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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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SPRAY-APPLIED POLYURETHANE FOAM TO INSULATE HEATED ROOMS EXCAVATED IN PERMAFROST

by

K. Robert Dorman[1] and Aldon E. Gooch[1]

ABSTRACT

Spray-applied polyurethane foam was used to insulate the walls of heated rooms excavated in permafrost. The experiment was designed to determine whether polyurethane foam can be sprayed successfully on frozen ground under freezing conditions and to measure the effectiveness of the insulation in maintaining--at elevated temperatures for an extended period--a room excavated in frozen ground.

Two manufacturers' foams were investigated in the laboratory. Subsequently, one of the foams was employed to insulate two small rooms, one in frozen gravel and one in frozen silt, in an experimental tunnel belonging to the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL) near Fairbanks, Alaska. Following insulation, heat was introduced into the two rooms. Heat migration across the insulating barrier into the walls, in addition to wall closures, was monitored over an 8-month period.

The results show that polyurethane foam can be successfully sprayed on frozen ground in below-freezing temperatures. Given this type of insulation, together with winter cold to supercool the surrounding ground, it should be possible to maintain a shaft or heated room in permafrost for several years.

INTRODUCTION

The work described in this report was conducted as a part of the Bureau of Mines Fairbanks Placer project. The goal of the Fairbanks Placer project, a team effort by several Bureau research stations, was to develop, if possible, an economical system for the mining of gold from placers buried in perennially frozen ground (permafrost).

Research at the Spokane Mining Research Laboratory (SMRL) deals with ground support. One of the problems facing SMRL personnel was that of selecting a suitable method of supporting, at elevated temperatures for an extended period, an underground room excavated in frozen ground. Such a room might be

[1]Mining engineer, Spokane Mining Research Laboratory, Bureau of Mines, Spokane, Wash.

needed for housing one of the subsystem operations such as primary washing and recovery. The most promising method of maintaining such a room was to keep it frozen by insulating the walls, back, and sill with a sprayed-on layer of polyurethane foam.

Spray-applied polyurethane foam had been used in both coal and metal mines to form fire seals and ventilation stoppings, and to insulate ventilation air from heat and moisture transmitted from walls and backs of openings (1, 5-6).[2] Some experimental work had been done on the use of urethane-foam granules as protective cover for ice and snow surfaces (3). However, no reference could be found to the use of sprayed-on polyurethane foam as insulation for frozen ground. Consequently, plans were made to test such an application in both the laboratory and the field.

This experiment sought to achieve two objectives: (1) To determine whether polyurethane foam can be sprayed successfully on frozen ground under freezing conditions, and (2) to measure the effectiveness of the insulation in maintaining--at elevated temperatures for an extended period--a room excavated in frozen ground. Two brands of commercial polyurethane foam were tested in the laboratory, one of which subsequently was used to insulate the walls, back, and sill of two small rooms excavated in permafrost near Fairbanks, Alaska. Heat was then introduced to the interior of the rooms. Thermocouples monitored the rate of heat migration across the foam barrier and into the frozen walls. Periodic closure measurements monitored the rate and amount of wall creep.

This report describes both the laboratory and field work and shows the results of 8 months of monitoring with thermocouples and closure measurements. The work was done in cooperation with the U.S. Army Cold Regions Research and Engineering Laboratory (USACRREL), of Hanover, N.H.

ACKNOWLEDGMENTS

In a large measure, the successful accomplishment of the project was made possible by the wholehearted cooperation and assistance of the U.S. Army Cold Regions Research and Engineering Laboratory. Both civilians and enlisted personnel aided in the installation of equipment and in routine observations. Special thanks are due Francis H. Sayles and the late John M. McAnerney, research civil engineers of USACRREL.

LABORATORY TESTING

Twenty-four frozen samples were sprayed with two manufacturers' polyurethane foams under freezing conditions, after which pull tests determined how well the foam adhered to the various materials. Efforts were made to duplicate as nearly as possible testing previously conducted with one of the foam systems at the Pittsburgh Mining Research Center (PMRC) (4). The major difference lay in the ambient temperatures--73° F at PMRC, between 14° and 32° F at SMRL.

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

Equipment

Two types of rigid urethane-foam systems were employed in laboratory testing, the Olin Mathieson Chemical Corporation's Autofroth-I system[3] (fig. 1) and the Mine Safety Appliances Company's (MSA) Rigiseal system (fig. 2).

The Autofroth-I system employs four material components: resin, catalyst, flushing agent, and nitrogen. Each component in an individual cylinder is fed to the gun through a network of hoses. Nitrogen supplies the driving force required for application. The correct ratio of resin to catalyst is automatically controlled by a preset, metering controller valve located in the gun. The Autofroth-I gun discharges from 30 to 80 percent preexpanded froth foam, dependent upon operating conditions.

The MSA Rigiseal system uses three components: resin, catalyst, and flushing agent. Compressed-air operated, the system requires a supply of air at 30 cfm and 70 psi minimum. The machine consists mainly of supply hoses, a pressure tank for flushing agent, a hand-held gun, and a two-piston pump that pumps the resin and catalyst from the drums to the gun. A correct ratio of the two components is maintained automatically by the relative sizes of the two pistons. In addition to driving the materials pump, the compressed air runs a small mixing motor located in the gun, supplies positive pressure to the flushing agent, and blows the froth onto the surface being foamed.

In both systems the mixing of catalyst and resin occurs in a mixing chamber at the discharge end of a light, hand-held gun.

The environmental test chamber, fabricated at SMRL, is a 4-foot-square wooden box, 4 feet in height, equipped with the cooling coils, compressor, and motor from a surplus ice cream freezer (fig. 3). The exterior was foamed with a 3-inch minimum thickness of Autofroth-I rigid polyurethane. Personnel wore vapor-type respirators to protect themselves from the toxic isocyanate vapors.

Miscellaneous equipment included a 200-pound-capacity pull-type scale, 2- by 2-inch pull plates made of punched steel plate, 8- by 8-inch aluminum sample pans, and a short length of 4-inch channel iron used as a hold-down device during pull testing (fig. 4). The bottom pan, serving as the container for the frozen sample, was bolted to a 36- by 36-inch plywood base in the cold box prior to foaming and to the channel iron for pull testing. The upper pan, from which the bottom had been removed, was placed over the lower pan in an inverted position; they thus served as an open mold for the foam covering.

Foaming Materials

Polyurethane Foams

Polymers resulting from the reaction of polyisocyanates and polyhydroxy compounds are called polyurethanes (7). Polyurethane foam systems usually

[3] Reference to specific trade names is made for identification only and does not imply endorsement by the Bureau of Mines.

FIGURE 1. - Autofroth-I System.

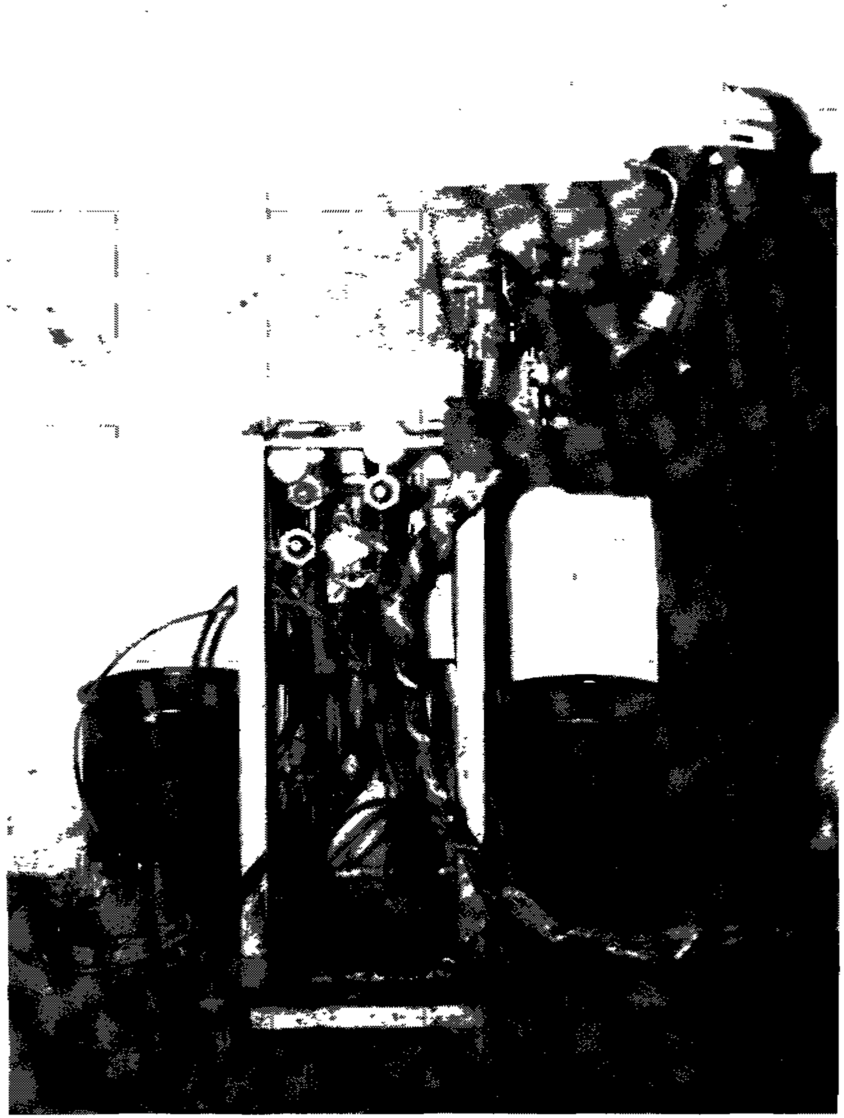


FIGURE 2. - Rigiseal System. *A*, Operator in lab.

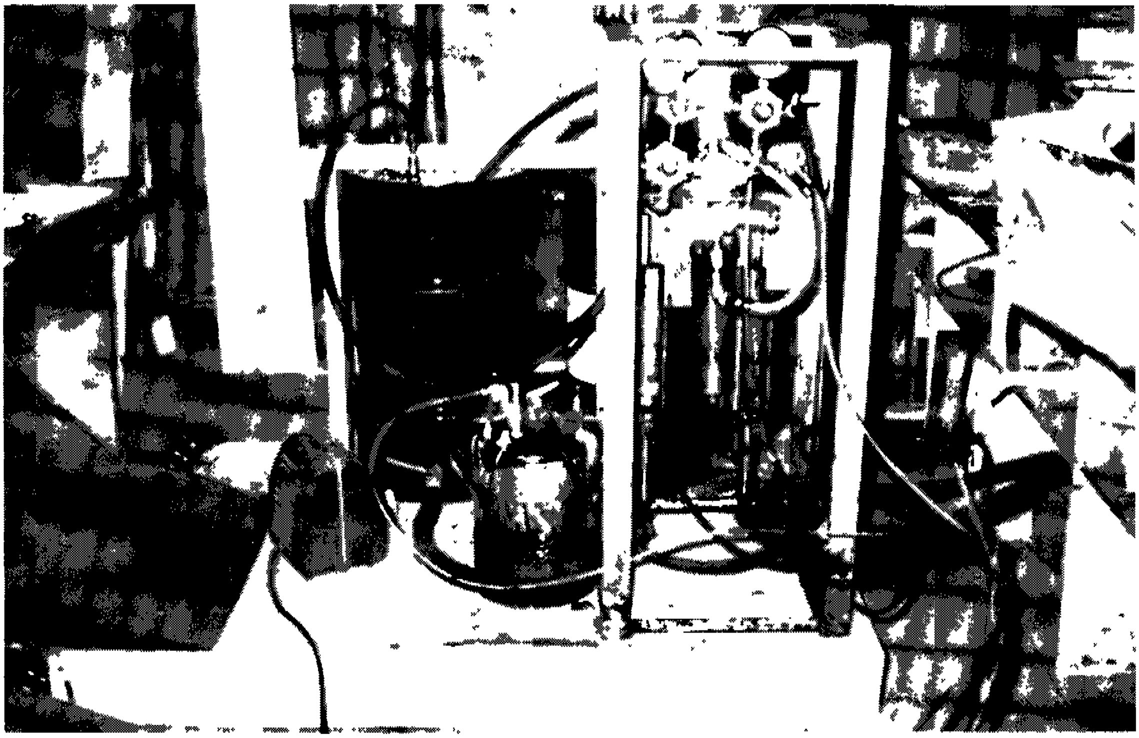


FIGURE 2. - Rigiseal System. *B*, On sledge at Fox, Alaska, installation.

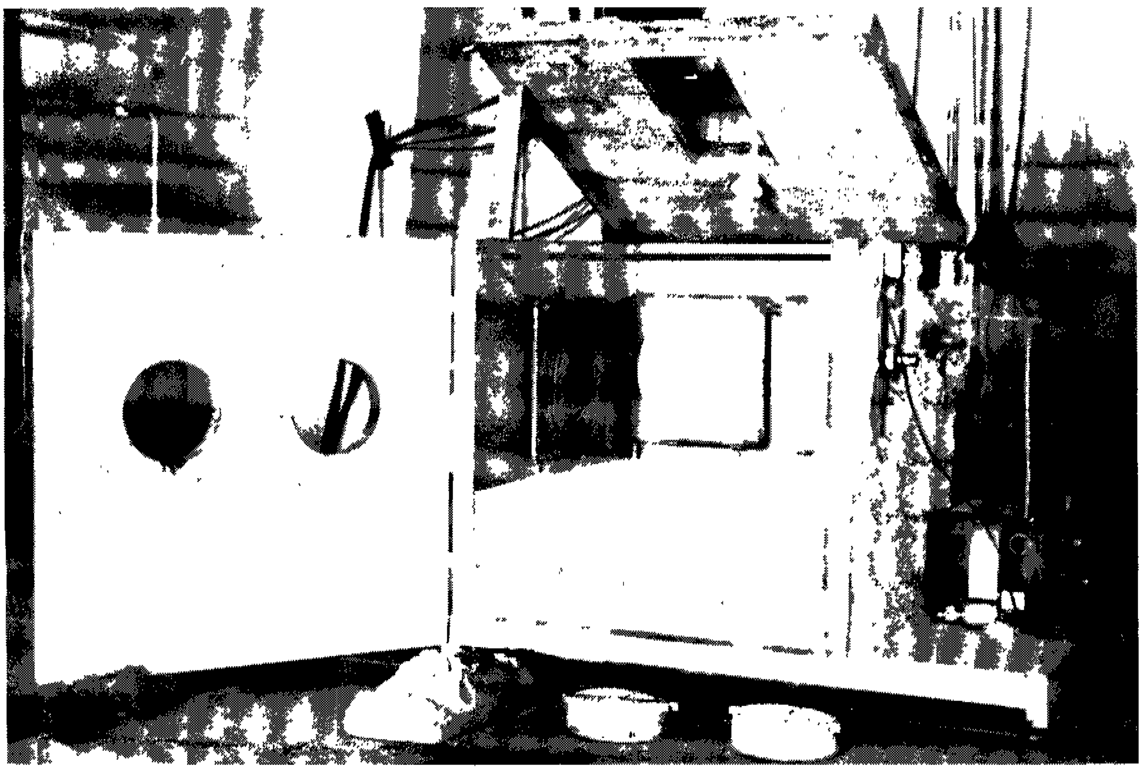


FIGURE 3. - Cold-Environment Box.

FIGURE 4. - Sample Pans and Hold-Down Device.

consist of two components, resin and catalyst. The resin contains the polyisocyanates; the catalyst contains polyhydroxy compounds, a catalyst to adjust the rate of reaction, an expansion agent, and a surface active agent that controls cell size. The expanding agent in both the Rigiseal and the Autofroth-I system is fluorocarbon refrigerant 11, having a boiling point of 74.8° F. However, in the Autofroth-I system, part of the fluorocarbon refrigerant 11 is replaced with fluorocarbon refrigerant 12, which boils at -22° F. This low boiling point results in a partial preexpansion of Autofroth-I foam as it leaves the nozzle of the gun. Both systems have excellent thermal properties, as shown in table 1. The respective properties of the two expanded foams are essentially identical.

Flushing Material

Because the hardened foam is highly resistant to most organic solvents, the gun must be flushed immediately each time foaming is interrupted. Ethyleneglycol monoethylether and methylene chloride are two recommended flushing agents. Methylene chloride is the flushing agent used both in the laboratory and in the field foaming operations.

TABLE 1. - Properties of expanded polyurethane foam[1]

Property	Brand name	
	Mine Safety Appliances Rigiseal	Olin Mathieson Autofroth-I
Density..............................pcf..	1.8-2.1	2.2-2.4
K factor.............Btu/hr/ft^2/° F/in..	0.14	0.13-0.14
Closed cells...................percent..	85-95	85-90
Moisture vapor transmission......perms..	2.5	2.0-3.0
Compressive strength..............psi..	28-35	28 (minimum)
Tensile strength..................psi..	-	40 (minimum)

[1]Data from manufacturers' literature.

Procedure

A sales representative of the H. J. Sales Co., Seattle, Wash., operated the Autofroth-I equipment. Having received training by a representative of the Mine Safety Appliances Co., SMRL research personnel applied the Rigiseal foam with Bureau-owned equipment on loan from the Bureau's Pittsburgh Mining Research Center.

The 8- by 8-inch aluminum pans, 2 inches in depth, were filled with materials containing varying amounts of water, bolted to a plywood base, and placed in the environmental cold box. Three samples were made of each combination. Table 2 provides a description of the combinations used to simulate permafrost materials. The same combinations were used for testing with the Rigiseal foam as were employed with the Autofroth-I, with one exception: fine mill tailings were used in place of eolian silt for Rigiseal testing. Prior to foaming, the upper pans were wiped with vaseline, inverted, and bolted to the sample pans.

TABLE 2. - Adhesion of polyurethane foam to frozen material

Description of material and sample No.	Weight, lb		Moisture content, pct	Maximum pull, lb	Failure	Remarks
	Of material	Of water				
			AUTOFROTH-I FOAM			
1/5 gravel-4/5 sand:[1]						
1.................	23.4	1.8	7.1	40	Gravel parted.	Good foam-gravel bond.
2.................	23.4	1.8	7.1	25	.....do.......	Do.
3.................	23.4	1.8	7.1	0	.....do.......	Do.
4.................	17.8	2.5	12.3	200	None[2].........	-
5.................	17.8	2.5	12.3	200	None..........	-
6.................	17.8	2.5	12.3	134	Foam ruptured.	-
Fine eolian silt:						
7.................	17.9	6.2	25.7	36	Foam-silt interface.	Some silt stuck to foam.
8.................	17.9	6.2	25.7	0	.....do.......	Foam friable at interface.
9.................	17.9	6.2	25.7	0	.....do.......	-
Ice:						
10.................	-	-	100.0	0	Foam-ice interface.	-
11.................	-	-	100.0	0	.....do.......	-
12.................	-	-	100.0	0	.....do.......	Parted when handled.
			RIGISEAL FOAM			
1/5 gravel-4/5 sand:[1]						
13.................	23.8	1.9	7.4	200	None..........	-
14.................	23.8	1.9	7.4	200	None..........	-
15.................	23.8	1.9	7.4	200	None..........	-
16.................	20.9	2.8	11.8	200	None..........	-
17.................	20.9	2.8	11.8	200	None..........	-
18.................	20.9	2.8	11.8	200	None..........	-
Fine mill tailings:						
19.................	15.0	4.2	21.9	0	Foam-silt interface.	Parted when handled.
20.................	15.0	4.2	21.9	30	.....do.......	-
21.................	15.0	4.2	21.9	90	.....do.......	-
Ice:						
22.................	-	-	100.0	0	Foam-ice interface.	-
23.................	-	-	100.0	30	.....do.......	-
24.................	-	-	100.0	0	.....do.......	-

[1] 1/4-inch - 1-inch rounded gravel, coarse sand.
[2] Sample later trimmed to 4-inch square failed at 163 lb pull.

The insulation was then applied in three passes. The first pass, a very light coating, formed a high-density layer about 1/32 inch thick next to the frozen surface, providing sufficient insulation to insure normal exothermic reactions in subsequent layers. The second pass formed a layer approximately 1 inch thick. A pull plate (fig. 5) was then centered over each pan in contact with the foam surface. The third, and final, pass produced a layer of 1-inch minimum thickness. Because the top of the cold box had to be opened during spraying, the air temperature at sample height rose from 14° to 32° F during the operation. However, once the box was closed, the temperature immediately began to lower. The foaming agents were kept at room temperature (68° F).

The polyurethane formulations used attained full strength within 24 hours. However, the foamed samples were left in the environmental cold box at 14° F for 1 week before tests were initiated to determine adhesion between foam and frozen material. Each pull test was completed within 5 minutes after a sample was removed from the cold box, well before the commencement of any thawing.

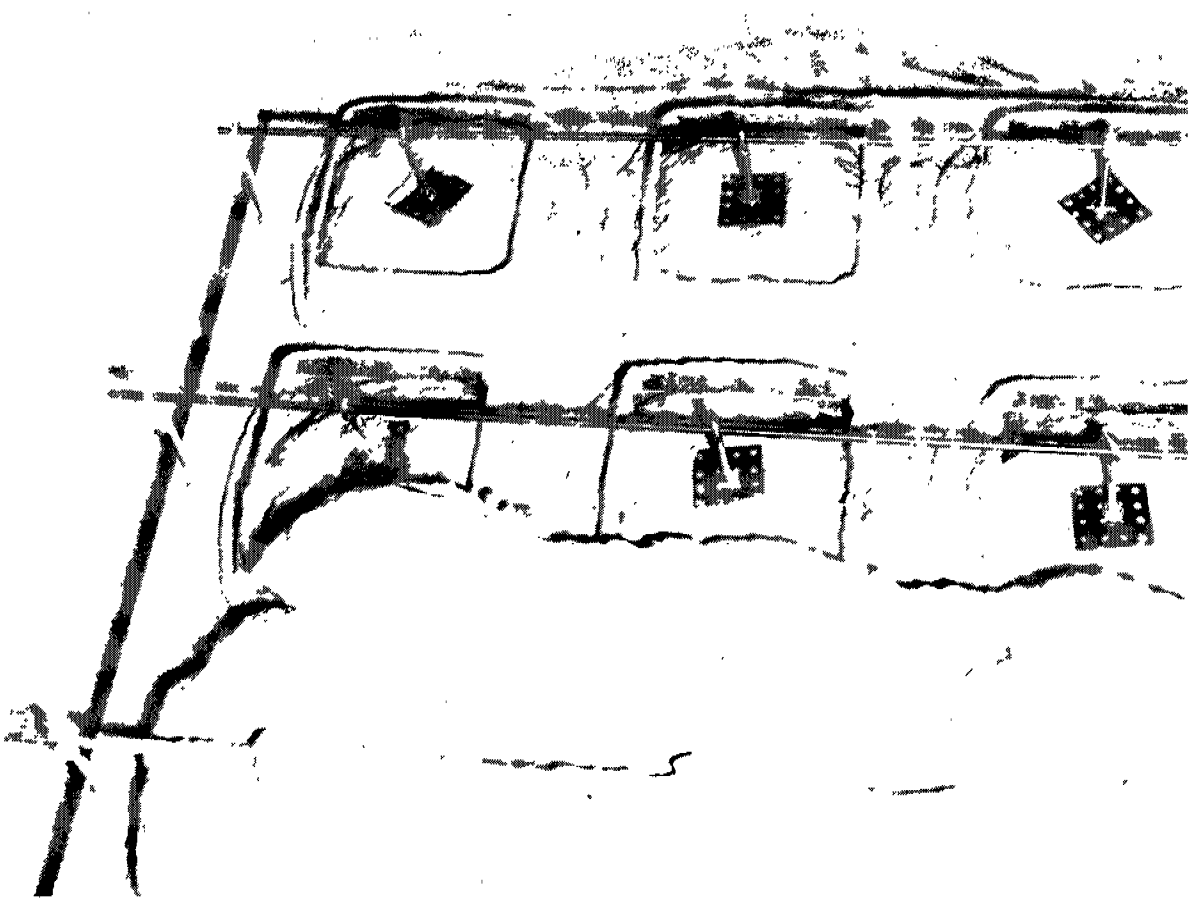


FIGURE 5. - Pull Plates in Position.

Testing procedure was as follows: A test sample was unbolted from the plywood base and freed from the surrounding foam layer by careful cutting of the insulation around the periphery of the pan. The inverted upper pan was next removed. Then the sample was removed from the cold box, bolted to the web of a 4-inch channel iron, and pull tested as illustrated in figure 6. A steadily increasing pull was applied perpendicular to the frozen surface until failure occurred, or until the 200-pound capacity of the scale was reached.

Results of Pull Testing

Pull-test results are given in table 2. Visual examination of samples 1, 2, and 3 revealed that the upper portion of the gravel-sand mixture had dried out before the sample became frozen. Consequently, parting occurred within the mixture rather than at the mixture-foam interface. The gravel and sand particles can be seen imbedded in the foam in figure 7A. A pull of 200 pounds was not sufficiently large to cause failure with any of the remaining nine gravel-sand samples. The foam layer on sample 4 subsequently was trimmed to 16 square inches (fig. 7C). A force of 163 pounds was required to pull this reduced section of foam from the frozen material (fig. 7D).

Of the six silt and mill-tailing samples, three adhered to some degree to the foam. Visual observation indicated that sublimation, prior to foaming, had formed a layer of dried dust on the sample surface. This layer is seen stuck to portions of the contact surface of the foam of sample 7 in the righthand side of figure 7B. Sample 23 gave the only indication of adherence to ice surfaces.

Laboratory testing showed that foam can be applied successfully to frozen material in a freezing environment when the reagents are kept at room temperature. Moreover, results indicated that the foam would adhere well to frozen gravels, somewhat to frozen silt, and only slightly to ice. The two polyurethane foams tested appeared to perform comparably. Furthermore, the cost of materials for either system is comparable. The Rigiseal system was chosen for subsequent field work in permafrost because the Rigiseal equipment previously had been purchased by the Bureau of Mines for testing in coal mines.

FIELDWORK: INSULATING ROOMS IN PERMAFROST

Two small rooms, one excavated in frozen silt and one in frozen gravel, were sprayed with the MSA Rigiseal foam in the Fox tunnel near Fairbanks, Alaska, in January 1969. Strings of thermocouples subsequently were employed to monitor heat flow in the ground surrounding the heated rooms.

Description of Site

The experimental adit at Fox, Alaska, approximately 10 miles north of Fairbanks (fig. 8), was driven in 1963 and enlarged in 1966 and 1967. Access to the site is provided by an asphalt-surfaced highway, connecting Fairbanks with Livengood to the north. The facility, which includes an office and shops, is the property of USACRREL. The adit (fig. 8), 360 feet in length, was excavated in perennially frozen silt (permafrost) in the toe of a bench

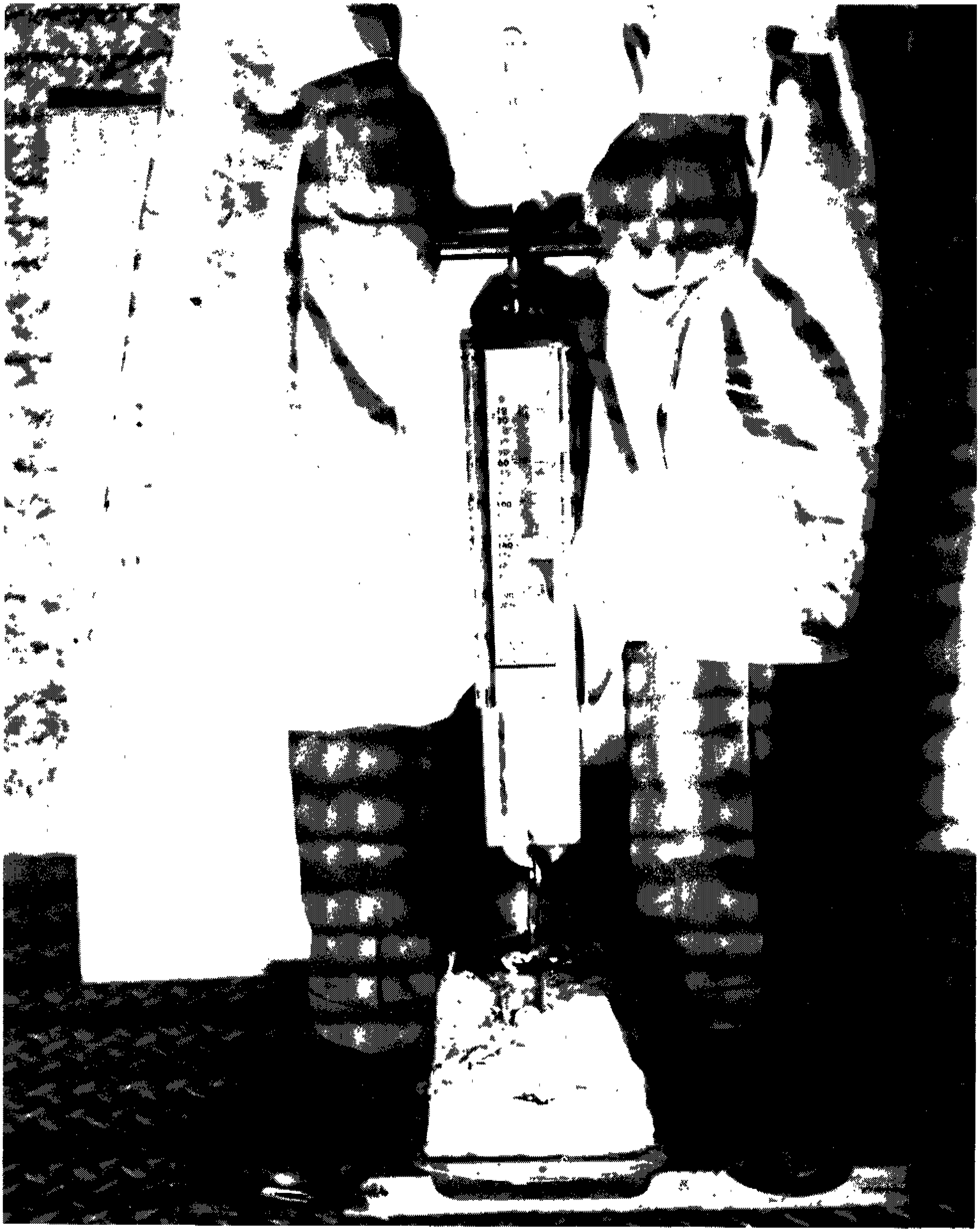


FIGURE 6. - Testing Adhesion Between Foam and Frozen Material.

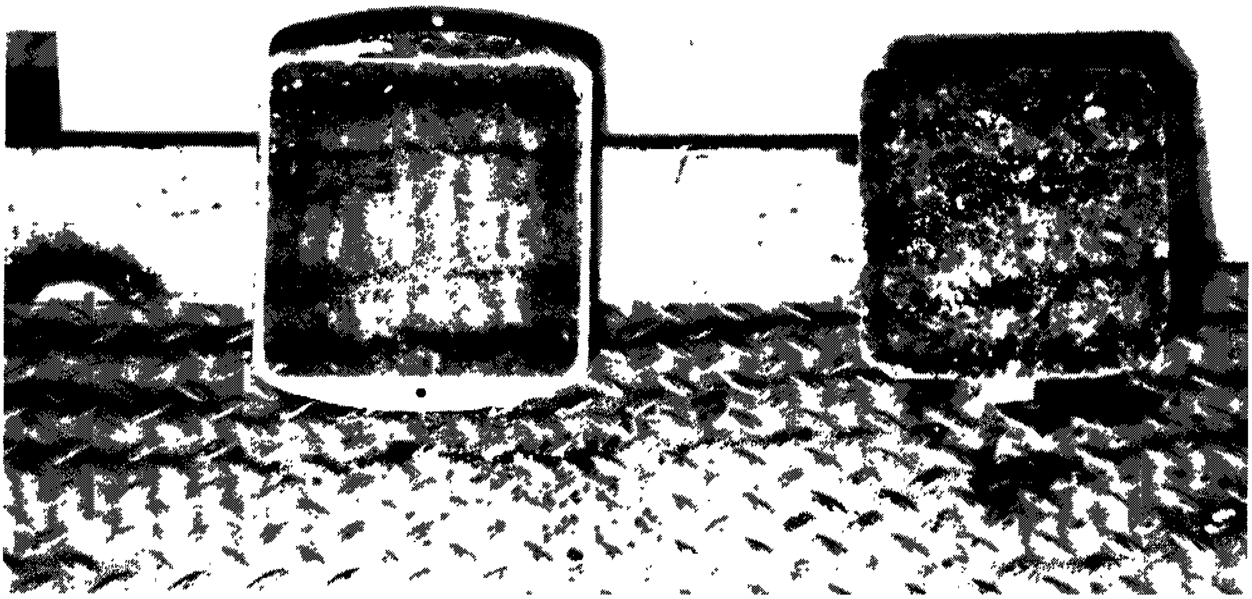


FIGURE 7. - Bond Between Foam and Frozen Material. *A*, Sample 2 after pull test.

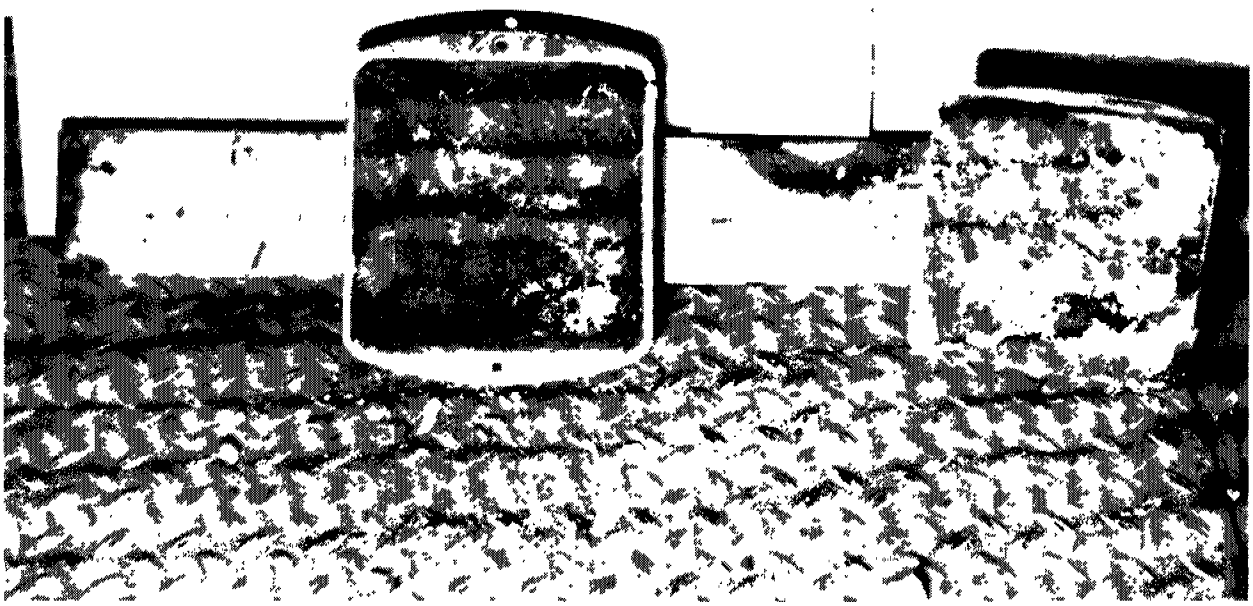


FIGURE 7. - Bond Between Foam and Frozen Material. *B*, Sample 7 after pull test.

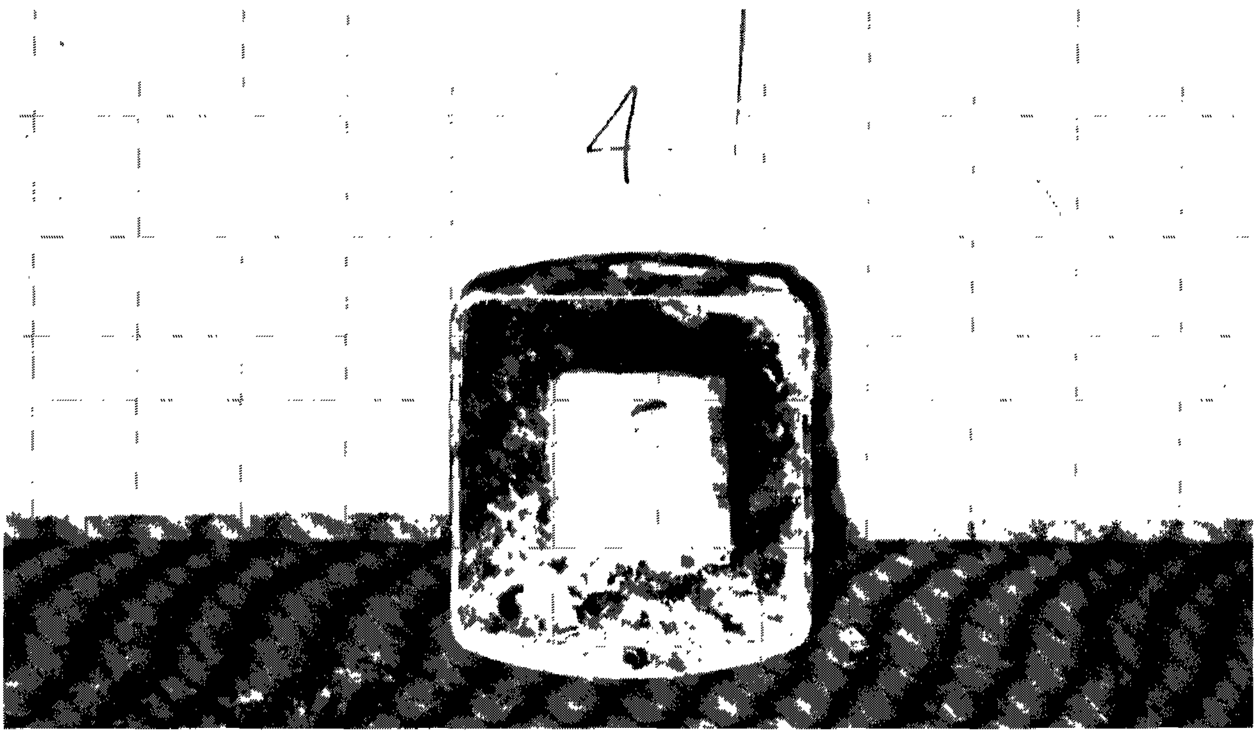


FIGURE 7. - Bond Between Foam and Frozen Material. *C*, Sample 4 trimmed to 16 square inches.

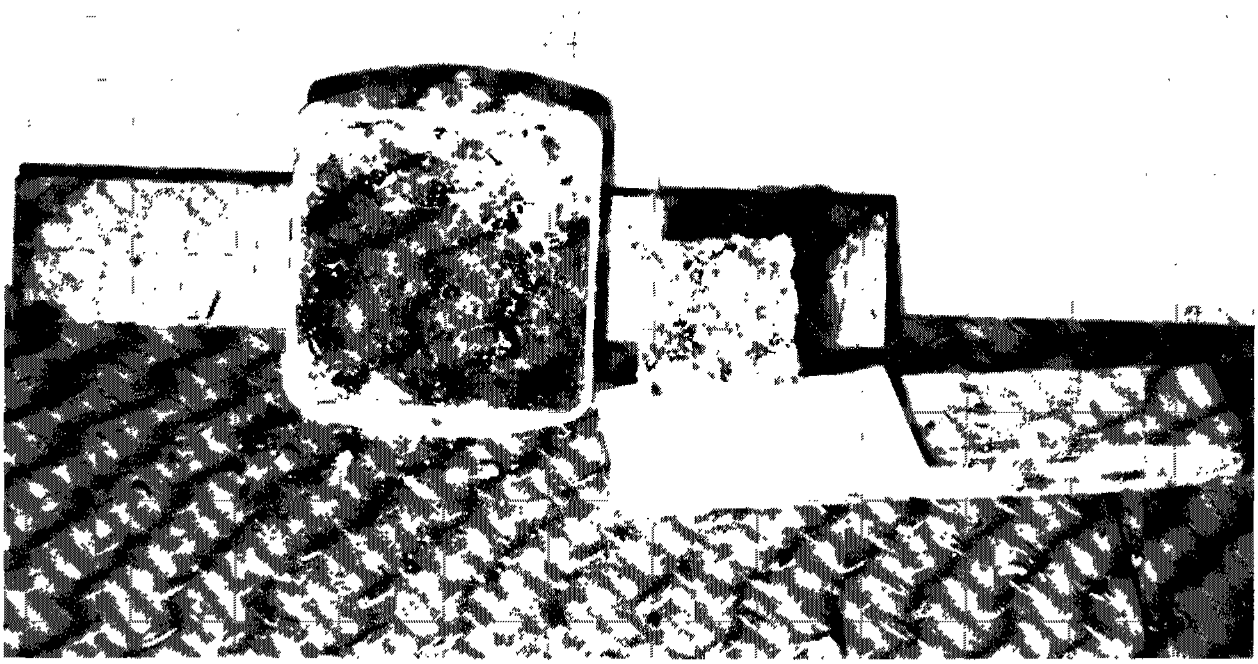


FIGURE 7. - Bond Between Foam and Frozen Material. *D*, Sample 4 after pull test.

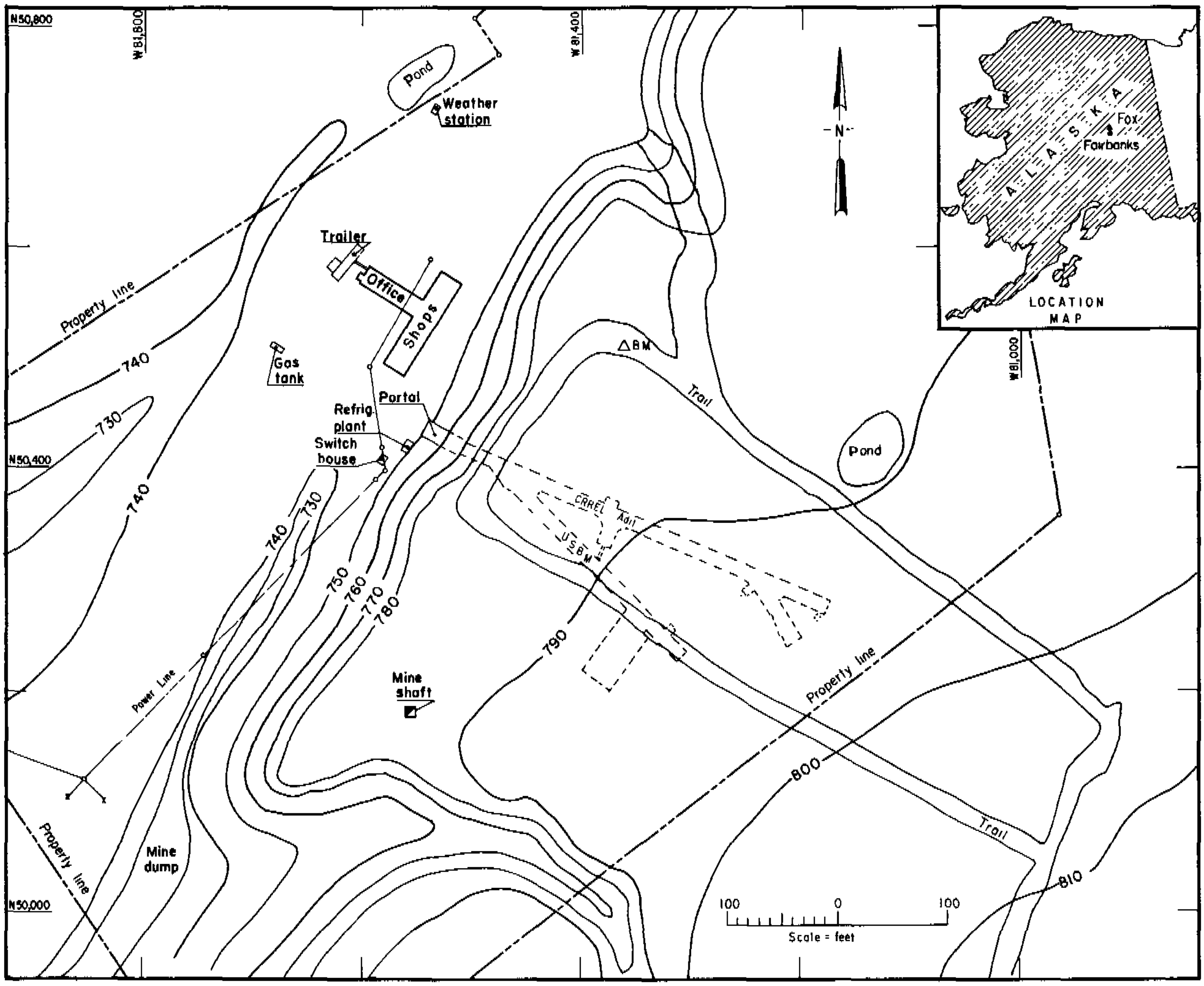


FIGURE 8. - Adit Site, Fox, Alaska.

left as the economic limit of earlier gold dredging. The small silt room later excavated and insulated by the Bureau is located near the far end of the adit. During the summer months, air within the adit is maintained at below freezing temperature by buried refrigerated pipes that surround the portal area and by fans which circulate the air through cooling coils located inside the adit. Also, the exhaust shaft is kept closed except in the winter.

So that the Bureau could conduct test work in the gravel horizon, Twin Cities Mining Research Center (TCMRC) personnel supervised the driving of an 8- by 15-foot winze on a 14- to 16-percent grade during the latter part of 1968 (fig. 9). The small gravel room insulated by SMRL personnel is situated near the bottom of this opening.

Conventional hard-rock jackleg drills with integral steel and 40-percent ammonia-gelatin dynamite were used to drill and blast the gravel room. For the silt room, located in an area free of ice wedges, a modified procedure was

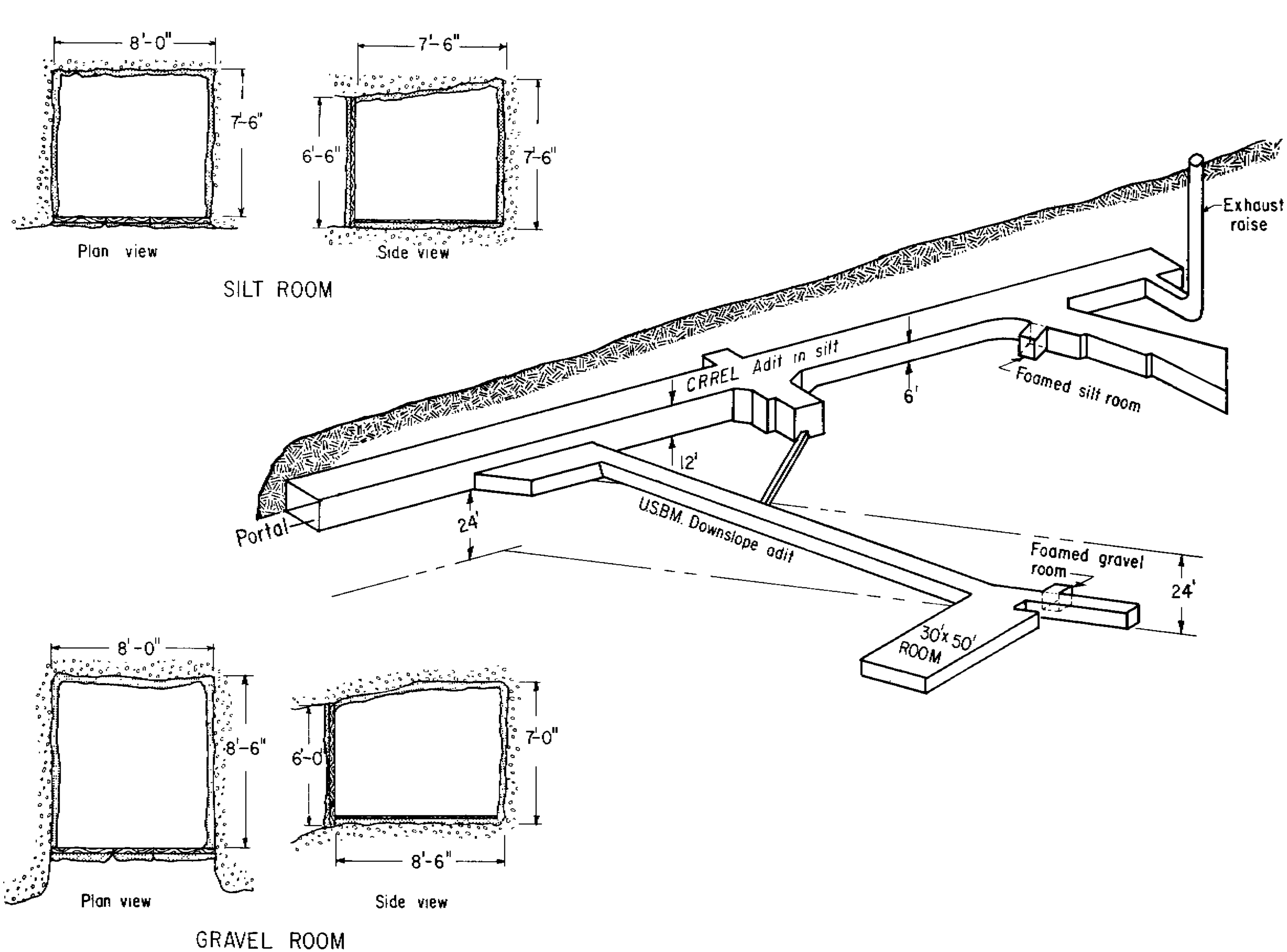


FIGURE 9. - Details of Adit.

employed. The outlines of the room first were sawed with a Joy coal cutter. The face was then drilled with a hydraulically powered coal auger and blasted with 40-percent ammonia-gelatin dynamite.

Geology

According to Péwé (9), a complex series of events occurred in Quaternary time which included in the Fairbanks area alternating deposition and erosion of silt and gravel, formation and destruction of permafrost, and climatic fluctuation. A typical creek valley in this area contains beds of early Quaternary gravel, auriferous in many places, overlain by numerous layers of both windblown and transported silt. Vertebrate and plant fossils are found in both the gravels and in the loess deposits. Permafrost is nearly universal in the Fairbanks area, except beneath hilltops and on those steeply dipping slopes having a southerly exposure. Ice wedges from 1 to 10 feet in thickness and up to 30 feet in height occur in the silt overlying the valley bottom.

The bedrock is a Precambrian formation of predominately quartz mica schist, called the Birch Creek Schist. The upper few feet, which is highly weathered in many areas, has the consistency of silty clay when thawed. The overlying gravel layer is a stream deposited mixture of mica schist, chlorite schist, phyllite, gneiss, and quartz cobbles in a matrix of poorly stratified sand (2).

At the test site the gravel ranges from 5 to 15 feet in thickness and varies from 7 to 11 percent in moisture content $\left(\frac{\text{wt } H_2O}{\text{wt solids}} \times 100\right)$. The overlying silt averages about 60 feet in thickness and is mostly silt sized, the coarsest fraction being of sand size. It contains a generous amount of organic material, consisting mainly of small twigs, and has a moisture content varying from 45 to 125 percent (10). In addition, massive ice lenses are found in the silt at the adit horizon.

Equipment

The same MSA foaming equipment used in earlier laboratory testing was employed in foaming the silt and gravel rooms at Fairbanks. Air was supplied by a large diesel-powered compressor permanently stationed near the portal of the experimental adit. Thermocouple strings to be inserted into drill holes in the walls of the rooms were fabricated by CRREL personnel. A thermocouple string was made by taping fine copper-constantan thermocouples to a 1-1/2-inch-diameter wooden dowel at varying intervals (fig. 10). The length of dowels and spacing of thermocouples were dependent upon the depth of the holes (fig. 11). Insulating rock wool was taped around the dowel at each end of individual thermocouples to prevent convection currents in the unfilled portion of the hole, and thus to insure that the temperature read was that of the ground in the immediate vicinity of the thermocouple. Output from the thermocouples was read in hundredths of a millivolt by a Rubicon, model 2735-S potentiometer and then converted into degrees Fahrenheit.

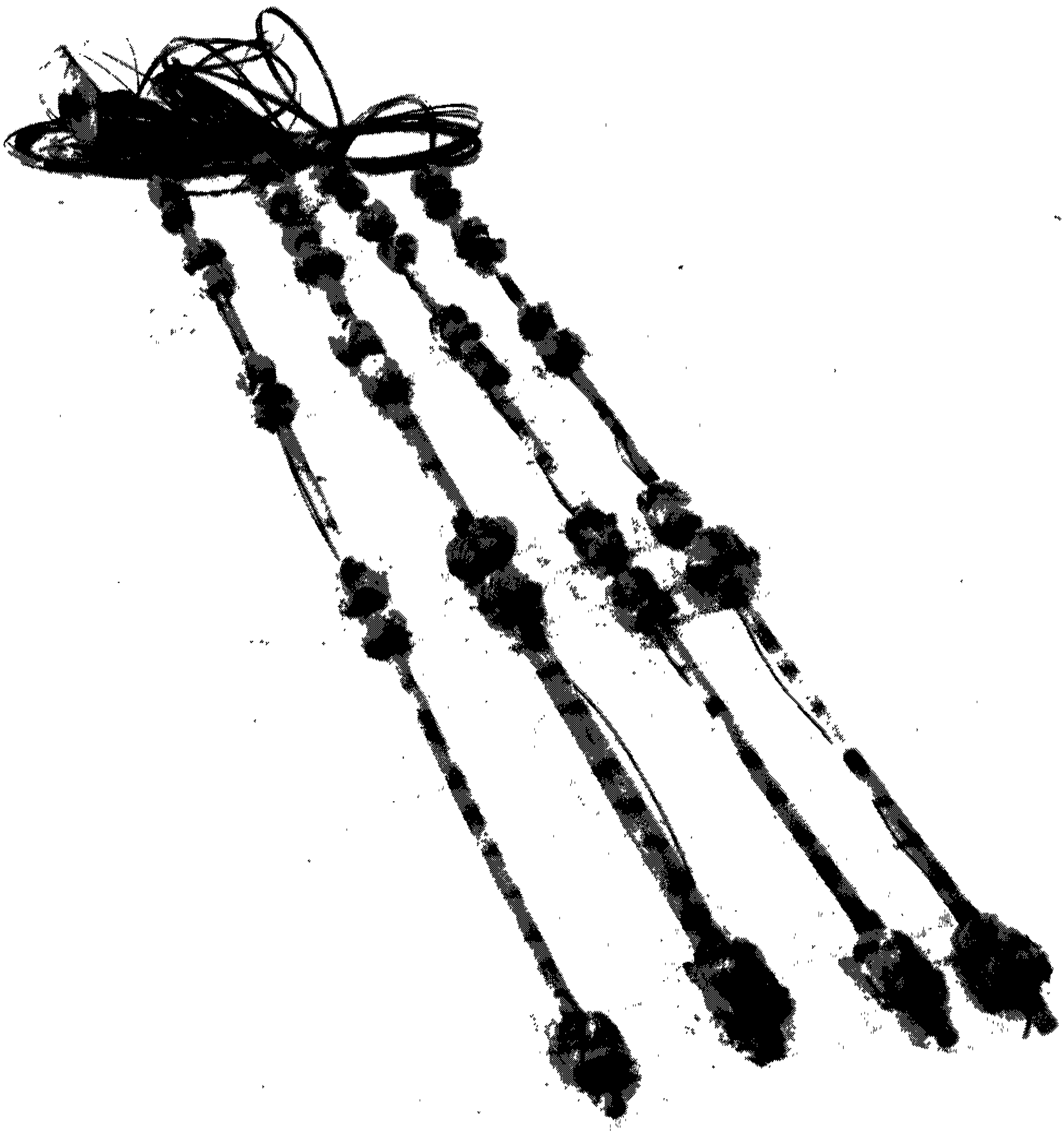


FIGURE 10. - Thermocouple Strings.

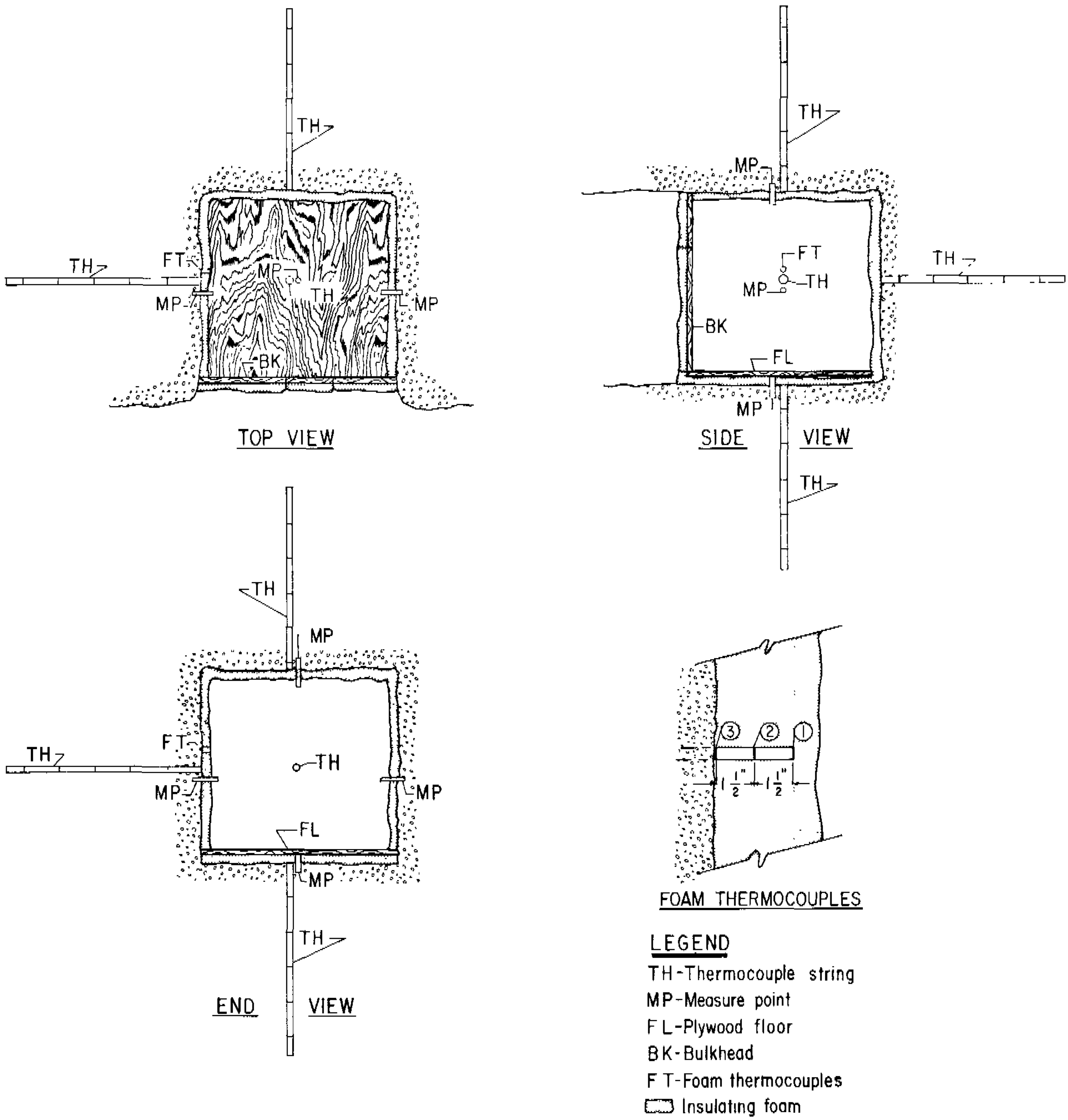


FIGURE 11. - Thermocouple and Closure-Point Location.

After foaming was completed, each room was equipped with an electrical, thermostatically controlled strip heater and small table-type circulating fan. Temperature within a room was monitored continuously with a thermograph.

Closure points consisted of 8-inch wooden dowels, with spherical steel cups on the outer ends, driven or grouted into holes drilled 5 inches in depth into the back, sill, and opposite walls of the two rooms. The original measuring device was an extensometer made from telescoping segments of type 304 stainless steel tubing and equipped on one end with a dial gage. This device proved unsatisfactory because of several mechanical failures of the gage during extreme cold weather and the difficulty in applying sufficiently precise temperature corrections.

Beginning June 6, 1969, an RM-100, Reed Invar Tube Extensometer, purchased by CRREL, was used to measure closures. Closure point ends were modified to match the ends of this new equipment. This new measuring device performed excellently.

Procedure

Closure points were driven into predrilled holes and grouted with mud if necessary, in the back, sill, side wall, and end wall of the rooms (fig. 11). The thermocouple leads were connected to a switching unit outside the room.

The bulkhead framework and sill stringers for both rooms were cut from 2- by 4-inch lumber and wedged in place. For each room, a 2-foot-wide door was then fabricated from 3/4-inch pine lumber, the floor was cut from 3/4-inch plywood, and the exterior bulkhead was cut from 1/4-inch plywood. Figure 12 shows some of the details.

Prior to foam application, project personnel assembled the entire spray system and bolted it to a wooden sledge (fig. 2) in a building adjacent to the tunnel. The assembly, after being checked to insure proper operation, was towed into the tunnel and positioned just outside the silt room. After the air hose was connected to the existing compressed-air line, the two strip heaters, which later were used to heat the rooms, were placed on the sledge and connected to an available power outlet. A tarp was then placed over the equipment. This arrangement kept the temperature of the foaming ingredients, which was initially 70° F, from falling below 60° F. Air and wall-surface temperatures varied from 14° to 16° F.

Bureau engineers followed the same procedure in foaming both rooms. First, the sill was foamed between and to the top of the 2- by 4-inch stringers, after which the plywood floor was laid over the stringers and nailed in place. The back, end wall, and side walls were foamed next, care being exercised to form a tight seal between walls and floor, and between walls and bulkhead framework. The 1/4-inch bulkhead then was nailed to the outside of the framework. Next, the bulkhead and door were foamed with a monolithic covering from outside the room (fig. 13).

The foam was applied in three to four passes. The first pass, which was a light application, formed an insulating sugary-textured barrier that did not rise because of the cold surface. Subsequent layers foamed almost immediately after impact (fig. 14). The finished thickness was maintained at a minimum of 3 inches in the silt room. As shown in figure 15, the relationship between heat loss and foam thickness is not a straight-line function. A 3-inch minimum covering was selected as being a good compromise between cost and benefit. This was reduced to a 2-inch minimum in the gravel room to insure that the remaining supply of material would be sufficient to complete the job.

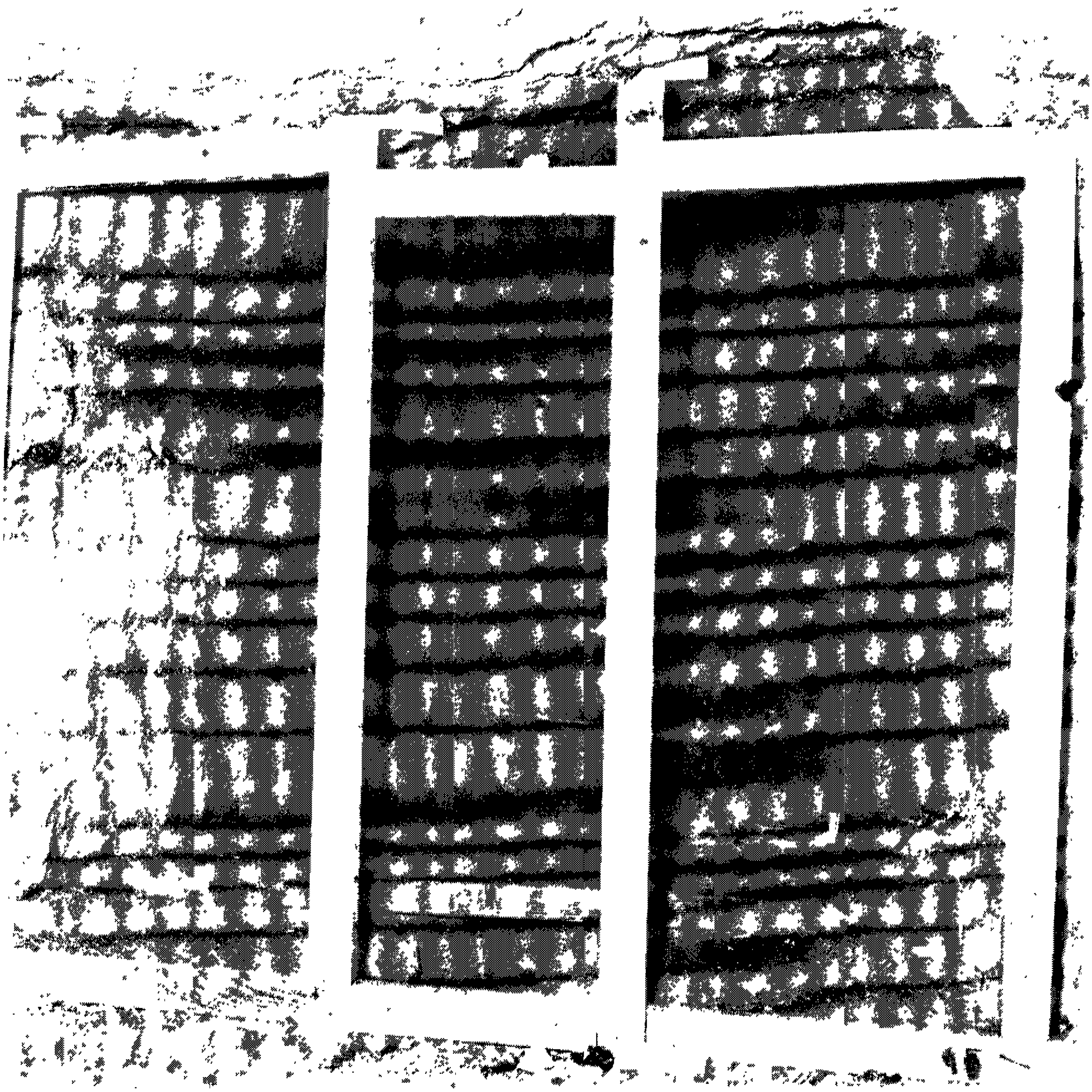


FIGURE 12. - Rooms Before Foaming. A, Gravel room, showing sill stringers and bulkhead frame.

The day following application, the foam was cut and trimmed from around the doors. A strip heater, fan, watt-hour meter, and thermograph (fig. 16) were installed in each room, and initial temperature and closure readings were made. Heat was introduced in the silt room on January 27, 1969, and in the gravel room on February 20, 1969.

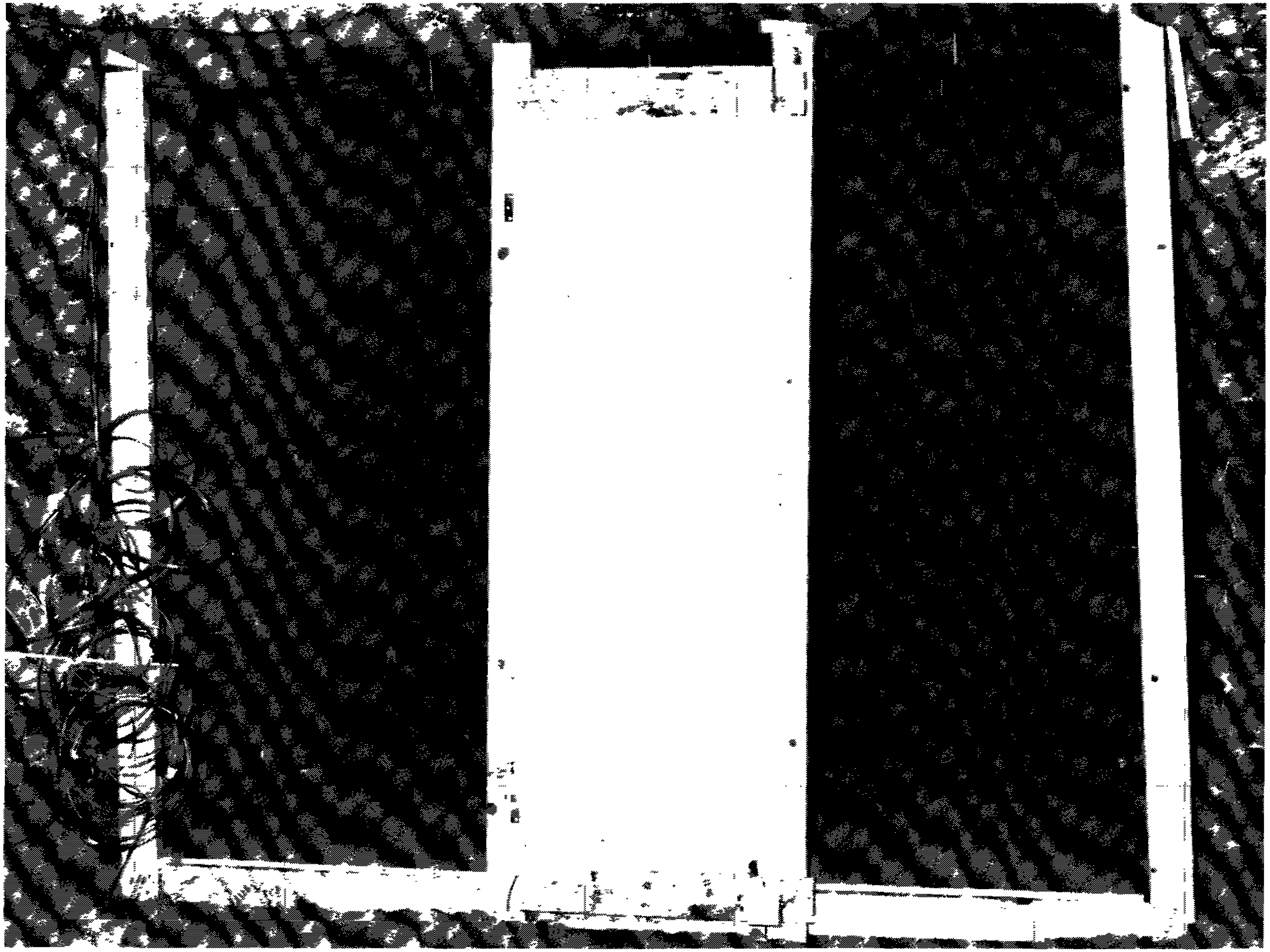


FIGURE 12. - Rooms Before Foaming. *B*, Silt room, showing door, floor, and thermocouple leads.

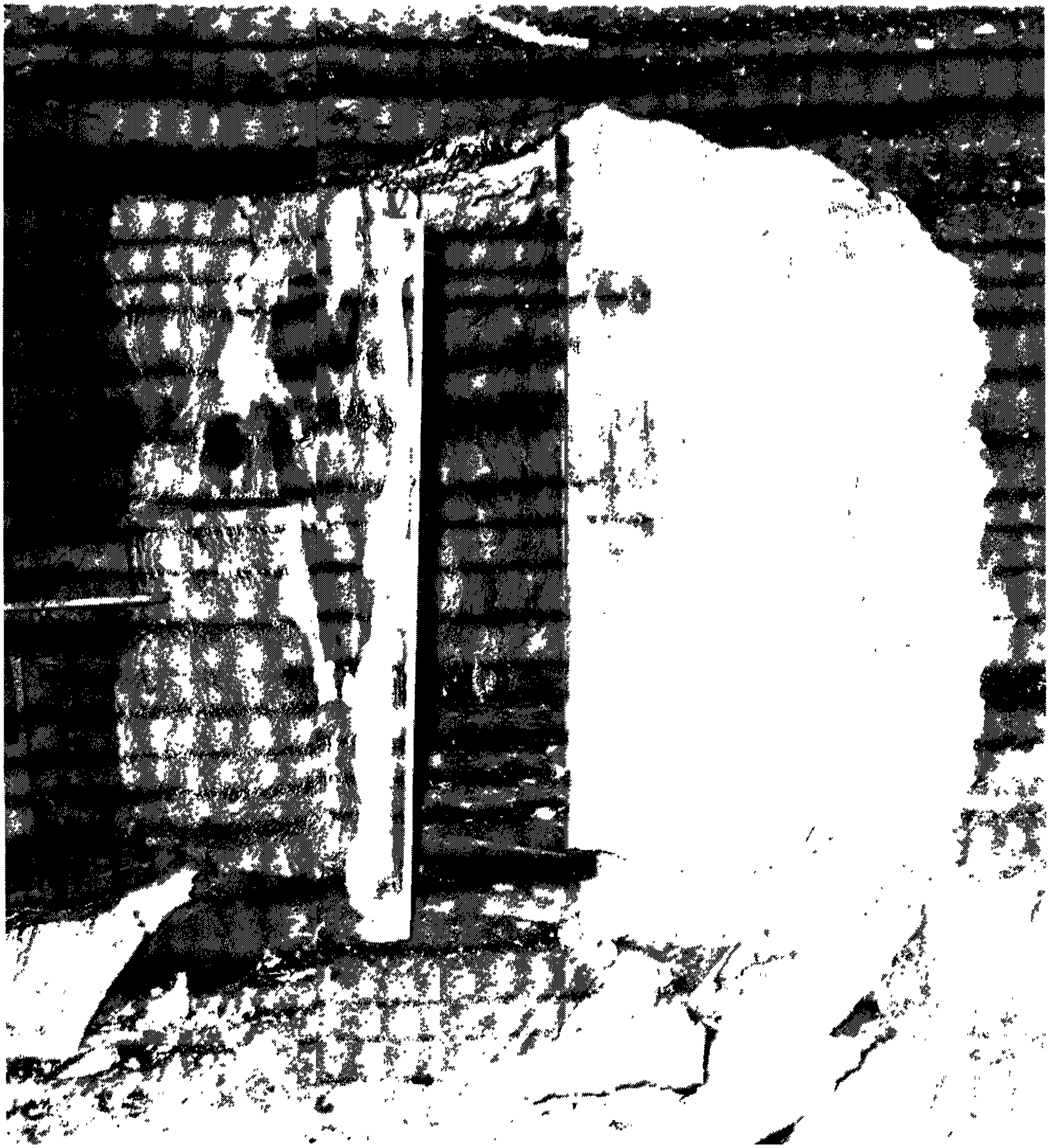


FIGURE 13. - Rooms After Foaming. *A*, Outside view of gravel room—bulkhead shaken by blasting.

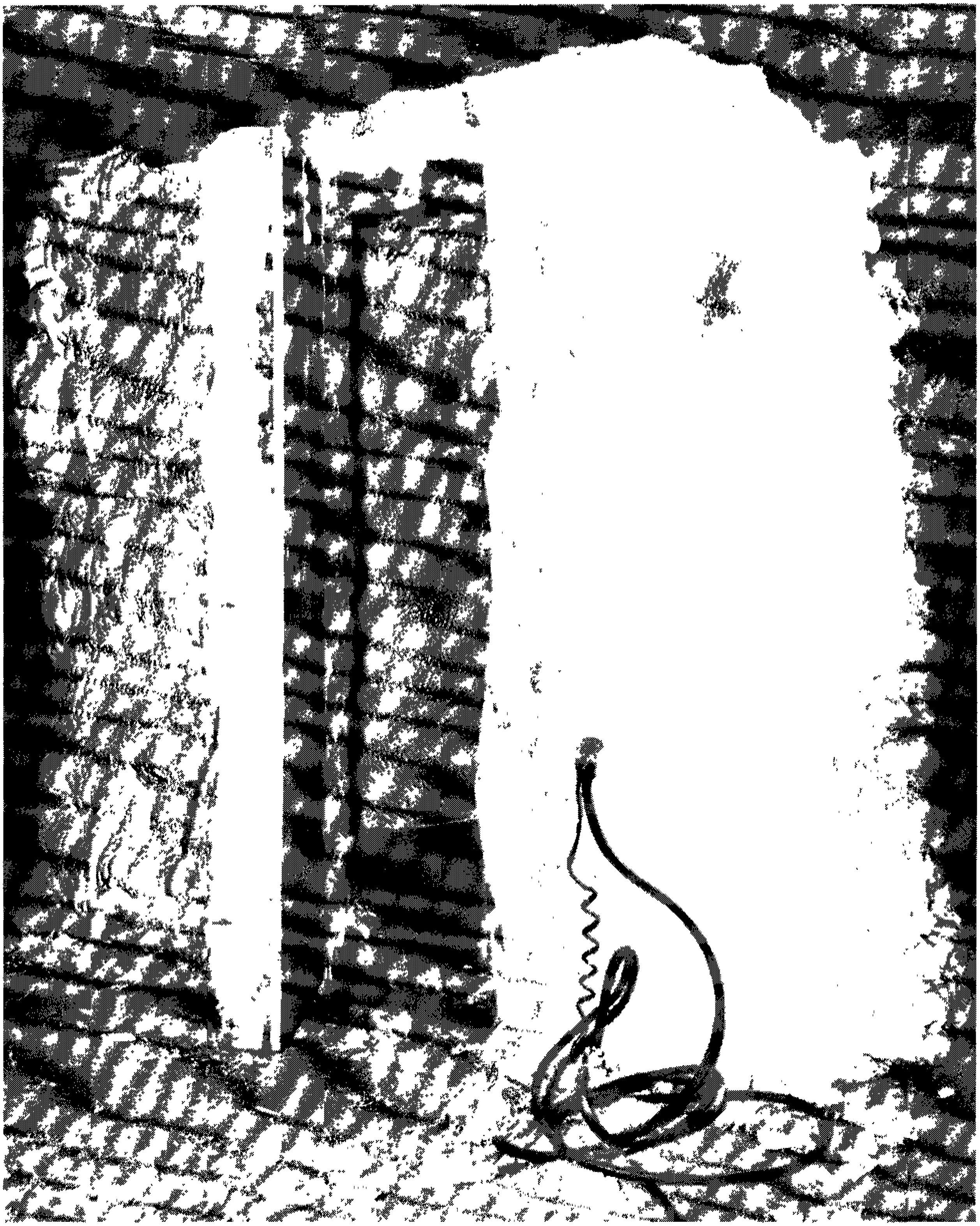


FIGURE 13. - Rooms After Foaming. *B*, Outside view of silt room.

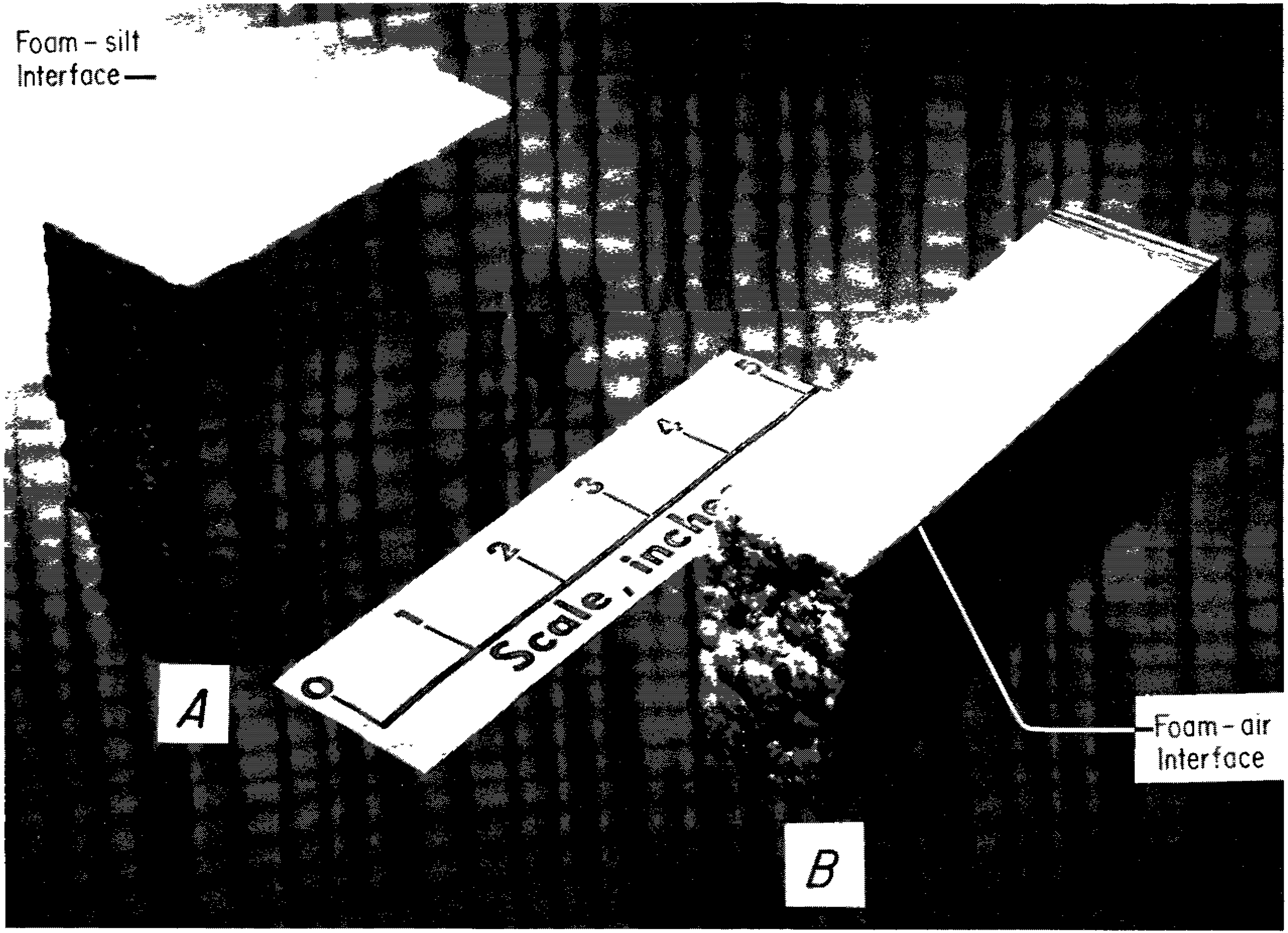


FIGURE 14. - Samples of Cured Foam. *A*, Sprayed on frozen silt; *B*, sprayed on bulkhead.

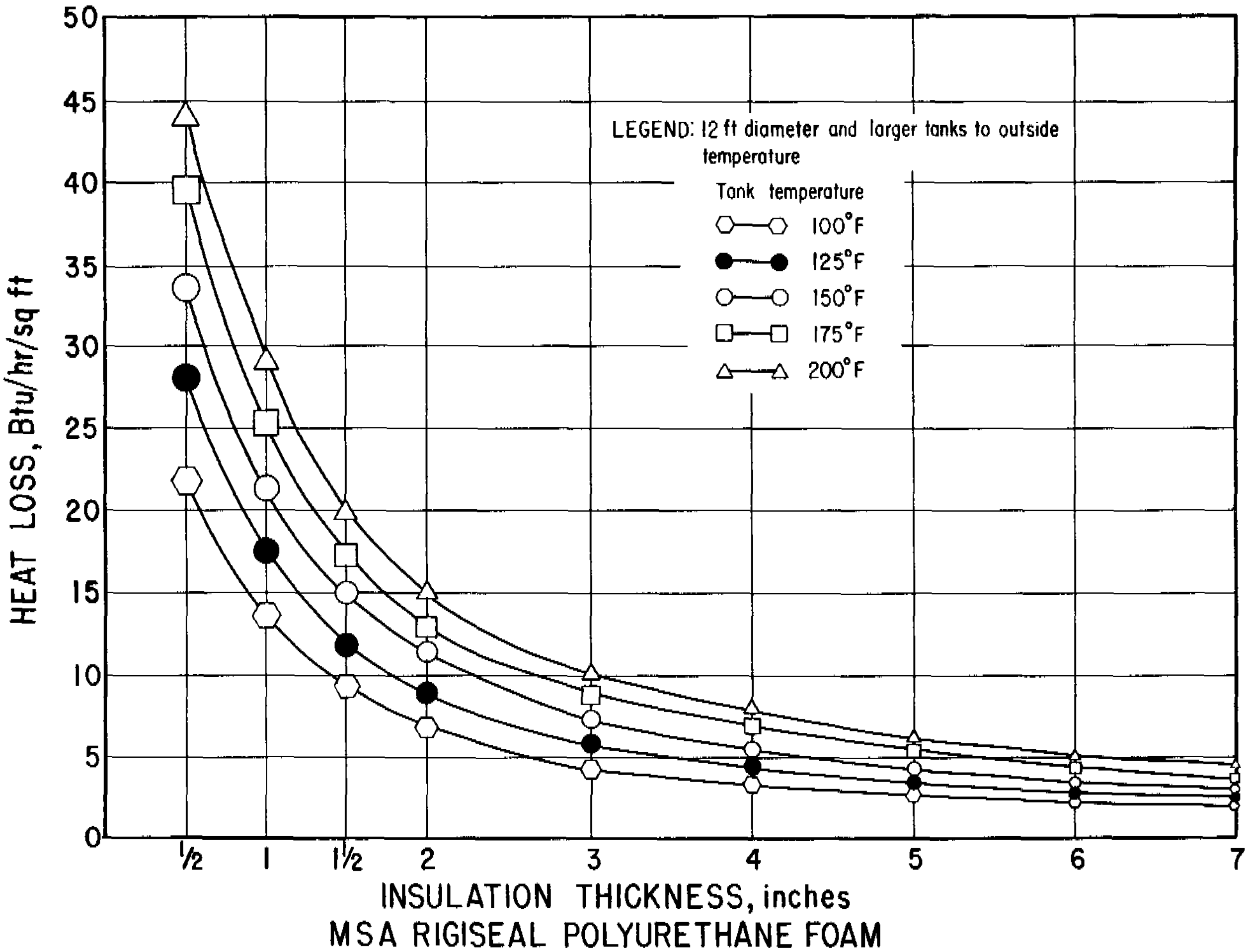


FIGURE 15. - Effect of Insulation Thickness on Heat Loss.
(Courtesy, Mine Safety Appliances Company)

Problems Encountered

The most vexing problem was fogging of the plastic eyeshield of the canister-type masks during the foaming operation. Because of the colder temperature of the ambient air, moisture from the operator's breath condensed on the inner surface. To circumvent the problem, the two operators alternated every few minutes; the one not foaming positioned himself in fresh ventilating air and heated his mask by placing it over a 150-watt light bulb. In operations of this type under cold-weather conditions, a system should be employed which provides a continual supply of fresh air between the wearer's face and his eyeshield.

The strip heaters and tarp cover kept the liquid ingredients sufficiently fluid for successful operation. However, the remnants of two drums, which attained a temperature of 40° F after being exposed to the cold for several hours, had to be used to complete foaming of gravel room. The ingredients had become sufficiently viscous so that they scarcely would flow through the hoses and gun; but after being placed next to a room heater for approximately an

FIGURE 16. - Heating and Monitoring Equipment Inside Foamed Room.

hour, they once again functioned properly. Heat tapes wound spirally around the supply hoses failed to prevent cooling of the materials in the hoses during down times. Perhaps a covering of insulation over the heat tapes would alleviate this situation. However, this problem was of minor consequence, because the cold material would flow through the gun and hoses until dissipated, and normal operation could then be resumed.

One observed property of the cured material could create difficulties with some types of applications. As the foam rises and hardens, considerable stresses evidently are produced within the material. When the material was being trimmed from around the door of the gravel room, a system of cracks, running to the extremities of the bulkhead, instantaneously developed radially from the point where the knife first penetrated the foam layer. The cracks later were filled with conventional rock-wool insulation. No cracking was observed, however, in the foam that was in contact with the frozen ground.

None of the numerous photographic shots made of foaming operations produced pictures. Evidently the shutter was rendered inoperable by ice which formed within the camera. Transporting a camera from a warm room to the extremely cold outdoors can result in moisture condensing from the entrapped warm air and subsequently freezing.

Foaming Labor and Costs

Application of the foam and most of the related activities were performed by two SMRL engineers. A third SMRL engineer, working on a related project, gave assistance from time to time. Three CRREL employees transported the supplies and equipment to the working area and assembled the compressed-air supply hoses, auxiliary lighting, etc. The time required is shown chronologically, reading from top to bottom, in table 3. Table 4 details the cost of labor and supplies. Although a greater thickness of foam was applied in the silt room, separate material and labor costs are not assigned to each room. Circumstances did not permit monitoring of the amount of material used in individual rooms.

TABLE 3. - Time required to foam silt and gravel rooms

Activity	Time		Men	Man-hours
	Min	Hr		
Assembling equipment..................	275	4.58	2	9.16
Moving equipment......................	120	2.00	5	10.00
Foaming...............................	201	3.35	2	6.70
Changing material drums...............	67	1.12	2	2.24
Installing floor and bulkhead.........	75	1.25	2	2.50
Idled by face mask problems...........	28	.47	2	.94
Disassembling and cleanup.............	240	4.00	1	4.00
Miscellaneous down time...............	49	.82	2	1.64
Total.........................	1,055	17.59	-	37.18

TABLE 4. - Insulating costs, silt and gravel rooms

Material costs:	
Foaming costs:	
Foam (712 lb at 89¢/lb)	$634
Airfreight--Spokane to Fairbanks (820 lb at 23¢/lb) (includes wt of drums)	189
Flush agent	15
Cleaning materials	5
Replacement filter and eyepiece	5
Total materials cost for foaming	848
Bulkheads and floors costs:	
Lumber	112
Miscellaneous	1
Total materials cost for bulkheads and floors	113
Total materials cost	961
Labor costs:	
(Based upon estimated Fairbanks wage of $6/hr)	
Foaming cost (37.2 hr[1] at $6/hr)	223
Bulkheads and floor costs (16 hr (estimated) at $6/hr)	96
Total labor cost	319
Total cost[2]	1,270
Cost per sq ft of surface foamed (690 sq ft foamed, minimum thickness = 2 in. in gravel and 3 in. in silt room):	
Materials:	
Foaming (848/690 sq ft)	$1.23
Bulkheads and floors ($113/690 sq ft)	.16
Total for materials	1.39
Labor:	
Foaming ($223/690 sq ft)	.32
Bulkheads and floors ($96/690 sq ft)	.14
Total for labor	.46
Total cost per sq ft of surface foamed[2]	1.85

[1] See table 3.
[2] Does not include overhead, supervision, or equipment costs.

Thermocouple and Closure Observations

Heat was introduced in the silt room on January 27, 1969, and discontinued on October 20, 1969. Heat was introduced in the gravel room on February 20, 1969, after nearby blasting was completed. Concussion had dislodged the insulated bulkhead (fig. 13A), which was repaired with conventional rock-wool insulation. Heating was discontinued in the gravel room on September 22, 1969, when thawing was noted in a small area of the back outside the room adjacent to a leak in the repaired insulation (fig. 17).

FIGURE 17. - Thawed Area Outside of Gravel Room Adjacent to Repaired Insulation.

Temperatures maintained in the silt and gravel rooms averaged 57° and 51° F, respectively. The transfer of heat across the insulating barrier and its migration into the frozen walls are shown by thermocouple readings in figures 18-27. A comparison of the graphs indicates that the walls of the silt room were colder than those of the gravel room at the time of insulation; the reason was that the silt room was excavated on December 4, 1968, the gravel room excavated on January 13, 1969, and the rooms were foamed on January 21, 1969. This difference in original temperatures is reflected in the greater rate of closure and total closure in the gravel room. Closures for the period between June 6, 1969 (the date the new invar measuring rod was first used), and September 23, 1969 (the day following discontinuation of heating in the gravel room), are presented in figure 28. The rate of horizontal closure increased in both rooms about the first of September. During the middle of August, vertical closure in the gravel room accelerated. It is not established whether vertical closure rate also increased in the silt room, for at this time vertical closure readings were discontinued in this room because the height had become too small to accommodate the measuring device.

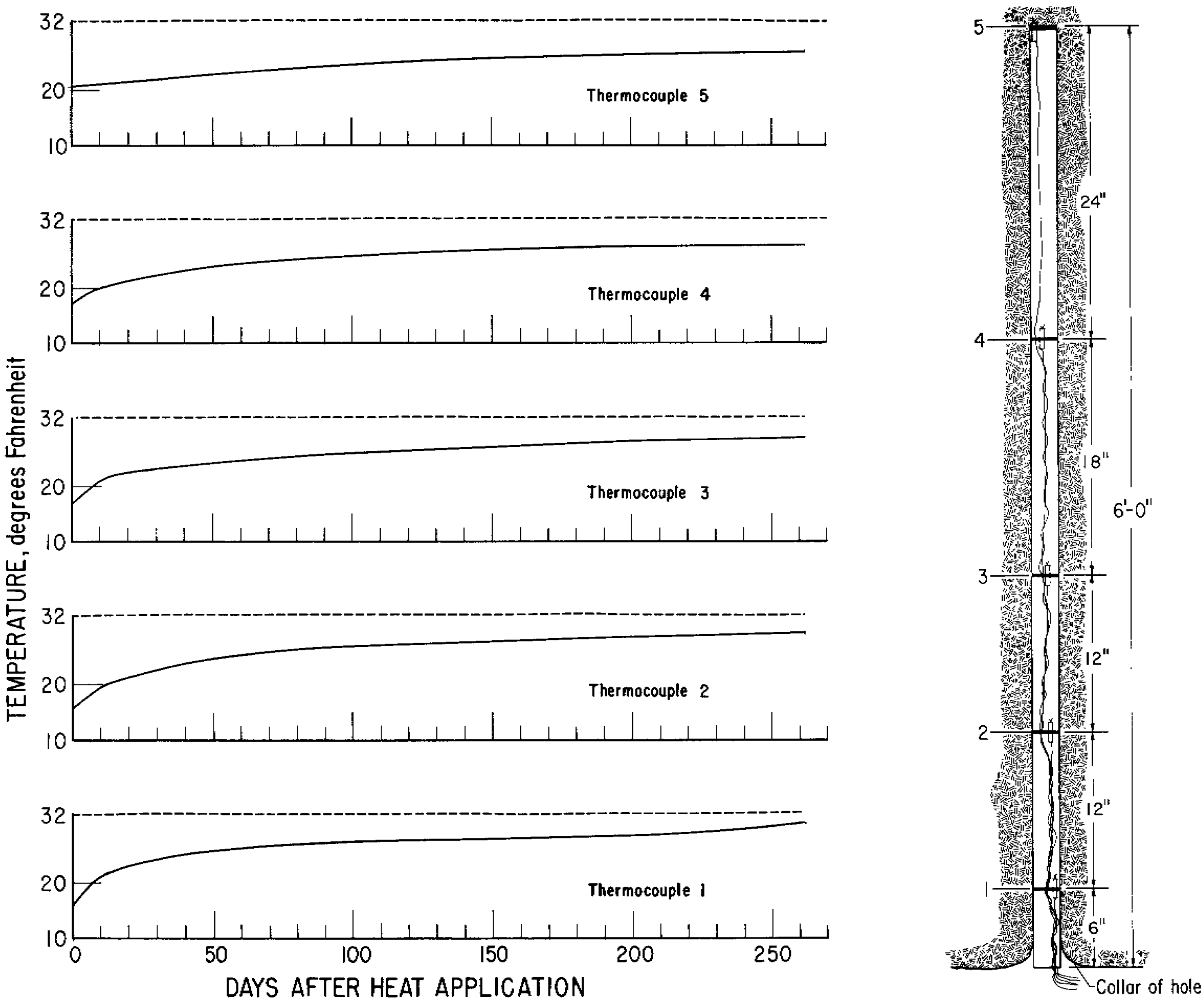


FIGURE 18. - Thermocouple Readings, Back of Silt Room.

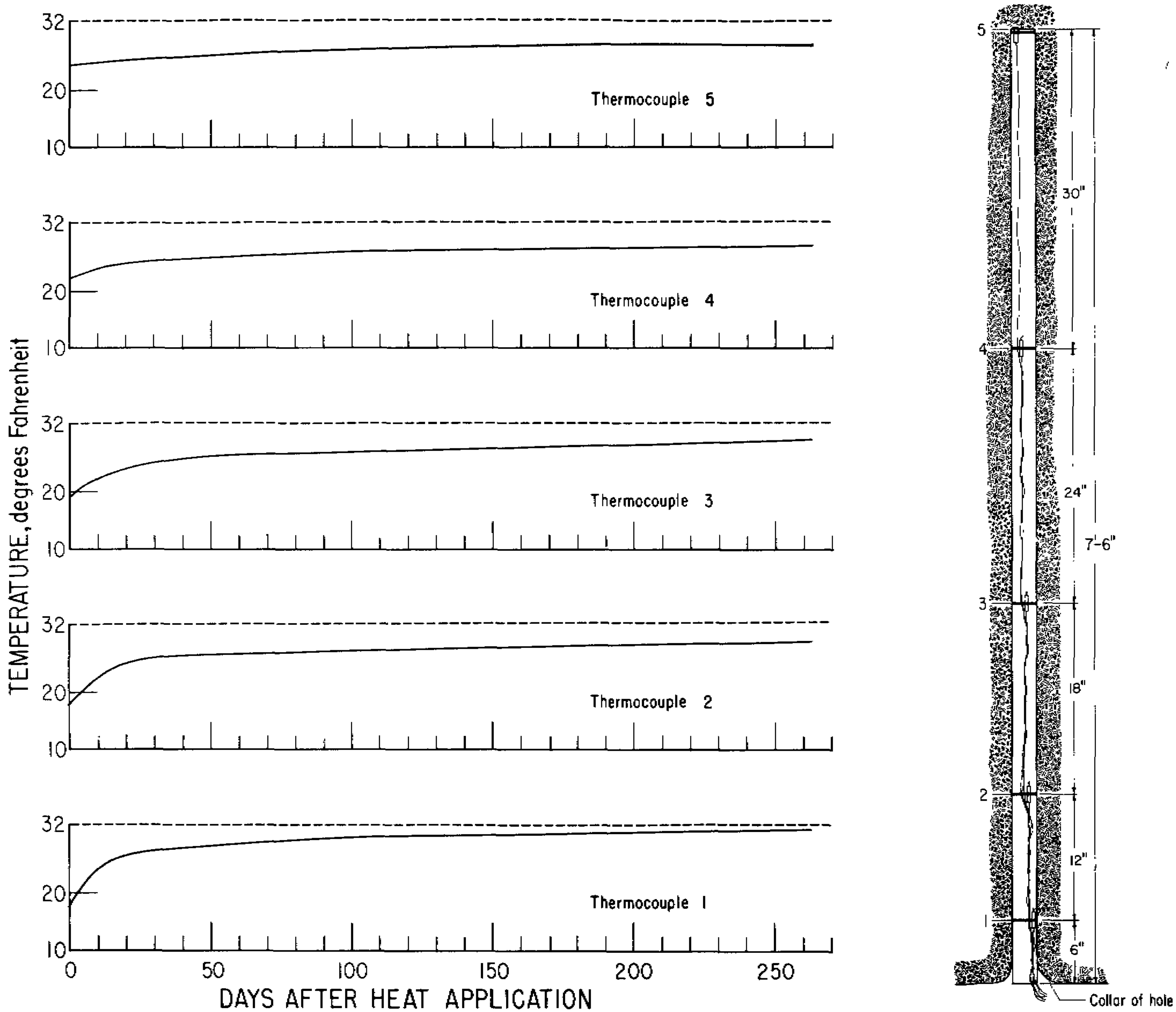


FIGURE 19. - Thermocouple Readings, End Wall of Silt Room.

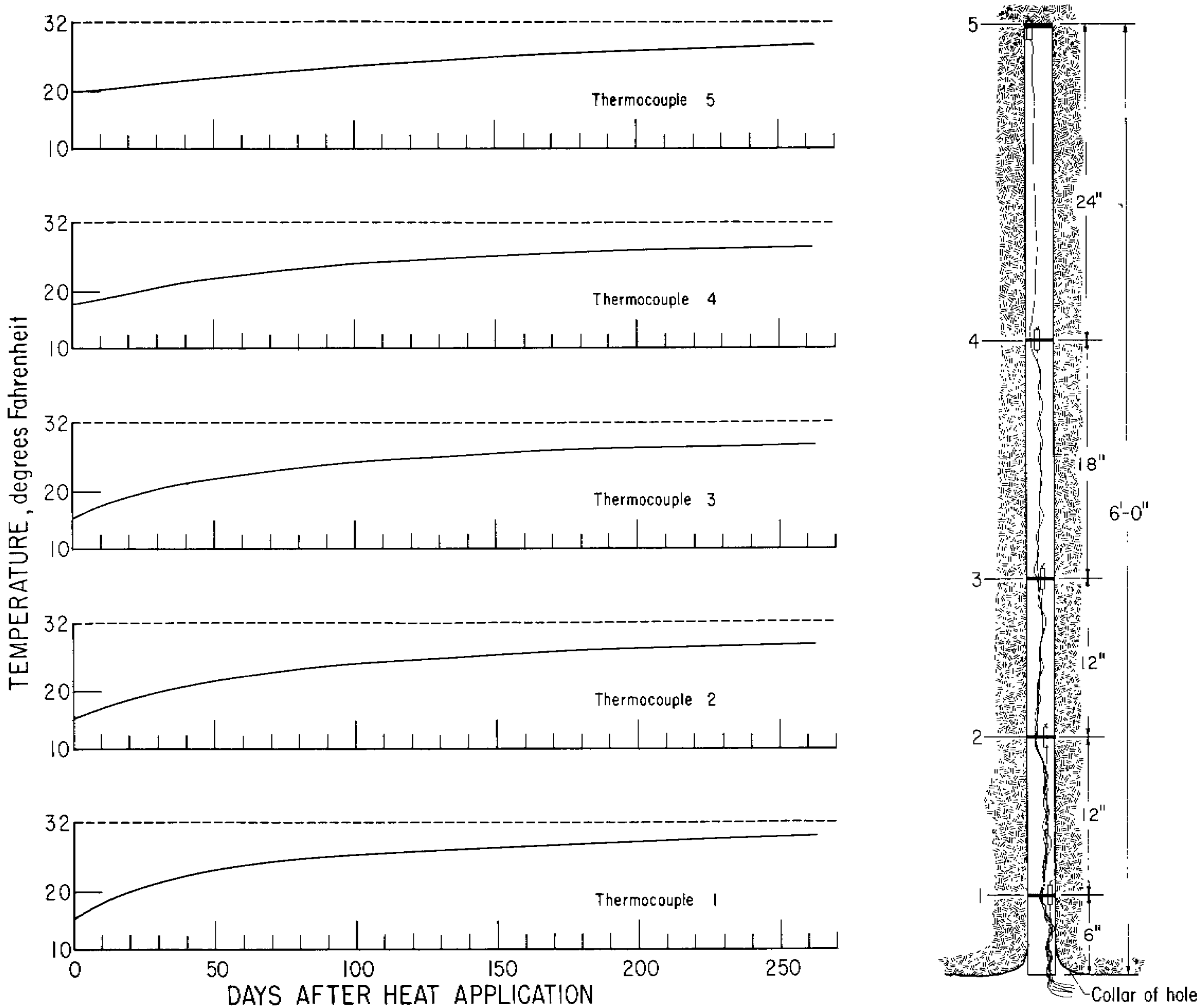


FIGURE 20. - Thermocouple Readings, Side Wall of Silt Room.

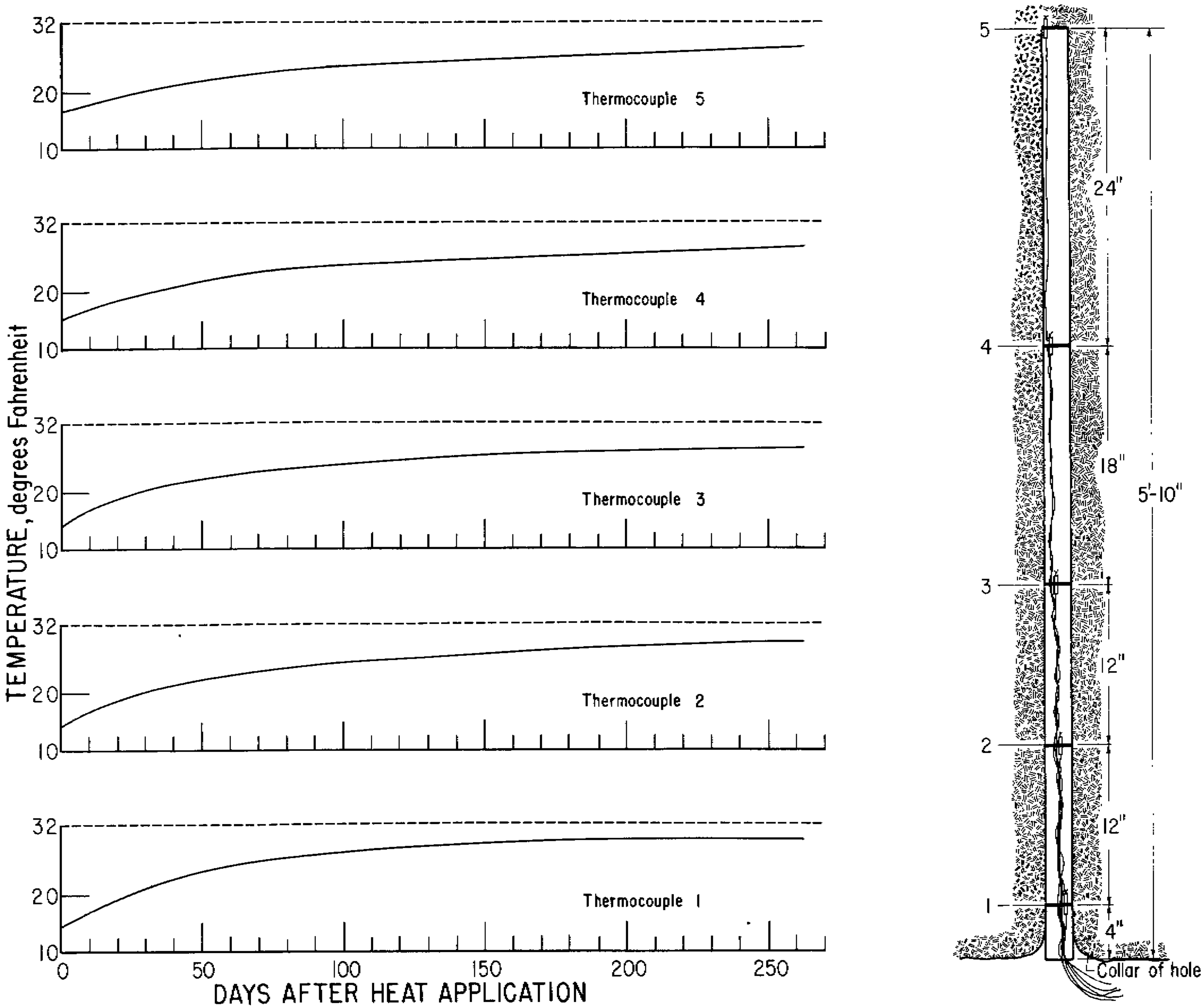


FIGURE 21. - Thermocouple Readings, Sill of Silt Room.

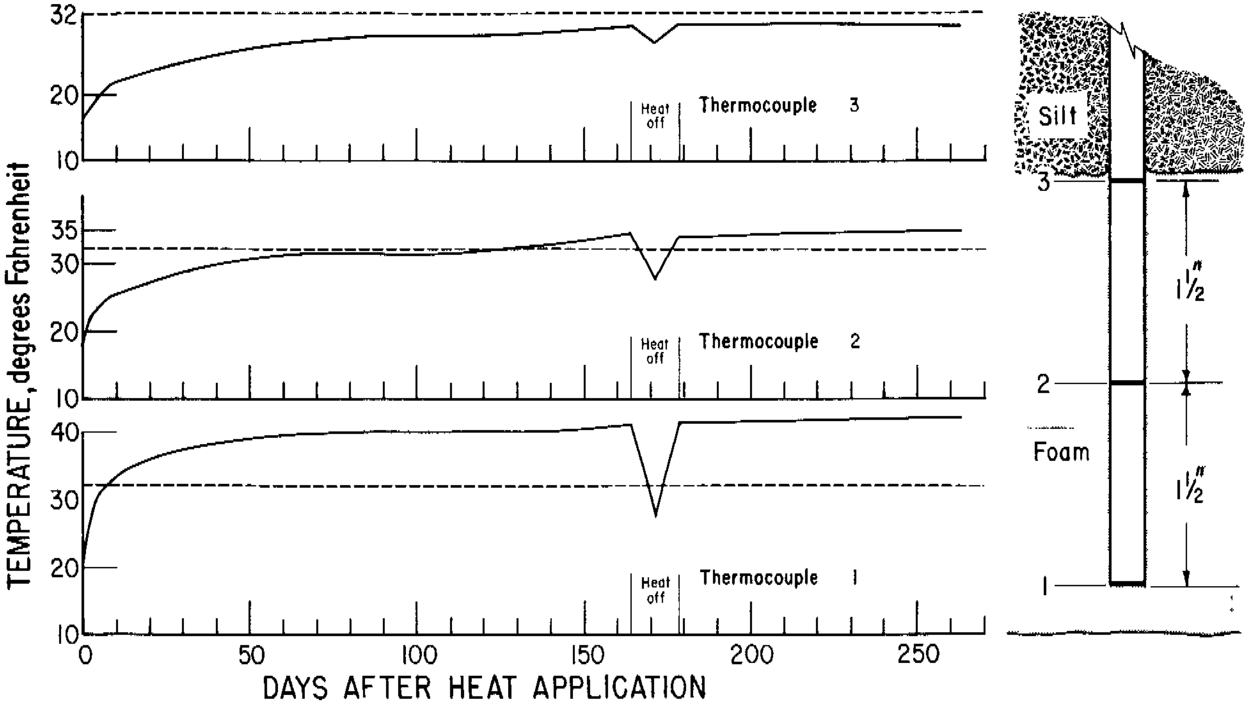


FIGURE 22. - Thermocouple Readings, Insulation in Silt Room.

An analysis of temperature reading in the walls indicates no apparent reason for the increases in closure rates in either foamed room. On August 7, 1969, the room adjacent to the foamed gravel room (fig. 9) was bulkheaded to allow ambient-air temperature to rise from 25° (result of refrigeration) to 28° F. As a direct consequence of air-temperature rise, the larger room exhibited an increase in vertical closure rate beginning the middle of August. This acceleration of closure in the larger adjacent room undoubtedly affected the closure rate of the foamed gravel room. However, no explanation has been found for the increase in horizontal closure rates of both foamed rooms approximately 2 weeks later.

Total closures from February 12 to October 24, 1969, as measured by steel tape, are given in table 5. Vertical closure of the gravel room was 2.4 times that of the silt room. Horizontal closure was 5.9 times that of the silt room. At least part of this difference can be attributed to the fact that the walls of the silt room were colder than those of the gravel room at the time insulation was applied. This condition still existed when heating and monitoring were discontinued. Figure 29 shows the effect of temperature on the strain of a frozen Manchester fine sand which is under compressive loading. The graph was constructed mathematically, using data derived by Sayles (8). The values are based upon an assumed 200 feet of overburden, averaging 120 pcf, acting over a 6-month period. Though these strain values are based upon laboratory results of unconfined compression tests on sand, the effect of temperature upon roof or wall closure in the silt and gravel rooms would be similar. Other factors that probably contributed to the differences in closure were differences in insulation thickness and physical properties of the surrounding medium.

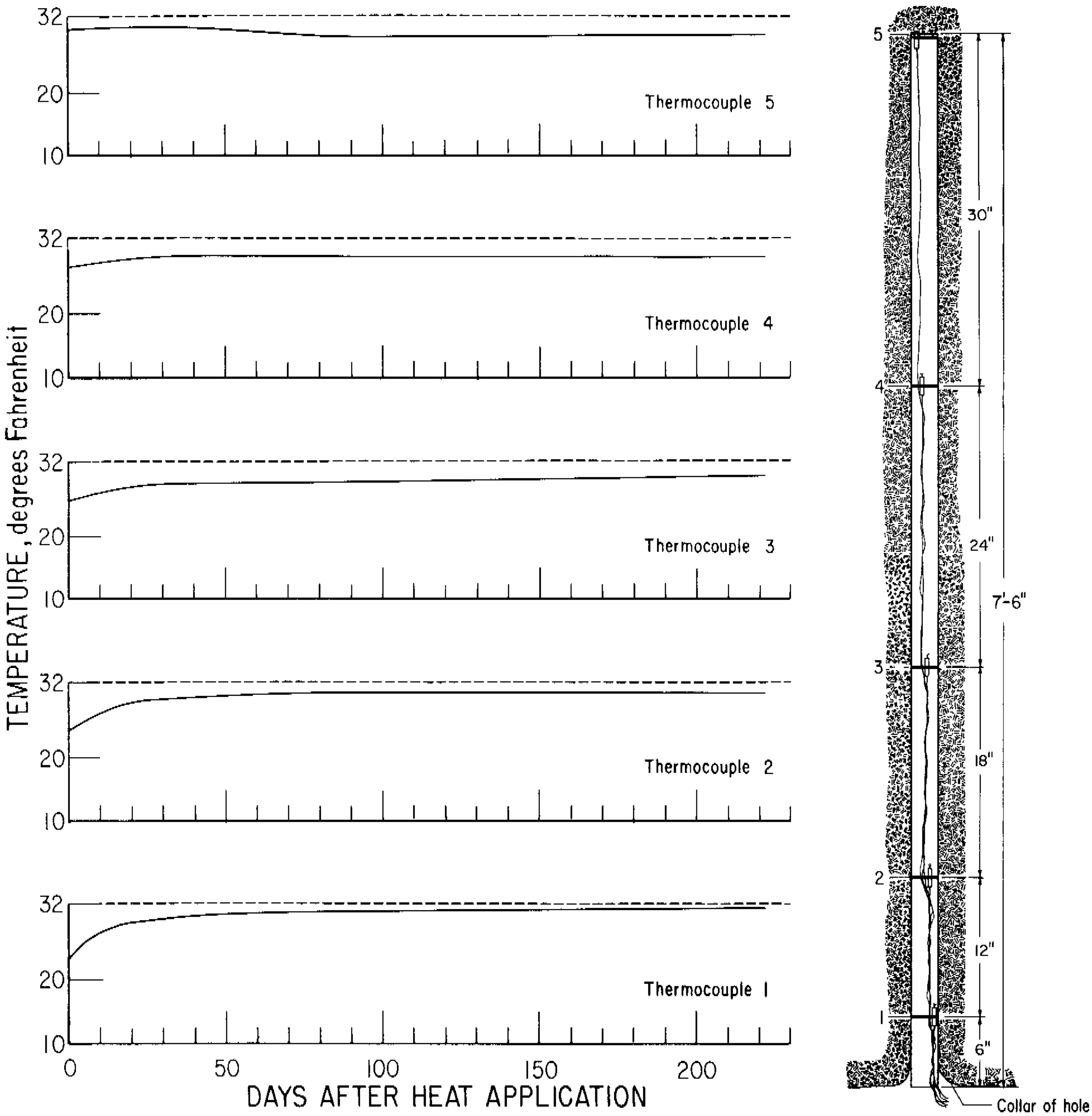


FIGURE 23. - Thermocouple Readings, Back of Gravel Room.

TABLE 5. - Total room closures

Room	Closure, inches	
	Horizontal	Vertical
Silt	0.38	1.88
Gravel	2.25	4.44

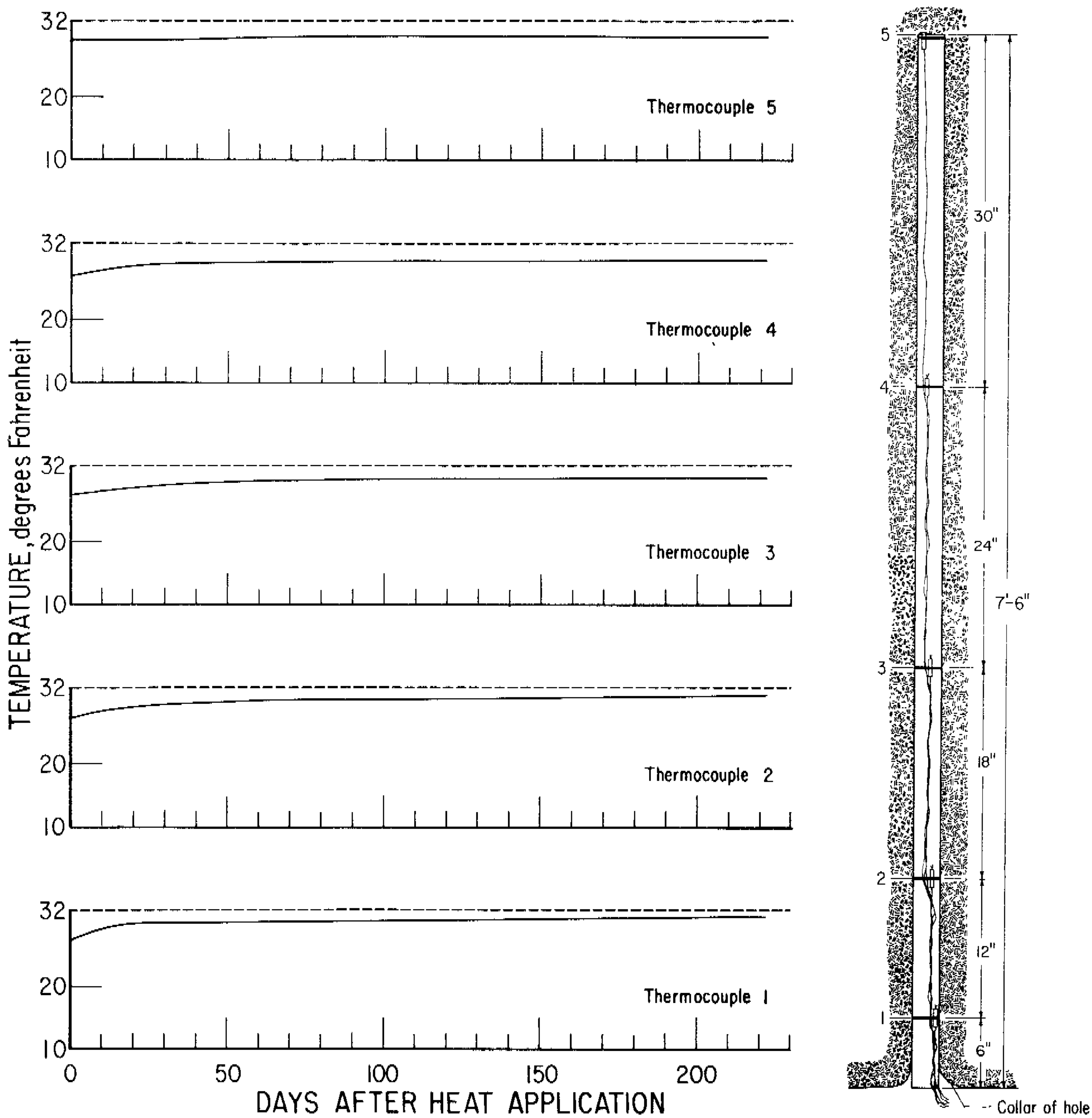


FIGURE 24. - Thermocouple Readings, End Wall of Gravel Room.

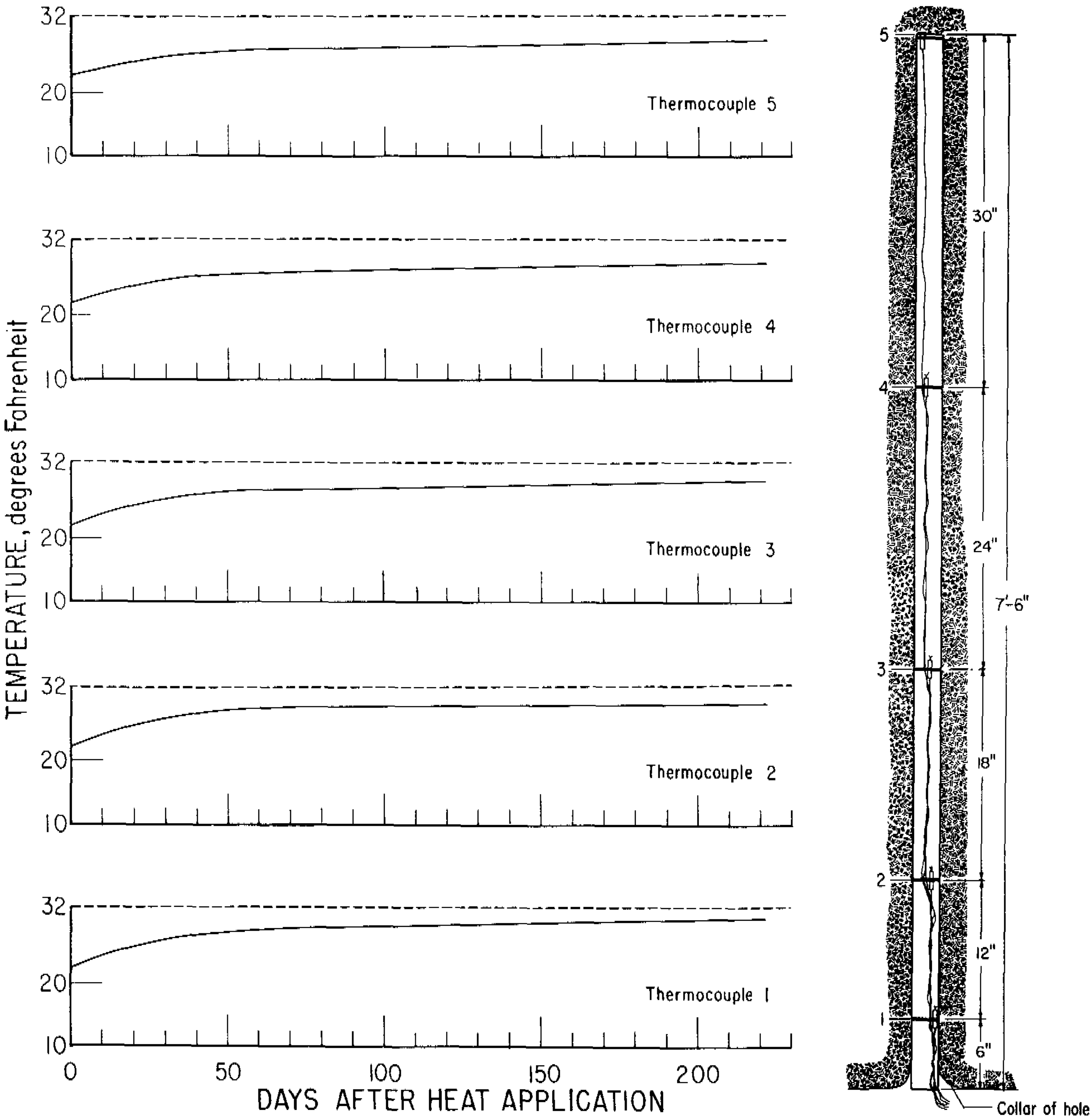


FIGURE 25. - Thermocouple Readings, Side Wall of Gravel Room.

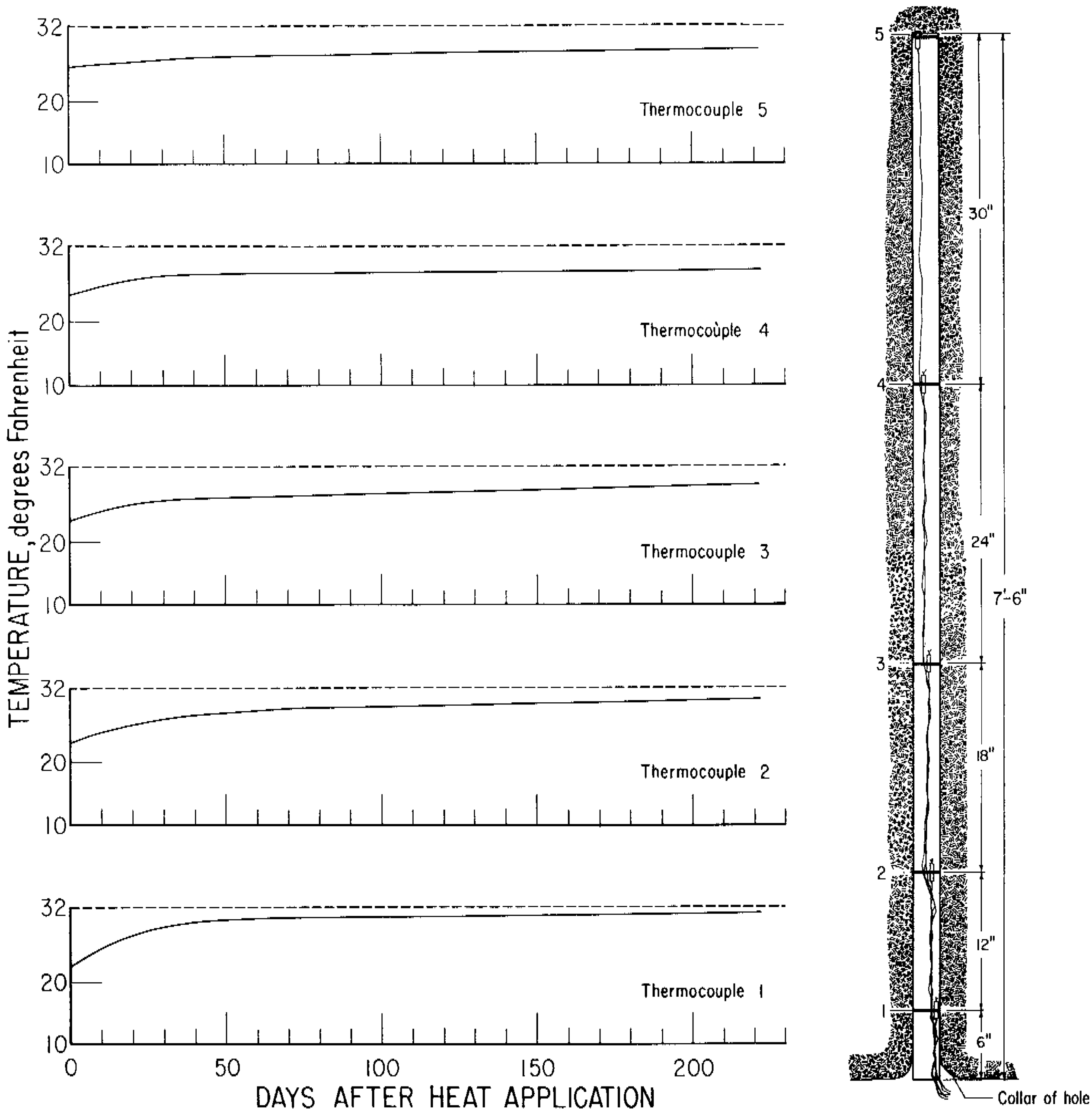


FIGURE 26. - Thermocouple Readings, Sill of Gravel Room.

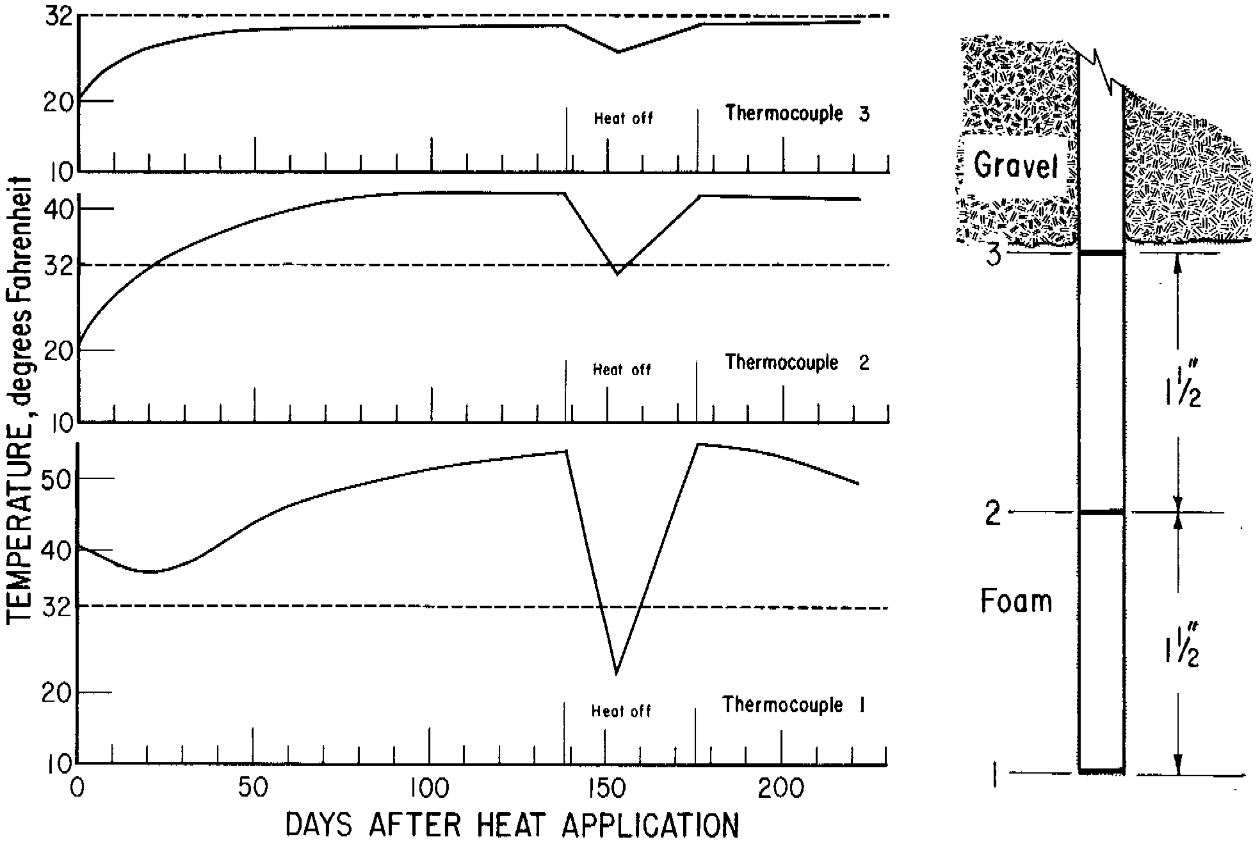


FIGURE 27. - Thermocouple Readings, Insulation in Gravel Room.

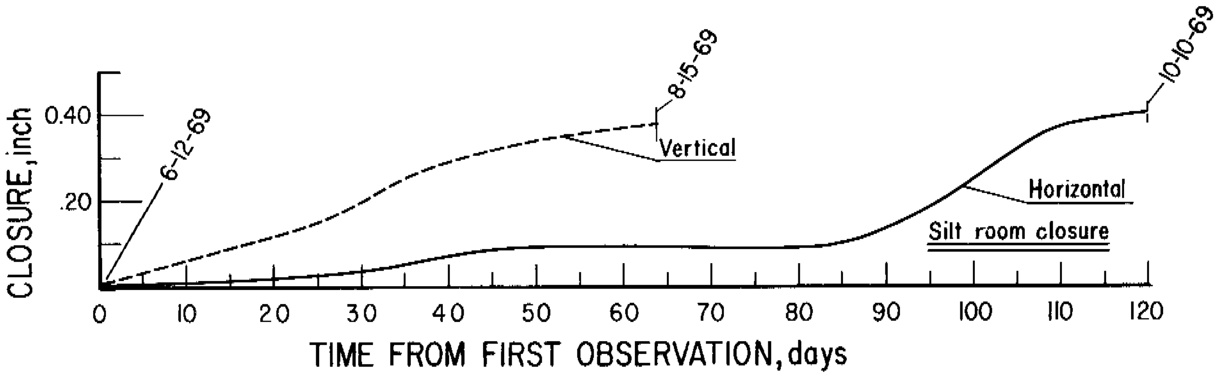
PROPOSED METHOD OF MAINTAINING SHAFTS AND HEATED ROOMS IN PERMAFROST

Obviously, it is desirable to exploit the extreme cold of winter whenever possible. A proposed method would utilize the winter cold to annually supercool the zone surrounding an insulated opening in permafrost.

In figure 30, holes are drilled and cased in the ground surrounding the shaft. In winter, cold air is pulled down the cased holes by a small fan and exhausted back up the shaft. The holes are sealed during the warmer months.

Rectangular ducts placed against the walls of the underground room afford passage for forced cold air during the winter months. The ducts are sealed during the summer.

In both schemes, the use of casing or ducts is necessary to prevent sublimation. Because creep cannot be entirely eliminated, soft squeeze blocking is required. With the scheme illustrated in figure 30, it should be possible to maintain a shaft or a heated room in permafrost for several years.



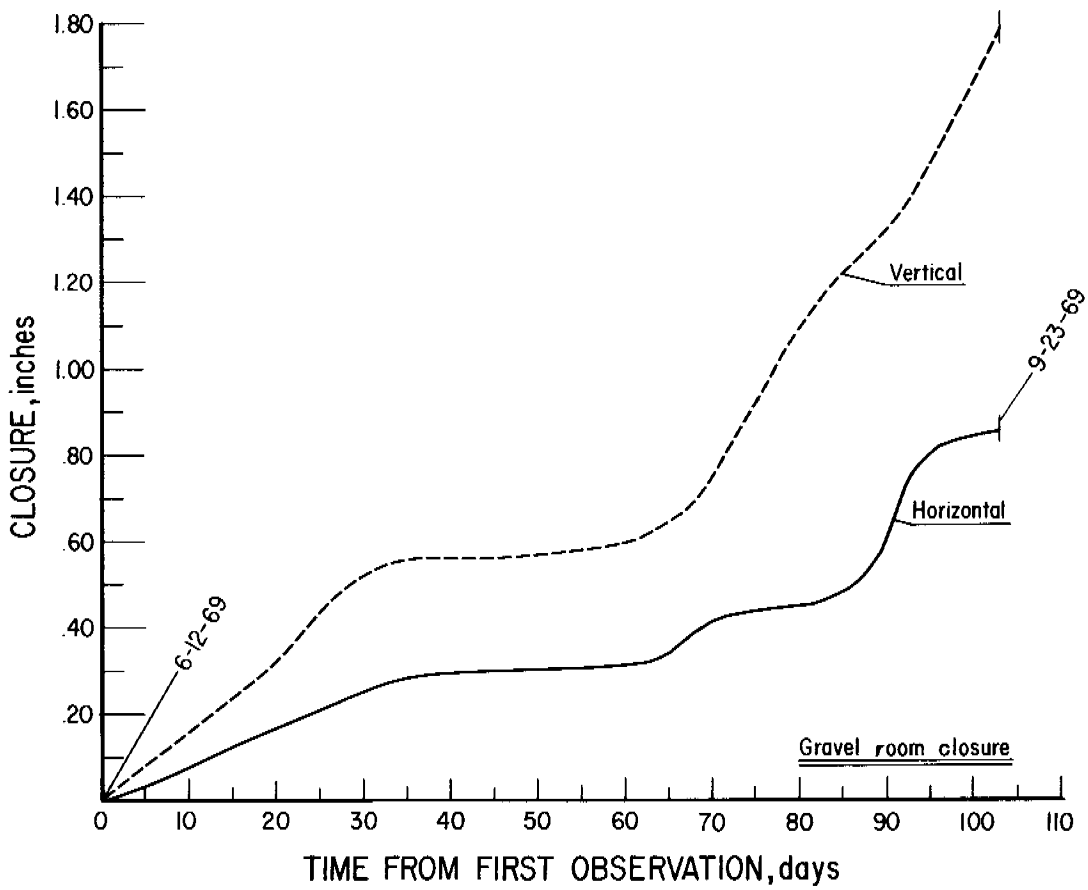


FIGURE 28. - Closure of Heated Insulated Rooms.

$$\epsilon = \left[\frac{\sigma}{\sigma_{01} (\theta + 1)^{a}} \right]^{1/K} \frac{t^{\psi}}{\psi} + \epsilon_0$$

$$\psi = \frac{M-1}{M}$$

$$M = \sigma^{1/w}$$

σ = applied stress, psi

ϵ = strain

ϵ_0 = initial strain

θ = temperature below freezing, °F

t = time, hours

σ_{01}, K, a, w are constants

For Manchester fine sand:

σ_{01} = 16,400 psi

K = 0.71

a = 0.46

w = 35

Assumptions:

Time = 180 days = 4,320 hours

Overburden is 200 feet in depth with average density of 120 pcf

Therefore σ = 168 psi

Note:

Formula and constants from "Creep of Frozen Sands" by Sayles(8)

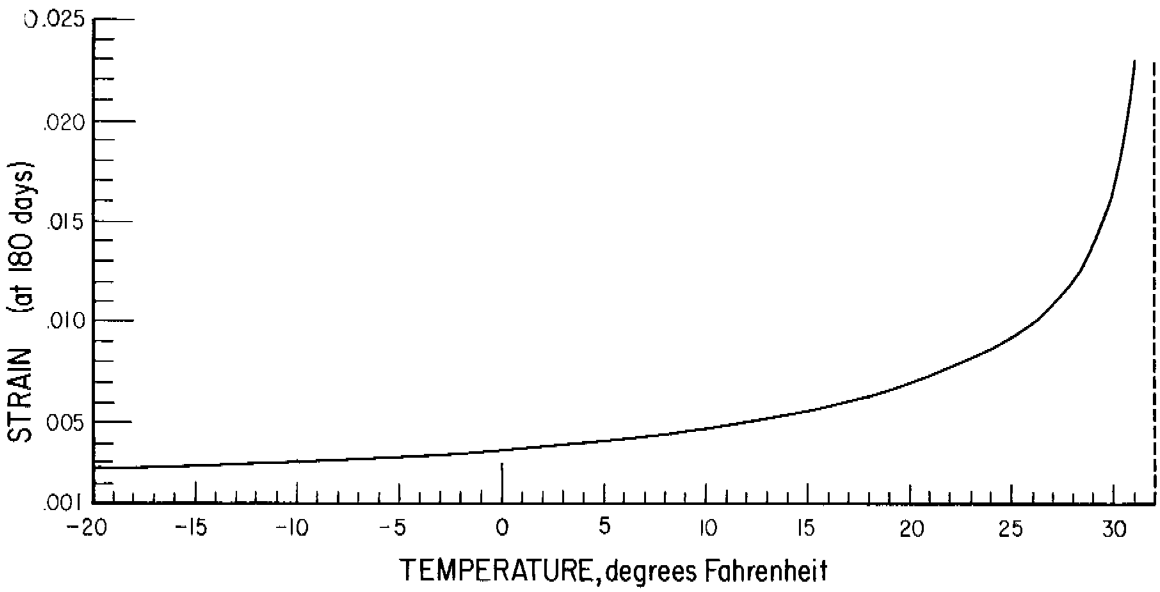


FIGURE 29. - Effect of Temperature on Strain of Frozen Sand.

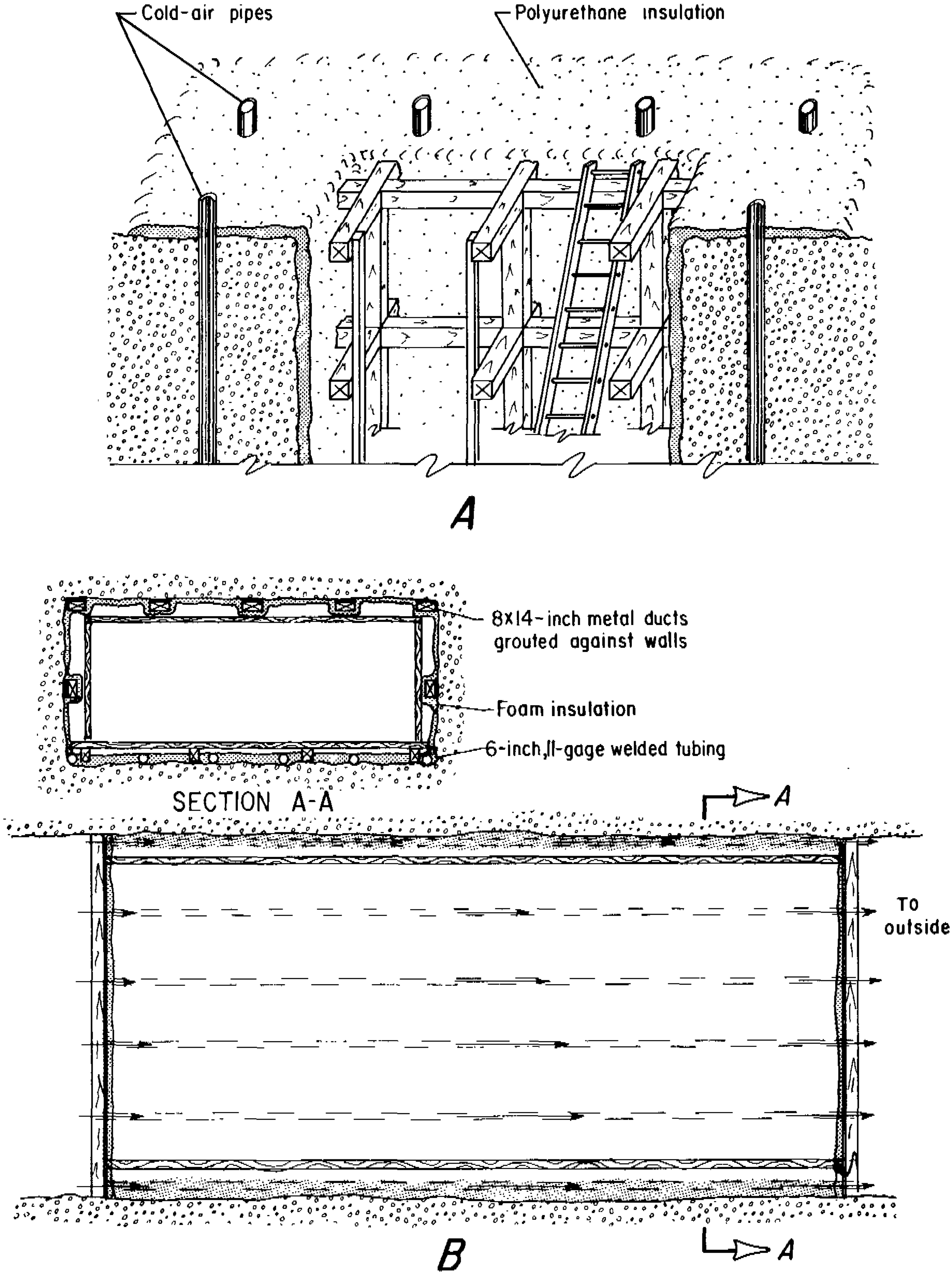


FIGURE 30. - Proposed Method of Maintaining Shaft or Heated Room in Permafrost. *A*, Shaft; *B*, heated room.

CONCLUSIONS

Based upon the laboratory experimental work and upon the foam application and subsequent monitoring in the CRREL tunnel, the following conclusions are advanced:

1. Polyurethane foam can be applied successfully to frozen silt and gravel.

2. Rigid polyurethane foam adheres well to frozen gravels; somewhat to frozen silt; and only slightly, if at all, to ice.

3. Polyurethane foaming can be conducted in a below-freezing environment.

4. During application, the liquid components used must be kept at a temperature in excess of 40° F.

5. An insulation over the heat tapes on the supply hoses would be helpful.

6. As the foam rises and cures, stresses are induced within the foam.

7. Face masks that direct a positive supply of fresh air in front of the operator's face should be used during foaming activity.

8. Spray-applied polyurethane foam proved to be an adequate form of insulation for a heated room excavated in permafrost.

9. A shaft or heated room insulated with polyurethane foam could be maintained in permafrost for several years by utilizing the winter cold to annually supercool the walls.

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