorado Mining Association, the Bureau of Mines, and the Department of Energy. The primary tasks of the study consisted of--

Technical review of currently applied techniques and materials;

Design of candidate systems and selection of systems for field testing; and

In-mine construction and measurements of leakage.

Six full-sized stoppings were built and tested in the Colony Oil Shale Mine with the cooperation of Exxon Company, USA.

DESIGN AND SELECTION OF STOPPINGS FOR FIELD TESTING

Review of the requirements of the sponsoring oil-shale mining companies for stoppings helped establish design guidelines that were utilized in the project. The guidelines were as follows and provided general direction in the development of designs for the candidate systems:

1. Minimum opening size requirements were 25 by 40 ft.
2. Maximum blast pressure requirement was 1.5 in w.g.
3. Acceptable leakage was 5,000 cfm.
4. Maximum static pressure requirement was 1.5 in w.g. for permanent stoppings and 0.5 in w.g. for temporary stoppings.
5. Materials had to have flame-spread rates consistent with approved materials currently used underground and, where possible, it was desirable to use native materials (mine waste or oil shale).

Using these design guidelines, a series of stopping designs was developed and submitted to a technical review committee for selection of the systems for field demonstration. The systems and their ranking for selection are described in detail by Adam (1).[5] The stopping designs presented to the committee are listed in table 1, where they are classified as temporary or permanent, along with whether they were selected for testing.

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

TABLE 1. - Stopping designs proposed for oil-shale mines

	Type
Stoppings selected for testing:	
Brattice and wire mesh...........	T
Damage-resistant brattice........	T
Muckpile.........................	P
Muckpile with brattice...........	T
Pipe with metal sheeting.........	P
Transformable brattice...........	P
Rejected concepts:	
Concrete lay-up panels...........	P
Metal lay-up panels..............	P
Styrofoam blocks with sealant....	T
Telescoping steel panels.........	P

P Permanent. T Temporary.

The materials selected for use in these stopppings are materials generally found in underground mining. Flammable materials were limited as much as possible and brattices were of approved materials. The use of mined oil shale for stopping construction was regarded by mine operators as desirable, but oil shale is flammable, and this should be considered in its use. Several selected stoppings used rigid expansive foam to some degree. While this foam is considered fire resistant, it still presents some potential hazard. It would be desirable to replace the foam with a nonflammable sealant, but no such substitute was located for this test program.

DESCRIPTION OF THE TEST STOPPINGS

The materials and techniques used to construct the test stoppings are discussed in this section, with construction drawings of the final installations. Detailed discussion of the construction was reported by Adam (1).

PIPE AND SHEETING STOPPING

The pipe and sheeting stopping is shown in figure 1. The structure was formed on telescoping, 5- and 6-in square section steel tubes set in holes in the floor and attached to angle iron anchored in the back with resin bolts. Panels of 16-ga corrugated, galvanized steel sheets then were attached using self-tapping screws. The perimeter and all sheeting edges were sealed with rigid, fire-resistant, expansive foam.

BRATTICE AND WIRE MESH STOPPING

The brattice and wire mesh stopping, shown in figure 2, was constructed of damage-resistant brattice cloth, pressed between layers of 12-ga chain-link fence. The brattice was a fiberglass mesh coated with vinyl, standard for underground application. The vertical edges were sealed with Velcro[6] fasteners at the seams and the wire fencing was attached to an angle iron that was anchored into the roof and floor with resin bolts. The edges of the chain-link fencing were wired together, and both the perimeter and all brattice seams were sealed with rigid, fire-resistant, expansive foam.

MUCKPILE STOPPING

The muckpile stopping is shown in figure 3. Mined oil shale was placed in the opening by using a front-end loader and shaped with a small bulldozer to within 6 ft of the back. A pneumatic stowing machine then was used to fill the final 6 ft with oil shale screened to minus 3 in. The pile settled approximately 1 to 2 in between construction and testing. This gap was sealed with rigid, fire-resistant, expansive foam just prior to the tests.

[6]Reference to specific products does not imply endorsement by the Bureau of Mines.

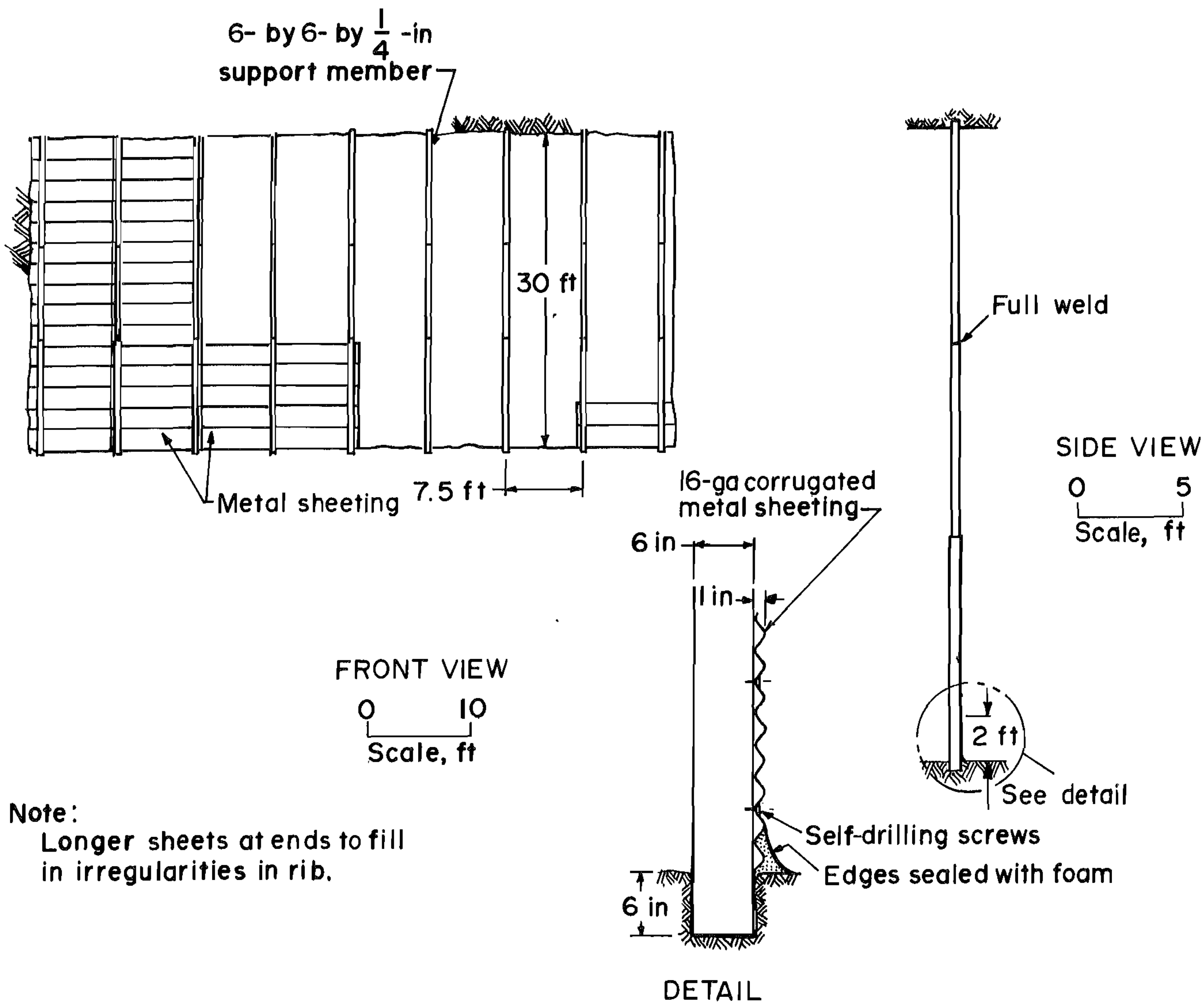

FIGURE 1.—Pipe and sheeting stopping.

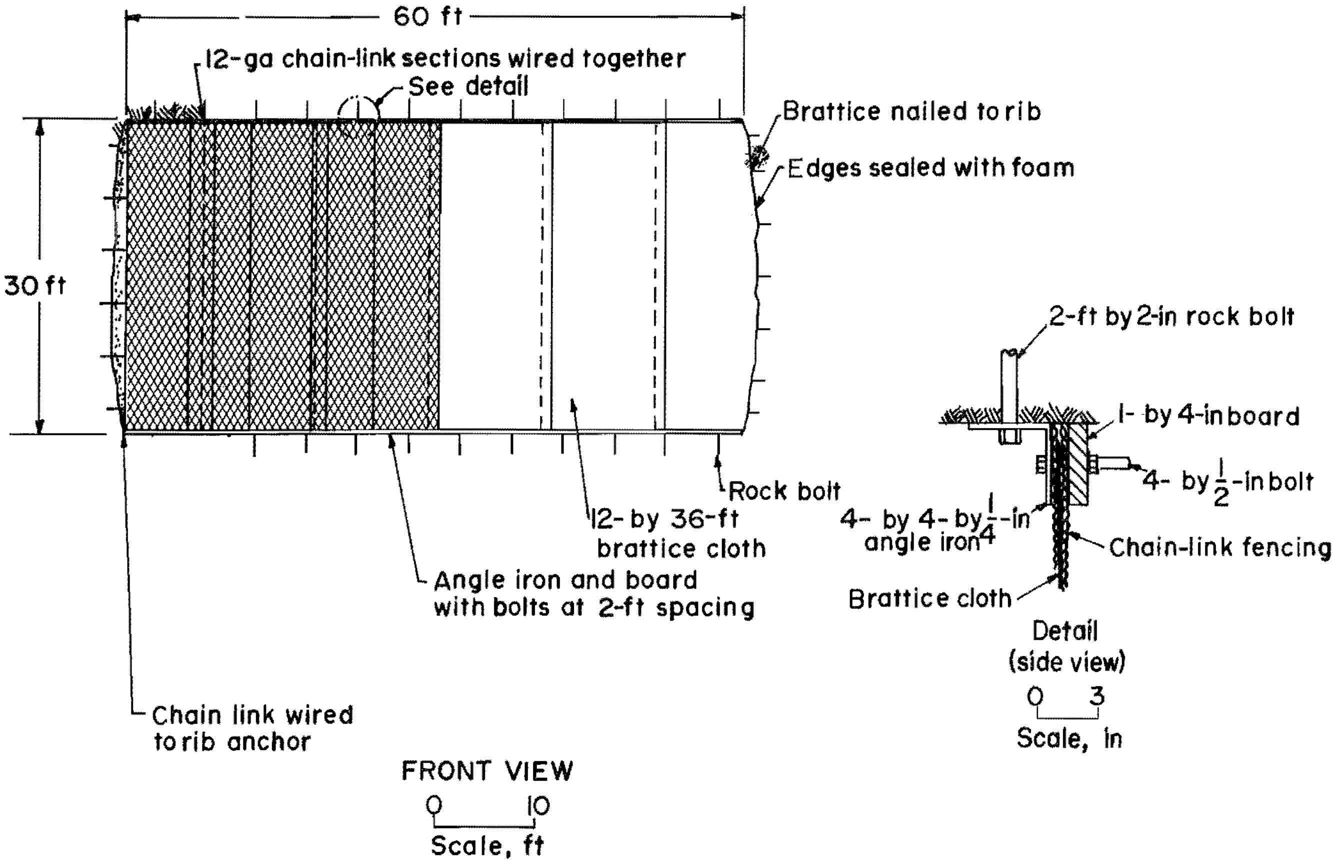

FIGURE 2.—Brattice and wire mesh stopping.

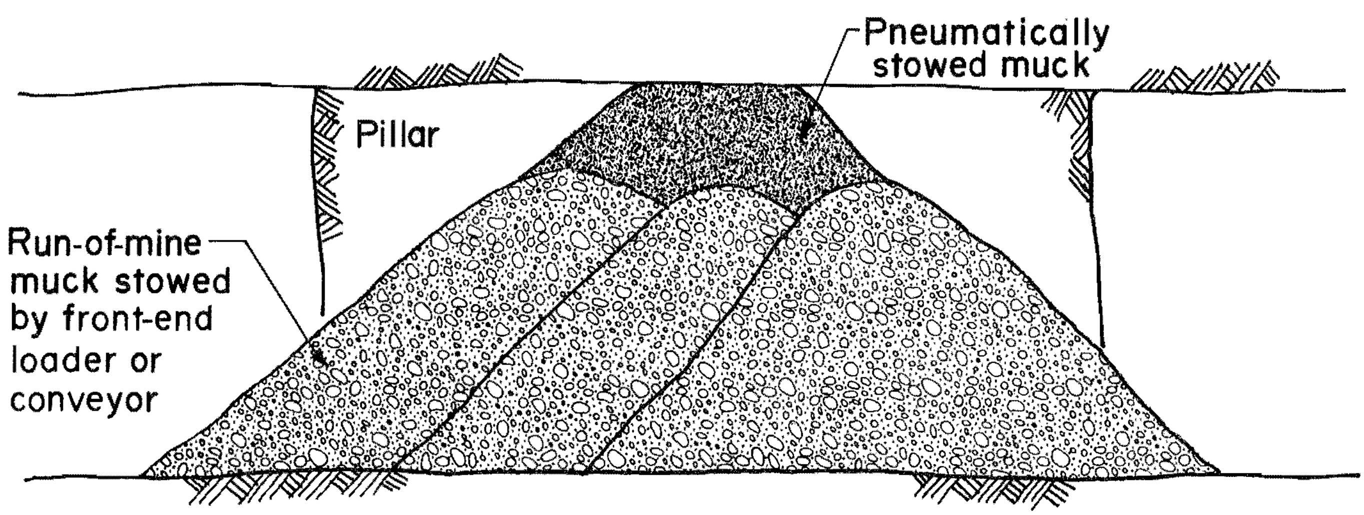

FIGURE 3.—Muckpile stopping.

TRANSFORMABLE STOPPING

The transformable stopping, shown in figure 4, was intended to provide a method of changing a temporary brattice stopping into a permanent stopping. The damage-resistant brattice was hung across the drift attached to 2- by 4-in boards anchored to the roof by expansion bolts. Frames of 6-in channel iron, 12 ft wide, were fabricated on the ground with 12-ga, chain-link fence on one side. These panels were placed against the brattice (on the low-pressure side) and anchored to the roof and floor with resin bolts. The chain link and brattice were secured at the rib using ram set, masonry nails, and the wire mesh was then sprayed with rigid, fire-resistant, expansive foam.

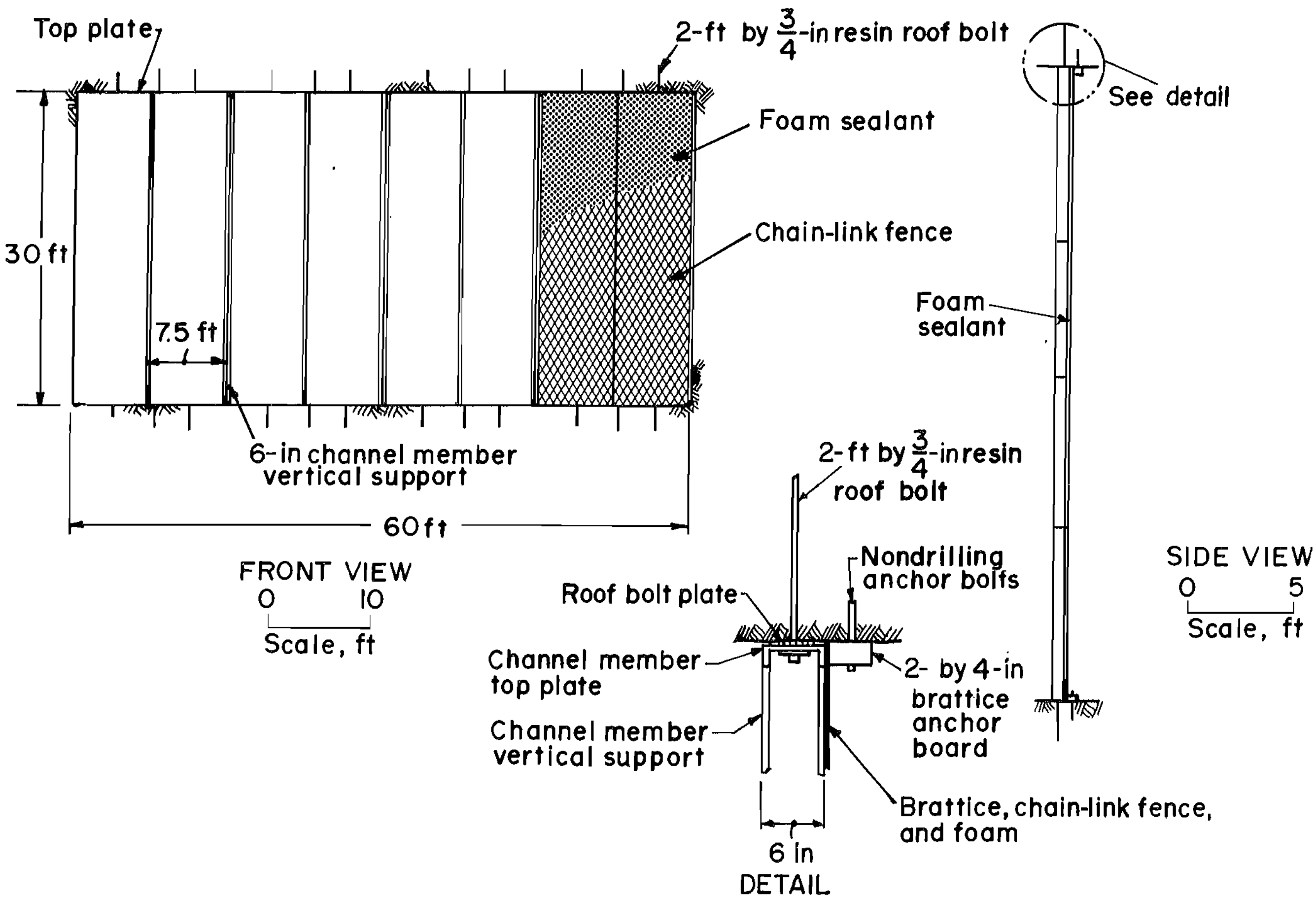

FIGURE 4.—Transformable stopping.

DAMAGE-RESISTANT BRATTICE STOPPING

The damage-resistant brattice stopping, shown in figure 5, consisted of 10-ft-wide panels of fiberglass mesh cloth covered with vinyl. The vertical seams were secured with Velcro fasteners. The brattice was wrapped around a 2- by 4-in board anchored to the roof with expansion bolts and attached to the rib using ram set masonry nails, with a 2-ft flap at the floor weighted down with large pieces of oil shale. The perimeter, excluding the floor, was sealed with rigid, fire-resistant, expansive foam.

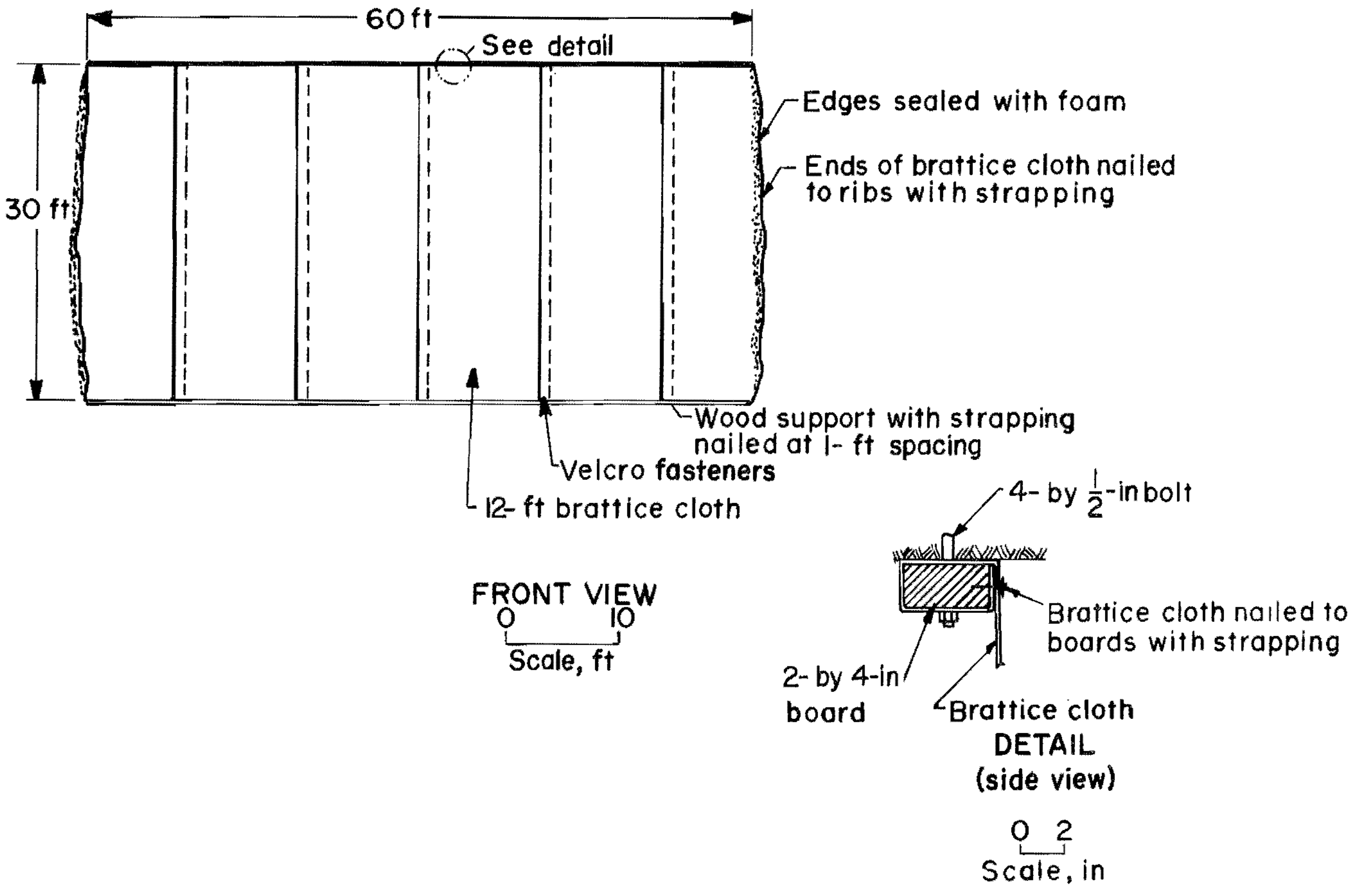

FIGURE 5.—Damage-resistant brattice stopping.

MUCKPILE AND BRATTICE STOPPING

The muckpile and brattice stopping is shown in figure 6. Mined oil shale was piled across the drift to within 15 ft of the roof. A damage-resistant curtain then was used to close the remainder of the opening. The brattice was wrapped around 2- by 4-in boards attached to the roof with expansion bolts and attached to the rib using ram set masonry nails. The sides and roof were sealed with rigid, expansive foam. A 2-ft flap of material at the bottom was sealed against the floor with large pieces of oil shale.

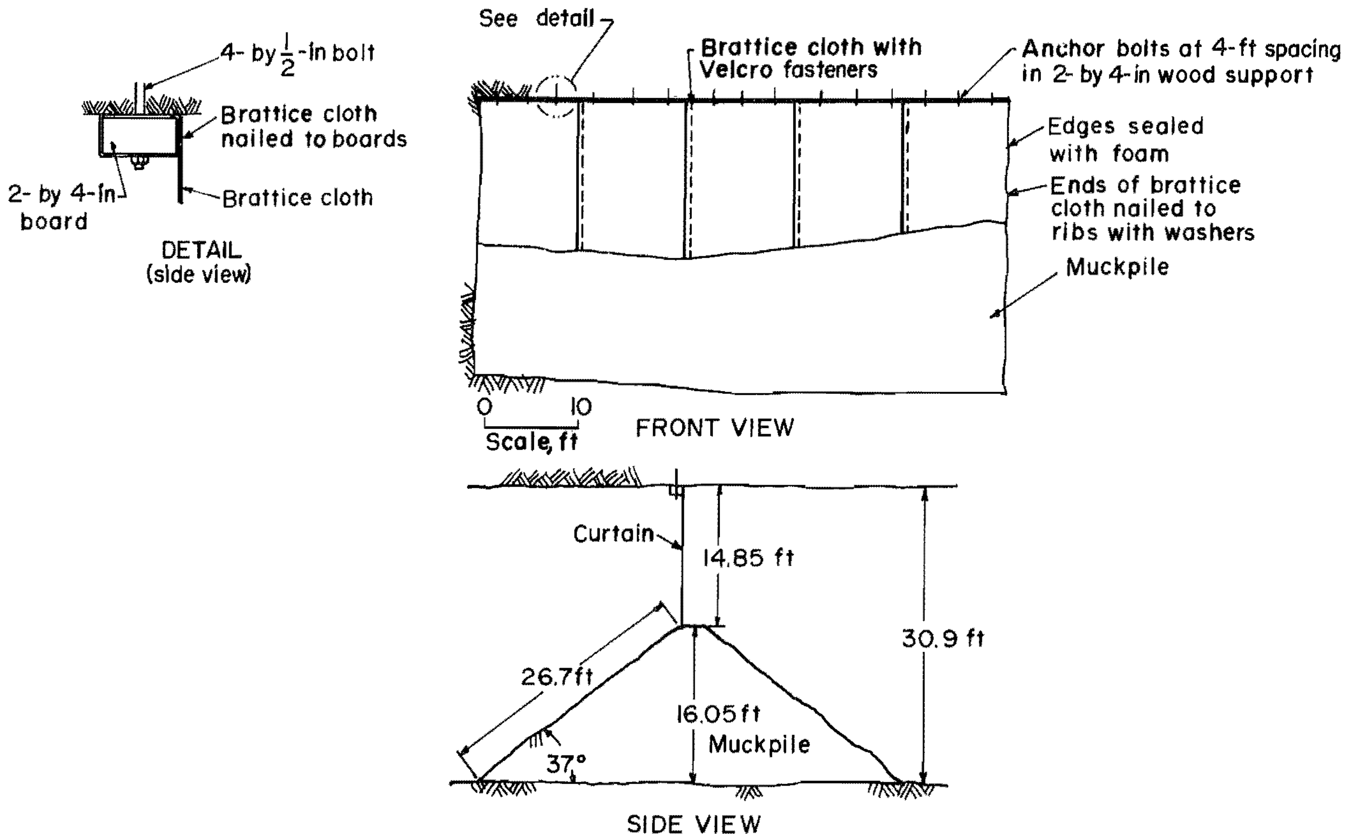

FIGURE 6.—Muckpile and brattice stopping.

FIELD MEASUREMENTS OF STOPPING LEAKAGE

The locations of the six stoppings erected in the Colony Mine are shown in the map in figure 7. The leakage rates of each structure were measured at different pressures soon after construction, and again 2 months after construction, to determine if leakage would increase with time. During this period, a full face blast experiment was conducted at the Colony Mine, and blast air pressures were measured across two of the stoppings. The test structures supported a differential pressure only during the leakage testing and blast testing; otherwise, they were not subjected to duty cycles representative of long-term active mining operations. The leakage rates measured are therefore more representative of stoppings in a relatively new or recently repaired condition.

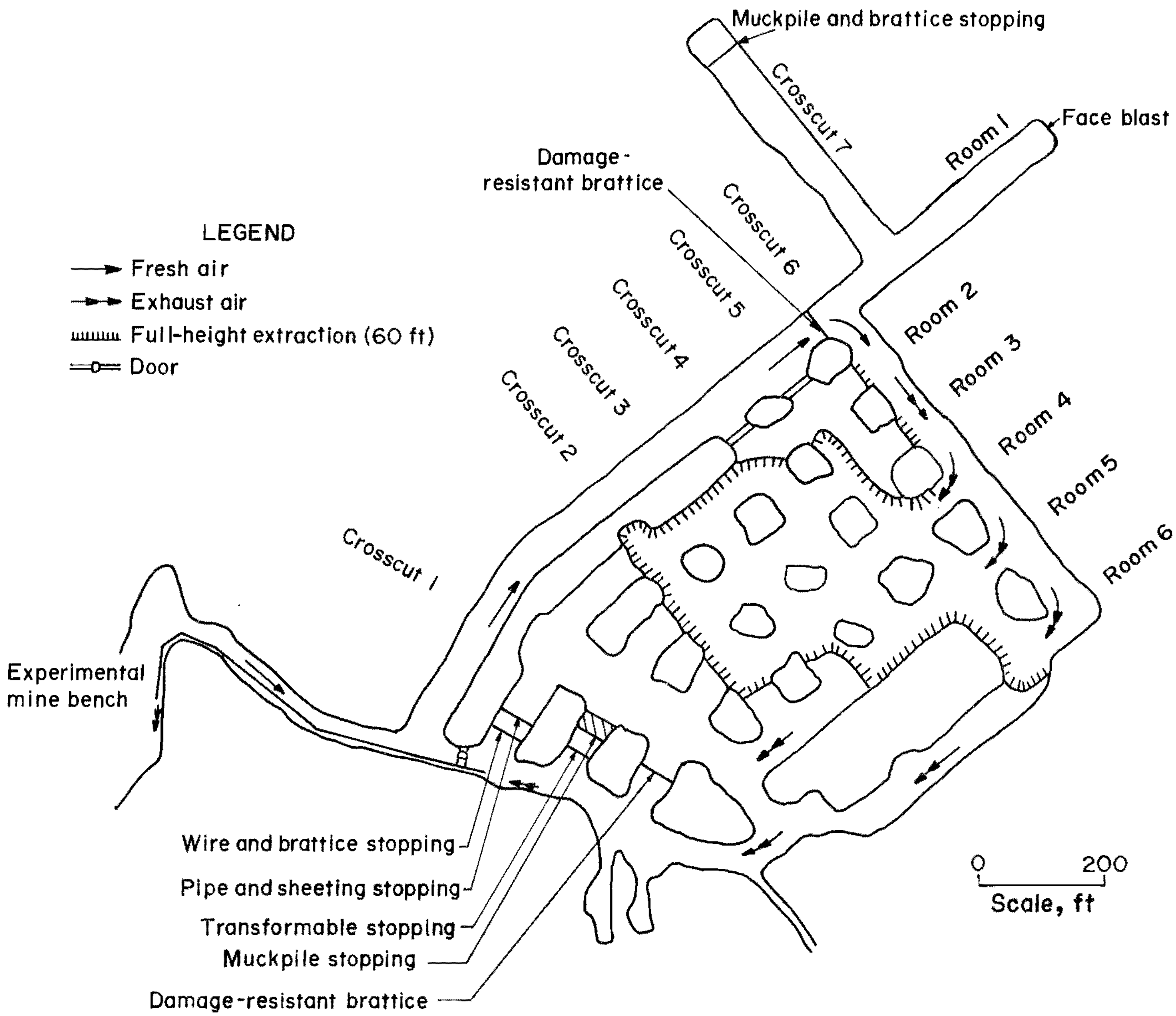

FIGURE 7.—Map of the Colony Mine showing stopping locations.

LEAKAGE TESTING TECHNIQUES

The leakage of each of the structures was measured by creating a differential pressure across the stopping and measuring the flow of escaping air. The techniques, developed by the Bureau of Mines, are reported by Vinson (2), and by Timko (3), and are illustrated in figure 8 which shows the experimental setup used to test stoppings built back-to-back. A pressure difference was created across the structures by injecting air at a constant flow rate into the volume between the two stoppings. Air leaked past each of the stoppings at a rate governed by the leakage area and the pressure difference. The flow rate of the leaking air was measured at the check curtains using both SF_6 tracer gas (3) and the brattice window method (2). Since these techniques are described in detail elsewhere, the discussion here will be limited to presentation of the results.

CHARACTERIZATION OF LEAKAGE VERSUS DIFFERENTIAL PRESSURE

Leakage rates for each structure were measured at different pressures to develop a relationship to extrapolate the experimental data in general applications at different pressures. An equation proposed by Kawenski (4) was found to predict the pressure dependence accurately and, therefore, was used to analyze the data. Equation 1 was fit to the experimental data using its log-linear form by developing a linear least-square curve fit of the leakage at various pressures.

$$Q = aP^N, \tag{1}$$

where Q = normalized leakage (cfm/ft^2),

a = an experimental coefficient,

N = an experimental coefficient,

and P = pressure difference (in w.g.).

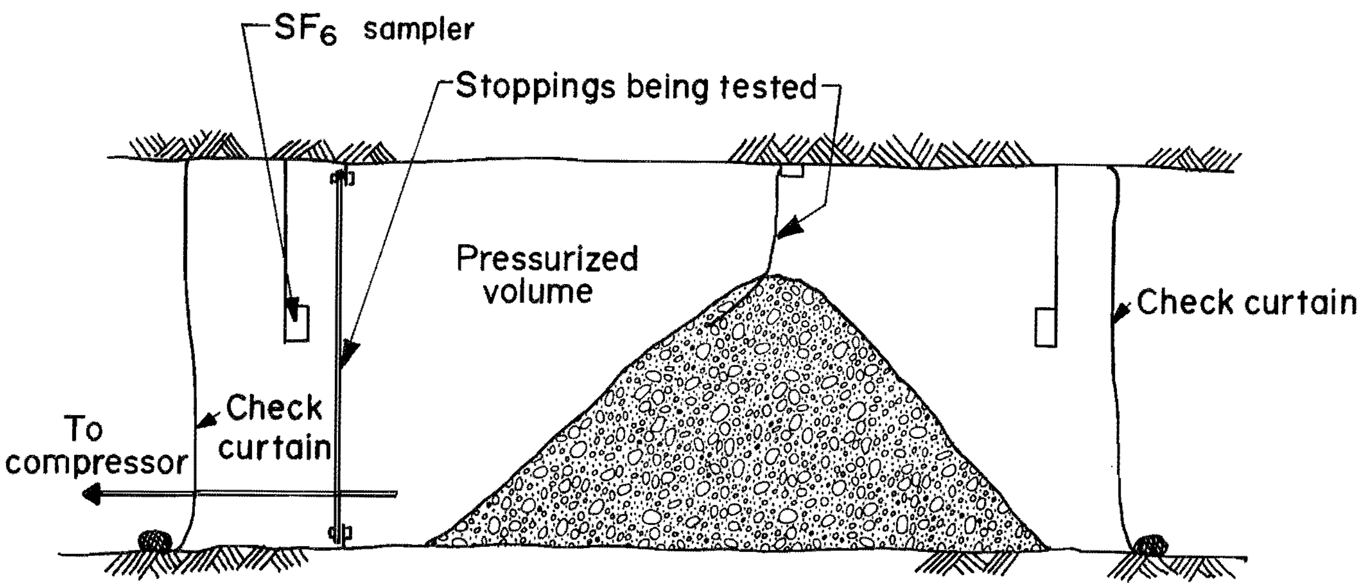

FIGURE 8.—Schematic illustrating tracer gas measurement of leakage through two stoppings built back-to-back.

The preblast measurements of leakage were made using a combination of the SF_6 tracer gas measurements and brattice window measurements. The tracer gas was used exclusively to measure leakage of the pipe and sheeting stopping and the brattice and wire mesh stopping. Both techniques were used for the damage-resistant brattice and muckpile and brattice stoppings, while the brattice window method was used exclusively for the transformable and muckpile stoppings. All post-blast measurements were made using the brattice window method.

The pressure dependence of the leakage is illustrated by the comparison in figure 9, which shows the normalized leakage versus differential pressure. The pipe and sheeting stopping has the lowest leakage, followed by the damage-resistant brattice, brattice and wire mesh, and transformable stopping. The muckpile and brattice and muckpile stoppings have the greatest leakage.

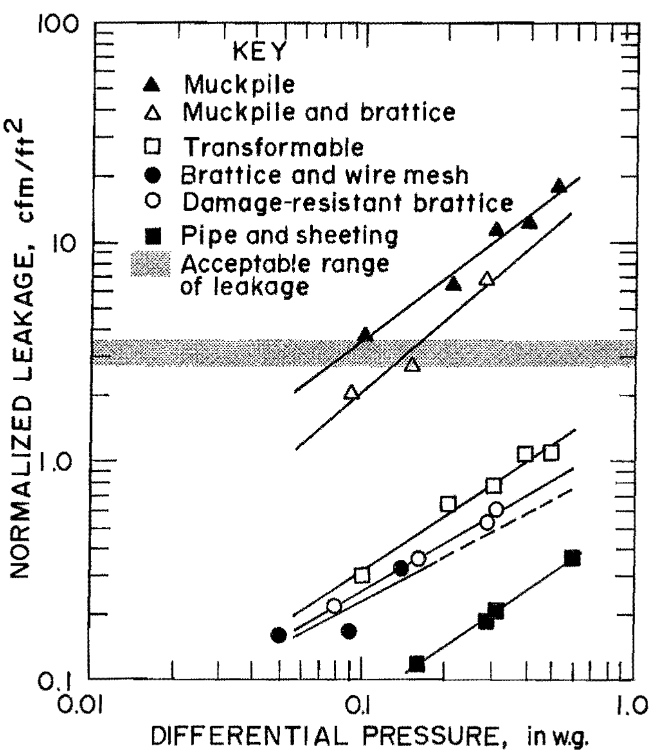

FIGURE 9.—Normalized leakage for newly built stoppings.

The results are compared with the acceptable leakage specification of 5,000 cfm developed from the survey of oil-shale companies. The 5,000-cfm specification is assumed to be a per unit limit and is divided by the range in the area of the test stoppings to give a range of 2.7 to 3.7 cfm/ft^2 in normalized leakage. The range is shown in figure 9 and indicates that all of the structures except the muckpile and muckpile and brattice stoppings easily meet the specification for pressures up to 1.0 in w.g. The leakage rates of the muckpile, and those of the muckpile and brattice stoppings almost meet the specifications at the pressure of 0.1 in w.g., which is expected to be typical in-panel pressure for these large sizes. If stopping size is reduced to 1,000 ft^2 (25 by 40 ft), the curves suggest that the muckpile and the muckpile and brattice have acceptable leakage for the low-pressure applications.

The total differential pressure capabilities of each structure are different, depending upon construction materials. The pressure capability is defined to be the maximum pressure that the structure can withstand before some type of permanent deformation results, causing the leakage behavior to depart from the log-linear form of equation 1. The pressure limits of the pipe and sheeting, transformable, and muckpile stoppings were not reached during the testing and are estimated to be greater than 1.5 in w.g. The damage-resistant brattice, and the muckpile and brattice stoppings lost their floor seal at approximately 0.1 in w.g and 0.2 in w.g., respectively. In both cases, the flap of extra floor material was dragged from under the rocks used to weight it down. The brattice and wire mesh stopping apparently failed during preblast measurements when a rock anchor at the roof pulled free at approximately 1.0 in w.g.

Although the transformable stopping had more extensive sealing than either the damage-resistant brattice or brattice and wire mesh stoppings, its leakage rate was greater. This was attributed to local rock conditions around the perimeter where the rib was more irregular and may have allowed air to leak around the stopping.

The results of the preblast and post-blast measurements are compared graphically in figure 10 to show effects of the blast on stopping leakage. The results of fitting equation 1 to each of the data sets are presented in table 2 for both the preblast and post-blast. The indices of determination, with the exception of the damage-resistant brattice, are very high indicating a good correlation between the data and the curves. The leakage-rate measurements are considered reproducible in view of the accuracy of the two techniques of measurement. The data-scatter and best-fit equations are similar for the pipe and sheeting, transformable, and muckpile stoppings. The leakage for the brattice and wire mesh stopping was reduced in the post-blast measurements because of repairs due to the damage that resulted from initial testing at higher pressure, but the general trend of the leakage

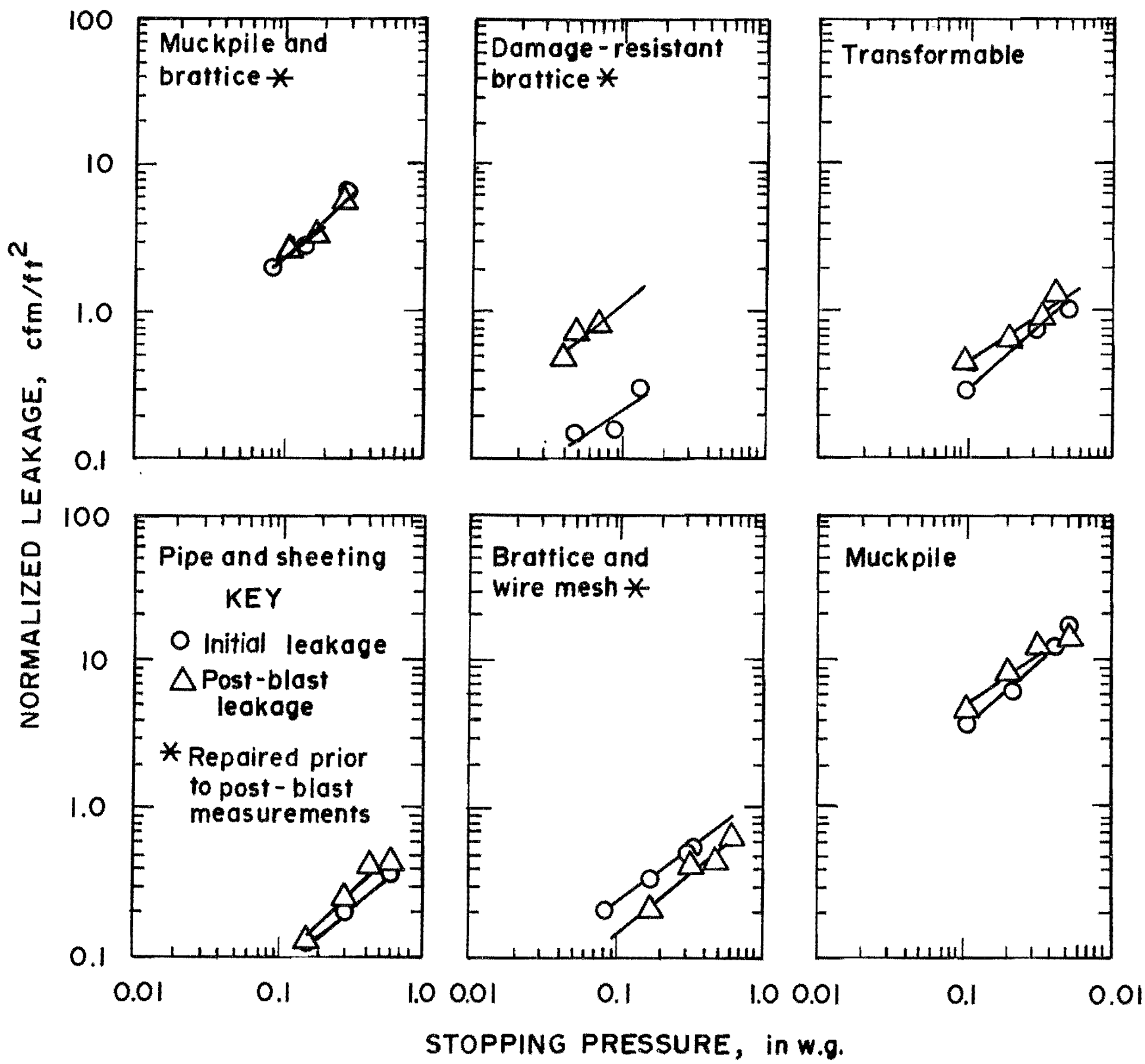

FIGURE 10.—Comparison of leakage for newly built and post-blast stoppings.

TABLE 2. - Coefficients of leakage equation for preblast and post-blast conditions

Type of stopping	Best fit to equation $Q = aP^N$				Index of determination	
	a		N			
	Preblast	Post-blast	Preblast	Post-blast	Preblast	Post-blast
Pipe and sheeting.	0.57	0.82	0.86	0.99	1.00	0.98
Brattice and wire mesh.............	1.36	.99	.72	.80	.99	.96
Muckpile..........	32.14	25.72	.95	.70	.97	.96
Transformable.....	2.20	2.39	.84	.72	.98	.97
Damage-resistant brattice.........	1.08	8.12	.67	.83	.74	.79
Muckpile and brattice.........	24.49	18.86	1.07	.94	.94	.97

a and N Experimental coefficients. Q Normalized leakage, cfm/ft^2.
P Pressure difference, in w.g.

remained the same. The brattice portion of the muckpile and brattice stopping was entirely rebuilt because of the damage caused by the blast; however, the leakage rate was virtually the same between the two sets of measurements.

The leakage of the damage-resistant brattice was significantly higher after the blast. In this case, resealing the Velcro fasteners after the blast was difficult because of the misalignment of some panels. It is expected that the original leakage rates can be restored in the general use of damage-resistant brattice; however, actual leakage will be largely dependent upon the care with which personnel reseal the seams. It can be expected that generally higher leakage will result from damage-resistant brattices that are subject to extensive resealing due to blasting or passage of equipment. The fact that the Velcro fasteners on the damage-resistant brattice in room 4 parted as a result of the shot located 1,500 ft away indicates that methods to transform brattice curtains into more rigid structures (wire-mesh reinforcement) are needed to reduce maintenance due to blasting after the face has moved a good distance. Otherwise, the brattice panels will need to be resealed along the seams after each shot.

BLAST PRESSURE CHARACTERIZATION

An experimental full face round (1,800 lb ANFO) was detonated at the end of room 1, as indicated in figure 7. The blast occurred at a distance of 700 ft from the muckpile and brattice stopping, and approximately 1,500 ft from the other five stoppings. None of the test stoppings were in direct line with the shot; however, an additional damage-resistant brattice was hung in room 1 to test survivability due to a direct blast pressure pulse.

Differential pressure transducers were installed on the pipe and sheeting stopping and the transformable stopping as illustrated in figure 11 to measure peak blast air pressures. The transducer output was recorded on a light-beam recorder to give sufficient resolution of the

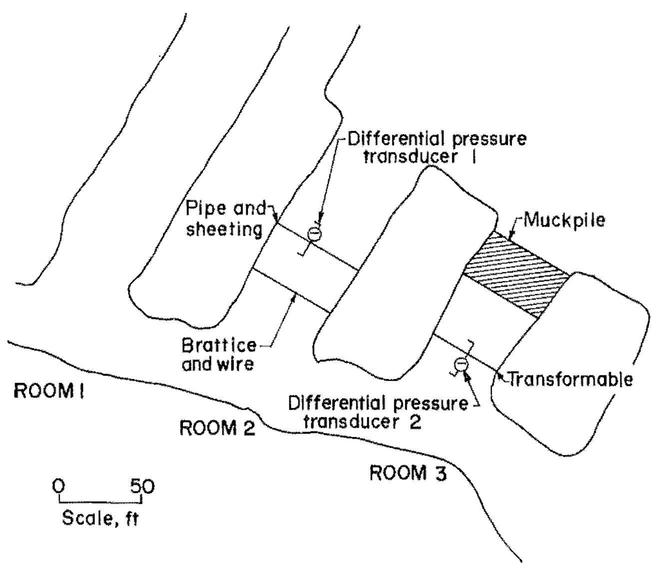

FIGURE 11.—Location of differential pressure gauges.

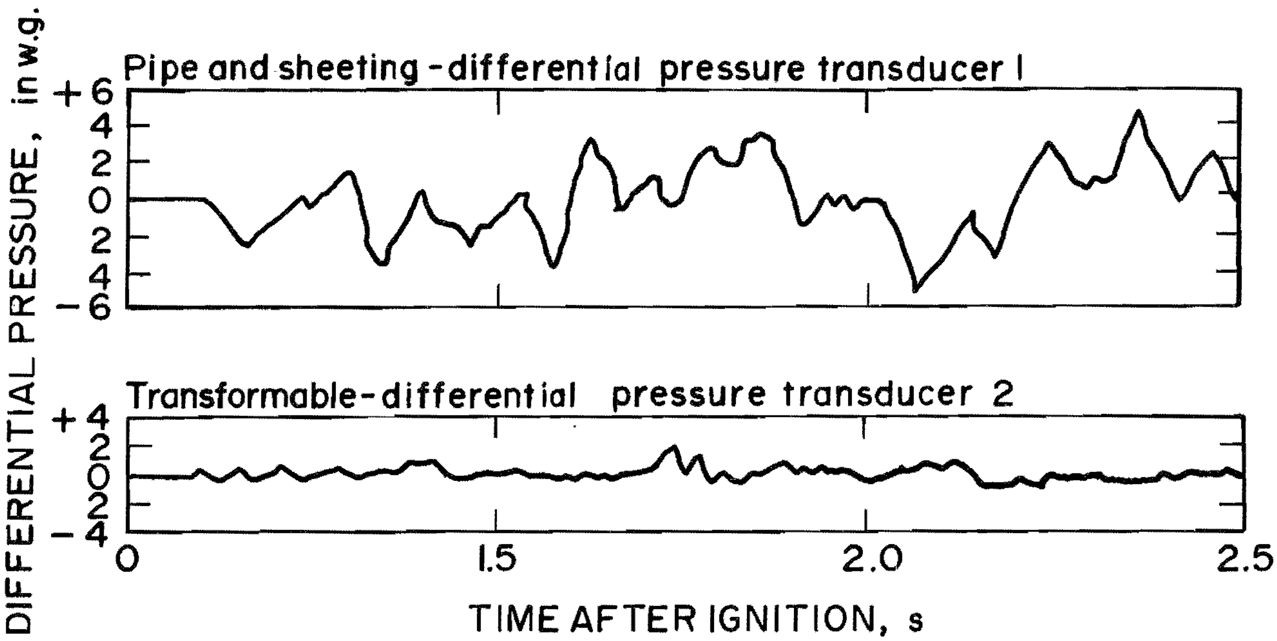

FIGURE 12.—Air blast pressure record measured across stoppings during blasting.

blast-produced air pulses on the time axis. Records of the blast air pressure with time are presented in figure 12. The pressure records indicate that the blast pressure arrived on the pipe and sheeting side of the structures with greater pressure than on the transformable side. The differential pressure oscillates partly due to the flexibility of the stoppings and reached a peak value of 4.2 in w.g., approximately 2.4 s after the blast. The peak pressure on the transformable stoppings was 2.3 in w.g., approximately 1.7 s after the blast. Another pressure transducer, within 300 ft of the blast and located in room 1, measured 41.5 in w.g.

Examination of all the stoppings after the blast indicated that only the muckpile and brattice stopping suffered permanent damage. The brattice had blown off the boards at the roof and was thrown towards the end of crosscut 7, with the board headers broken between anchors.

The Velcro fasteners of the damage-resistant brattice in room 4 parted as designed, and the bottom pulled free of the rock holding the bottom flap against the floor. High-speed motion pictures of the damage-resistant brattice located in room 1 indicated that the seams all parted, and that individual panels flapped back and forth, reaching as high as the roof. The Velcro fasteners partially resealed themselves, and the stopping survived the air blast. This type of temporary damage was easily repaired by resealing the Velcro fasteners.

COMPARISON OF PROJECTED STOPPING PERFORMANCE

The selection of stoppings to be used in oil-shale mining should be based upon optimization of the leakage rate, capital cost, and durability to evaluate overall performance. A ventilation performance and cost model was developed to simulate a two-section room-and-pillar oil-shale mine and to evaluate the effects that various combinations of permanent and temporary stoppings would have on total air requirement. The incremental cost was for ventilation due to leakage of the stoppings then estimated and added to capital and operating costs based upon the costs developed during the in-mine construction to develop a monthly cost comparison. A detailed description of this model is provided by Adam (1).

The cost and performance model was exercised using various combinations of permanent and temporary stoppings. The resulting monthly costs for the two-section operation include the effects of the different total leakage resulting from using different stoppings. Table 3 compares the total leakage and monthly cost of the different combinations and shows the variance in percent normalized to the lowest cost-leakage combination. The lowest cost-leakage combination has a variance of 100 pct. This comparison is shown graphically in figure 13 where the variance from the best performing combination of stoppings is presented for both cost and ventilation performance. Figure 13 shows large differences in ventilation performance (total leakage); however, leakage is only one variable in the cost performance and its effect is highly buffered by capital cost and maintenance cost.

Using brattice and wire mesh in both the mains and panels is the most attractive economically; however, there is some question about whether it represents a substantial enough structure for a permanent stopping. Both second- and third-ranked combinations have the same drawback. The optimal combination is to use the pipe and sheeting stopping in the main entries as a permanent stopping, with the brattice and wire mesh in-panel. This combination ranks fourth cost-wise, with a monthly cost of 16 pct more than the lowest cost. The pipe and sheeting stopping has the additional advantages of good durability and noncombustibility. The leakage performance of the pipe and sheeting and brattice and wire mesh combination is very good, and is only 20 pct greater than pipe and sheeting exclusively.

TABLE 3. - Two-section total cost and leakage comparison

Type of stopping		Monthly costs	Cost variance, pct	Total leakage, cfm	Leakage variance, pct
Mains	Panels				
BWM	BWM	$14,031	100	9,280	234
BWM	PS	15,378	110	8,450	213
BWM	DRB	15,766	112	19,120	483
PS	BWM	16,222	116	4,760	120
BWM	MB	16,422	117	22,680	573
BWM	Muck	16,880	120	65,210	1,647
PS	PS	17,572	125	3,960	100
BWM	Trans	17,602	125	12,450	314
PS	DRB	17,929	128	14,260	360
PS	MB	18,571	132	17,630	445
PS	Muck	18,888	135	58,710	1,483
PS	Trans	19,784	141	7,830	198

BWM Brattice and wire mesh.
DRB Damage-resistant brattice.
MB Muckpile and brattice.
Muck Muckpile.
PS Pipe and sheeting.
Trans Transformable.

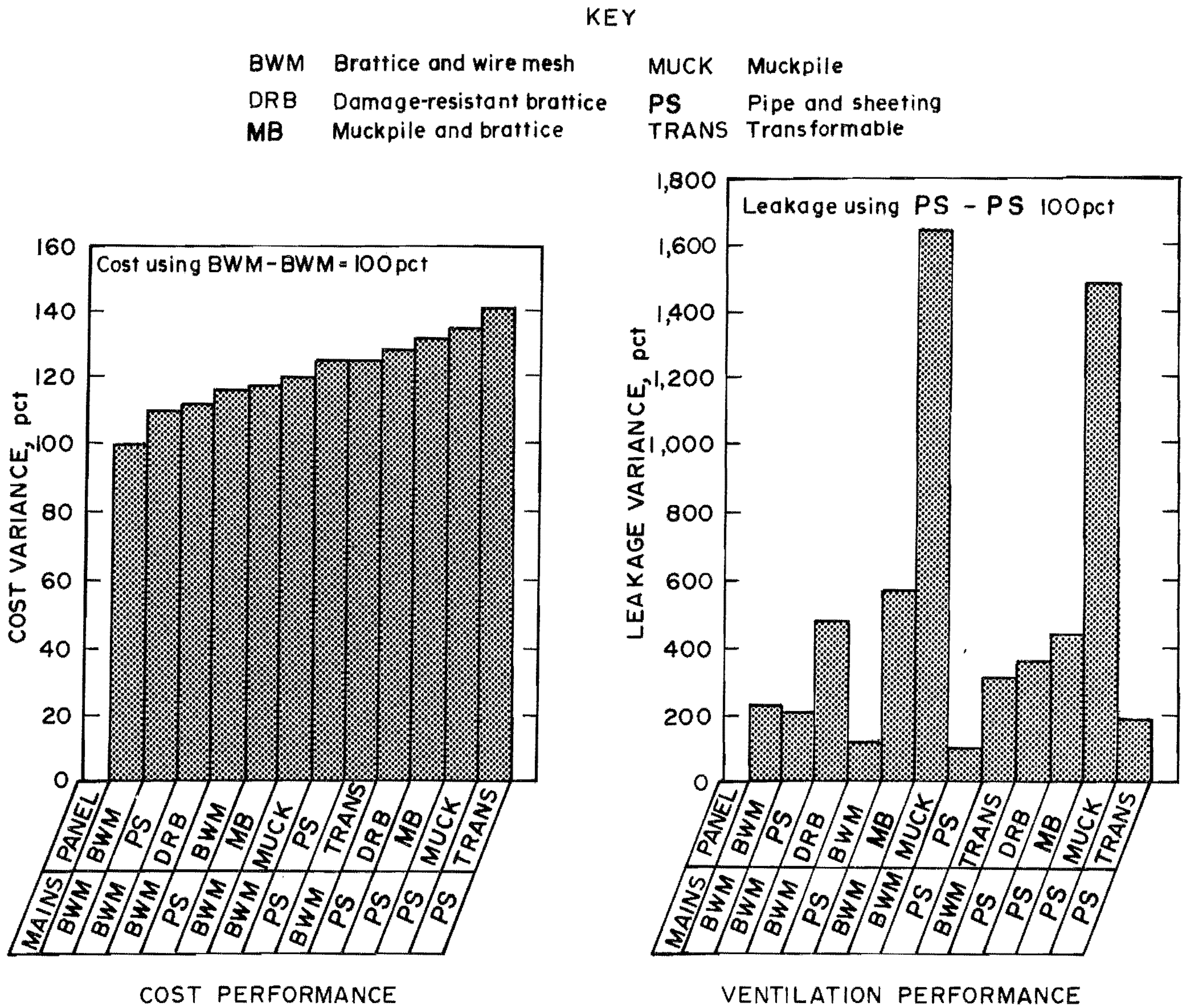

FIGURE 13.—Comparison of cost and ventilation performance of various stopping combinations.

CONCLUSIONS

The major conclusions derived from this work were--

The large-sized ventilation control structures required for oil-shale mining can deliver the required low rates of leakage at an acceptable cost.

The stoppings survived peak blast air pressures that ranged between 2.3 and 4.2 in w.g. The pressures were measured across two of the stoppings located approximately 1,500 ft from the blast.

An overall performance assessment, using a model of the ventilation system for a two-panel oil-shale mine and incorporating cost data, indicated that a combination of the brattice and wire mesh stopping, in both main entries and panels, is the most cost-effective stopping. Other combinations with similar cost-effectiveness are brattice and wire mesh in main entries, with either the pipe and sheeting or damage-resistant brattice in the panels, or pipe and sheeting stoppings in the main entries, and brattice and wire mesh stoppings in the panels.

Both the SF_6 tracer gas and brattice window method produced acceptable leakage results. SF_6 gas was an effective way to measure leakage, especially for the lower leakage rates. The brattice window method was especially useful for the higher leakage rates. The brattice window method produced better results than previous testing had shown, because the large size of the stoppings resulted in larger total quantities of air leakage.

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