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technical note

A PROPOSED SYSTEM OF UTILITY PIPING INSTALLATION IN SNOW, ICE, AND PERMAFROST

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SUMMARY

Installation of piping in northern climates where the ground is frozen all year round (permafrost) has been a difficult engineering problem. Hot water and steam lines, even when installed with thick insulation or in utilidors, have eventually thawed the supporting ground which resulted in breakdowns of the systems. Cold piping, such as water and sewage, are subject to freezing and stoppages, breaking of the pipe, and under full flow conditions thawing of the supporting soil. The investigation reported herein was undertaken in an attempt to develop an economical method of installing utilities in permafrost.

Field experience and literature on the subject all point to the fact that utility structures in permafrost have failed because the thermal balance of the ground eventually becomes disturbed and thawing occurs. The principle of maintaining the thermal balance between the warm piping and the cold ground with a system of refrigerated piping was suggested by Mr. I. L. Winsor of Seattle. The tests conducted in the cold chamber of this Laboratory have been very encouraging and indicate that such a system is practical in both frozen ground and in ice.

INTRODUCTION

The necessity for constructing bases in the Arctic and Antarctic is dictated by the tactical problems of global warfare. The engineering and design of these bases is fraught with problems for which precedence is meager. Many of these bases are on permanently frozen ground (permafrost), and on ice or packed snow which may be either on the land or floating in the sea. The successful construction and operation of permanent utility distribution systems in the permafrost areas has been notably unsuccessful. The liquid carrying utility services have been particularly troublesome. Costly maintenance problems and unsatisfactory service conditions have arisen in almost all installations of water, sewage, and steam piping in permafrost. No installation of this type of utility has been attempted in ice or hard packed snow so far as is known.

Because of this, the Laboratory has investigated many systems of utilidors and insulations which indicated a possibility of success. As a result of tests conducted in a cold chamber in the early part of 1955, it was suggested that a system of refrigerated tracer lines designed to maintain the thermal balance between the utility piping and the frozen soil be investigated. This idea has a parallel in the system sometimes used under the floors of refrigerated warehouses in temperate climates when warm water is circulated through piping to prevent freezing of the subgrade. In the system proposed by this report, refrigerated brine is circulated to maintain the frozen soil structure of permafrost supporting a heated piping system. This report is a description of those tests and the results.

BASIC PRINCIPLES

The basic problem in protecting a utility system supported by permafrost or ice is one of maintaining the permafrost or ice in its original frozen condition. As long as this is done, the structural characteristics of the supporting soil or ice is maintained and stability is not lost. This problem was graphically demonstrated by installing a 4-in., 330-F steam line in a box of permafrost with 12 in. of insulation around the pipe. Figure 1 shows how the surface temperature of the insulation gradually rose until the surrounding ground thawed.

The 12 in. of insulation provided in this setup had an over-all coefficient of transmission (U) of 0.05 Btu/sq ft (°F) (hr) which is considered excellent. In spite of this the outside of the insulation eventually rose to a temperature over 32 F. This is because insulation will not stop the flow of heat but merely acts as a resistance material. If the heat is not conducted away from the surface of the insulation, at a rate equal to the rate at which it leaks through the insulation, the surface temperature will rise. This temperature will rise until conduction of heat through the insulation equals the conductance of heat away from the outside surface of the insulation. As ice and frozen soil are poor conductors, any attempt to depend on conductance from the insulation surface is doomed to failure.

Another problem which must be considered in construction in permafrost is the fact that the normal temperature of permafrost in most areas is as little as one half a degree below freezing. Heat flow depends on inducing a temperature gradient. It is therefore impossible to produce heat transfer through permafrost because the necessary temperature difference for conductance will produce thawing.

This problem has been demonstrated in the field by constructing heated buildings on 6-ft thick beds of gravel fill. This type of structural support provides insulation between the building and permafrost but experience shows that thawing temperatures will eventually be reached in the permafrost below the insulating pad.[2] Figure 2 is an example of the thermal unbalance and the thawing caused by a water line in permafrost.

THE THERMAL BALANCE SYSTEM

The method of installation of buried utility piping proposed by this report involves the use of refrigerated brine piping as a heat sump or collecting system. Figure 3 illustrates this basic system as it was tested at this Laboratory.

The component equipment involved includes:

1. A brine chiller.

2. A direct expansion refrigeration machine to serve the chiller.

3. An outside air coil to chill the brine when the air temperature is below the desired brine temperature. This will make it necessary to use mechanical refrigeration during the summer months only.

4. A brine circulating pump.

5. Brine tubing.

6. Temperature controls.

Before discussing the engineering design criteria of the Thermal Balance System, the Laboratory test data will be presented and discussed.

LABORATORY TEST PROGRAM

The first Laboratory investigation of the problem of installing hot piping in permafrost was made by installing an 8-ft long, 4-in., 100-psi steam line in artificial permafrost (Figure 1). As pointed out in the Introduction, the insulation only delays, not preventing, the thawing of the ground. As a result of this, it was decided that the only solution lay in considering the permafrost as unable to absorb any heat. Therefore, a heat absorption device must be installed between the insulation and the permafrost.

The first test of the Thermal Balance System of permafrost protection involved the use of the same 4-ft by 4-ft by 10-ft long box as previously used. The steam and refrigerated tracer piping setup is shown in Figure 5. The insulation thickness was 10 in. and the tracer lines were 3/4 in. copper tubing. Good results were obtained but the steam pipe was not long enough to provide conclusive heat balance data.

A second series of tests were conducted in a 20-ft long box with 2 ft by 2 ft inside dimensions. This box is illustrated by Figure 6. A part of the temperature-time data is plotted in Figure 7. A section of the box is shown by Figure 8 with the isotherms plotted to show temperature gradients through the insulation and soil. The pattern of temperatures shows that heat was leaking out the corners of the insulation to the permafrost which was only held in the frozen condition by the low outside air temperature. The heat gain to the brine tubing amounted to approximately 34 Btu/hr per ft of steam pipe. The U value of the insulation, 0.20 Btu/hr (ft^2) (°F) indicates that the heat gain to the brine should be approximately 200 Btu/hr per ft of steam pipe.

Because of the above, a condensate meter was added to the steam line and more thermocuples were included in the setup. Data from this run produced the following results:

Heat loss from 20-ft long 4-in., 100-psi steam pipe=
  5.4 lb/hr condensate x 807 Btu/lb =
  4358 lb/hr or 218 Btu/hr per ft of trench.

Heat gain to brine in tracer lines =
  9.7 lb/min. x 60 x 0.8 Btu/lb x (8.5 F -0F) =
  3950 Btu/hr or 198 Btu/hr per ft of trench.

Heat loss calculated from U of insulation =

$$\frac{Km\ 2\pi\ L\ \Delta T}{\log_n \frac{r_1}{r_o}} = \frac{0.2 \times 2\pi \times 20 \times 291}{\log_n \frac{6.6}{1.25}} = 4400 \text{ Btu/hr or } 220 \text{ Btu/hr per ft of trench.}$$

This three way heat balance, checking with 10 per cent, confirms the assumption that it is practical to collect the heat with the tracer lines. The next step was to determine the most economical method of preventing overheating the soil between the tracer piping.

The practicality of lining the ditch floor and walls with a good heat conductor such as expanded metal was investigated. One way to do this would involve wiring strips of expanded metal to the tracer piping. A cost analysis showed that this material would add approximately $1.00 per running foot of steam line to the material costs for 12- by 12-in. ditch. The addition of 4 tracer lines to the original 4 pipe system would add only $.50 per foot to the cost. For this reason a setup was made using 2 tracer lines on each of the 4 sides of the insulation. The eight 1/2-in. black iron pipes as installed gave a spacing of 6-in. centers (Figure 10).

The third set of tests were conducted with the 8 tracer lines and the 20-ft long, 4-in. steam pipe arranged as shown in Figure 9. With this setup the heat balance showed the following results:

Heat loss from 100 psi steam = 4071 Btu/hr or
204 Btu/hr per ft of trench

Heat gain to brine = 3960 Btu/hr or
198 Btu/hr per ft of trench

The isotherm gradient in the insulation is shown by Figure 10.

ECONOMICS OF THE THERMAL BALANCE SYSTEM

Any system of insulating utility piping must be designed on the basis of the economics of heat conservation. Insulating materials are expensive, usually costing more than the piping it protects. Heat loss from piping is a long range cost reflected in fuel, boiler water treatment, and pumping costs. For these reasons, preformed insulations are manufactured in varying thicknesses so that the designer may select the most economical thickness for his problem.

The Thermal Balance System of piping protection in permafrost is no exception to this. The use of a minimum insulation thickness will be reflected in increased refrigeration equipment first costs and operating power costs. Conversely, the use of a thicker layer of insulation will reduce the size and cost of the refrigeration system and its operating cost by increasing the initial investment in insulation.

A comparison of costs per foot of trench based on different insulation thickness on a 4-in., 100-psi steam line shows the following:

Insulation U Value, Btu/hr (ft^2)(°F)	0.20	0.12
Steam piping	$1.50	$1.50
Pipe supports, anchors and expan. joints	.70	.70
Chilled brine tracer piping	1.00	1.00
Insulation	2.20	4.40
Material cost per ft of trench	$5.40	$7.40
Heat loss per ft of pipe	200 Btu/hr	119 Btu/hr
(For estimating purposes, assume 1000 ft of steam line in the system)		
Total refrigeration load	200,000 Btu/hr	119,000 Btu/hr
Chiller capacity	16.7 tons	10 tons
Cost of refrigeration equipment, pumps and controls	$5000.00	$3500.00
Cost per foot of trench	$5.00	$3.50
Cost of system material & equip.	10.40	10.50

This calculation indicates that the first cost of materials is approximately the same for systems using different insulation thicknesses. The long range economic problems must therefore govern the design. The labor cost for the systems have been omitted because they are nearly the same and vary from location to location. Equipment shipping costs are also considered to be nearly equal.

Consider the savings in fuel and refrigeration power consumption:

Insulation U Value, Btu/hr (ft^2) (°F)	0.20	0.12
Heat loss from pipe (per ft)	200 Btu/hr	119 Btu/hr
Boiler fuel oil (80% comb. eff.) wasted by heat loss per ft of pipe	17.5 gal/yr	10.4 gal/yr
Diesel oil consumed by an engine-generator to power the refrigeration system (per ft of trench)	17.6 gal/yr	8.8 gal/yr
Total fuel consumed by system per ft of buried pipe	35.1 gal/yr	19.2 gal/yr

This calculation clearly illustrates the economy of providing ample insulation on utility systems of all types. If these figures are applied to a simple 1000-ft distribution system (without any refrigeration system) the one with an insulation U value of 0.20 will consume 17,500 gal of fuel a year to make up for the heat loss alone. By increasing the insulation thickness to provide a U value of 0.12, the fuel consumed for heat loss will be reduced to 10,400 gal/year; a saving of 7,100 gal/year.

The fuel required for the Thermal Balance System, if a 1000 foot system is considered, amounts to 35,100 gal/year if the insulation U value is 0.20 and 19,200 gal/year if the insulation U value is 0.12. A saving of 15,900 gal/year with the increased insulation.

The above discussion is only to point up the need for careful consideration of insulation during the design phase of a utility system. This is particularly serious in the advanced base situation where the shipping problem dominates all others. The added space required to ship insulation will often be more than compensated for by the saving in fuel oil.

The Thermal Balance System requires more equipment than a plain insulation system but the added cost and complexity is considered justified because it makes burial of hot piping in snow, ice, and permafrost a practical operation. As far as is known, no other system has been satisfactory over a period of more than a few years.

The cost of power for the refrigeration in the Thermal Balance System has been estimated above on the basis of using mechanical refrigeration device being required only during the warmer summer months. The Alaskan map, Figure 11, illustrates the months each year that mechanical refrigeration is required to operate the system.

CONCLUSIONS

The system of pipe protection reported herein shows promise of solving one of the most difficult problems found in Arctic construction. It is therefore recommended that a complete investigation be authorized as outlined in Appendix A, Project Proposal dated 7 February 1956.

REFERENCES

1. U. S. Army, Office of Chief of Engineers, Military Intelligence Division, "Permafrost or Permanently Frozen Ground and Related Engineering Problems," August 1945.

2. Northwest Territory Division of Building Research, National Research Council, Canada, "Building Foundations on Permafrost, McKenzie Valley," June, 1951.

APPENDIX A

PROJECT PROPOSAL

General Statement of Objective

Construction of buildings and facilities on and in permafrost is costly and present techniques have generally been unsatisfactory. Settling and heaving of structures has caused structural damage and failure. Preliminary investigation at NAVCERELAB has shown promising results using a system of refrigeration to maintain the frozen structure of the permafrost under and around structures or utilities and prevent settling and heaving.

Limitations of Present Insulations

Reports from Canadian and United States bases in permafrost areas have invariably shown that present installations using pilings, gravel fill, insulating materials, etc., to support structures and utilities have had a high percentage of failures within the first few years of service. The reference listed at the end of this proposal gives evidence of the field experience with typical construction methods.

Justification

The Navy's work in the arctic and antarctic areas require that buildings be constructed on snow, ice, and permafrost. A preliminary test program at NAVCERELAB has indicated that a system using refrigerated tracer lines shows promise of solving problems of construction on and in these frozen materials. An economic and engineering analysis will be available in the near future outlining the advantages and disadvantages of the proposed system of structural protection. As present methods have been unsuccessful, any possible solution of the problem should be investigated.

Suggested Program

Evaluation of the proposed system on snow, ice, and permafrost will be made in the Laboratory Cold Chamber facilities and with available refrigeration and heating equipment. The costs of operation and equipment will be carefully analyzed as well as the field installation problems. Pilot installations should be made on typical advance bases arctic facilities in order to completely evaluate prototype systems. It is felt that this can be accomplished by fabricating a small prototype building locally incorporating this technique and shipping it to the advance base for erection and in-service testing. A prototype piping system can be similarly prefabricated and field tested.

Funds Required

It is estimated that the following budget will be required:

FY 57	Prototype	$8000
FY 57	Laboratory labor and materials	$6000
FY 58	Prototype	$5000
FY 58	Laboratory labor and materials	$6000
	Total	$25,000

Time Schedule

Two years will be required to develop the necessary design criteria for field use of this system. Interim reports will be published giving all pertinent information as it becomes available. This proposal may fit into the existing project on snow, ice, and permafrost, in which case two new subtasks might cover construction of buildings on snow, ice, and permafrost, and installation of utilities in snow, ice, and permafrost. Completion date: June 1958.

References

N.R.C. of Canada, Report No. 8, "Building Foundations on Permafrost, McKenzie Valley, N.W.T.".

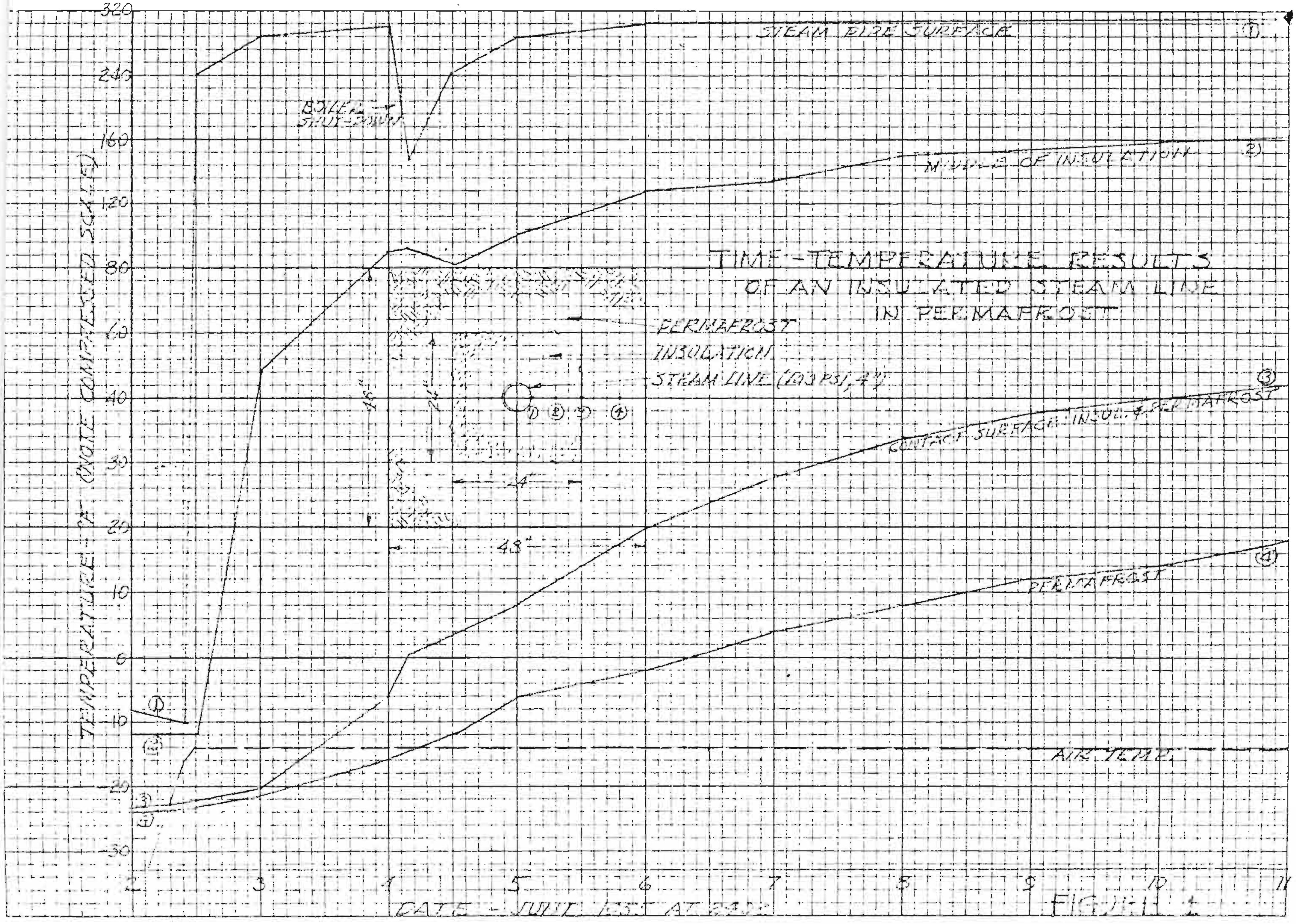
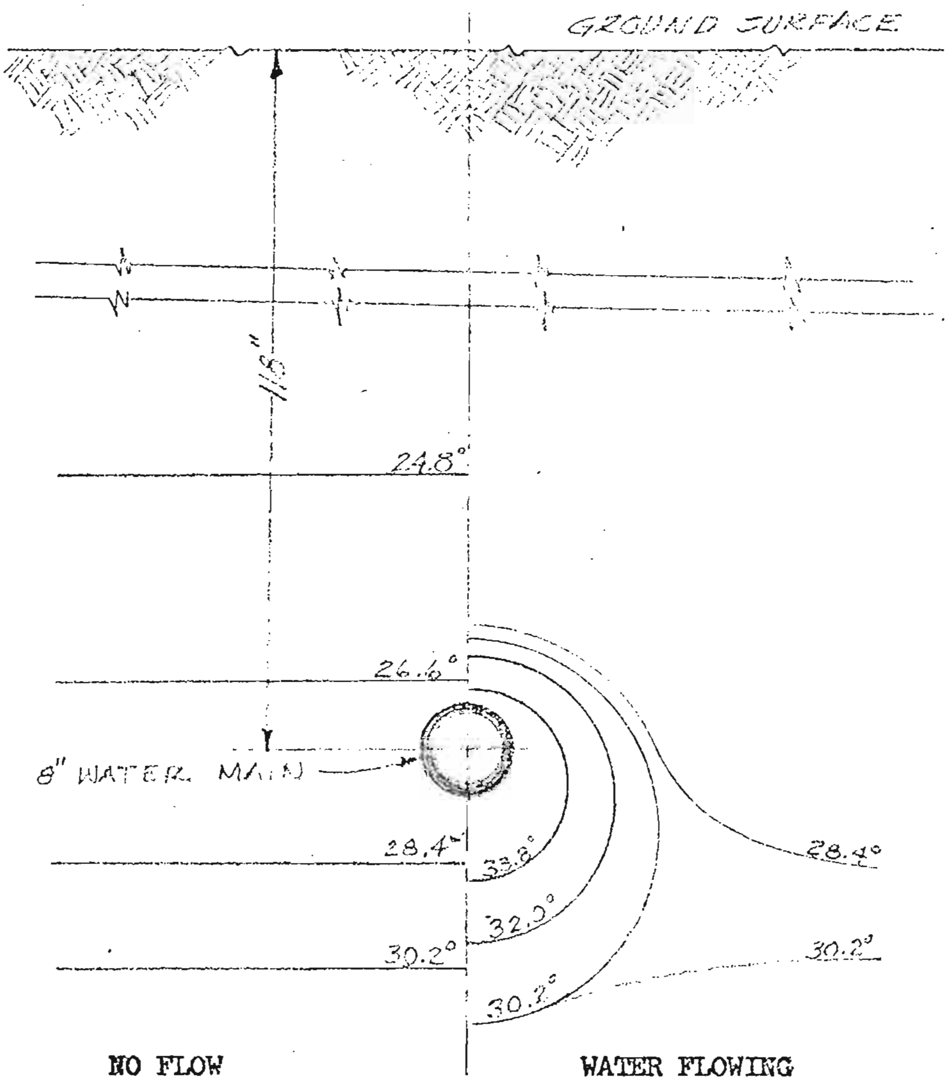

STEAM PIPE SURFACE
BOILER SHUT-DOWN
MIDDLE OF INSULATION
TIME-TEMPERATURE RESULTS
OF AN INSULATED STEAM LINE
IN PERMAFROST
PERMAFROST
INSULATION
STEAM LINE
CONTACT SURFACE INSUL. & PERMAFROST
PERMAFROST
AIR TEMP.
TEMPERATURE °F (NOTE COMPRESSED SCALE)
DATE - JULY

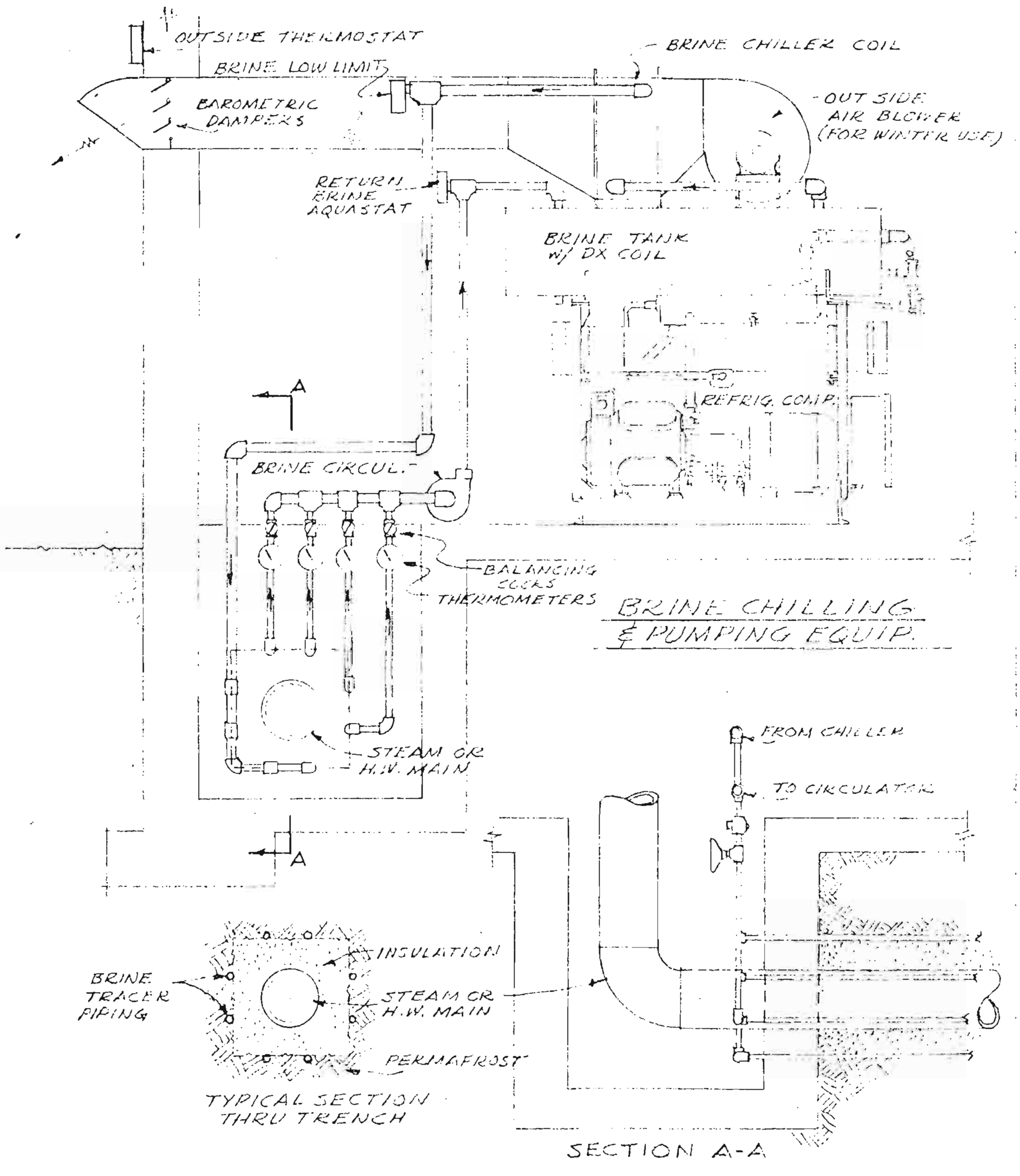
FIGURE 1



ISOTHERMS IN PERMAFROST
AROUND A WATER MAIN

Adapted from Figure 76, Reference 1.

Control Sequence: Return brine aquastat maintains brine at 20 F or below. Outside thermostat switches control from DX coil chiller to outside air chiller when air temperature is below 15 F. Low limit on brine at 10 F.



THERMAL BALANCE SYSTEM FOR PERMAFROST

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12 FEB 1956 S. GILES

FIGURE 3

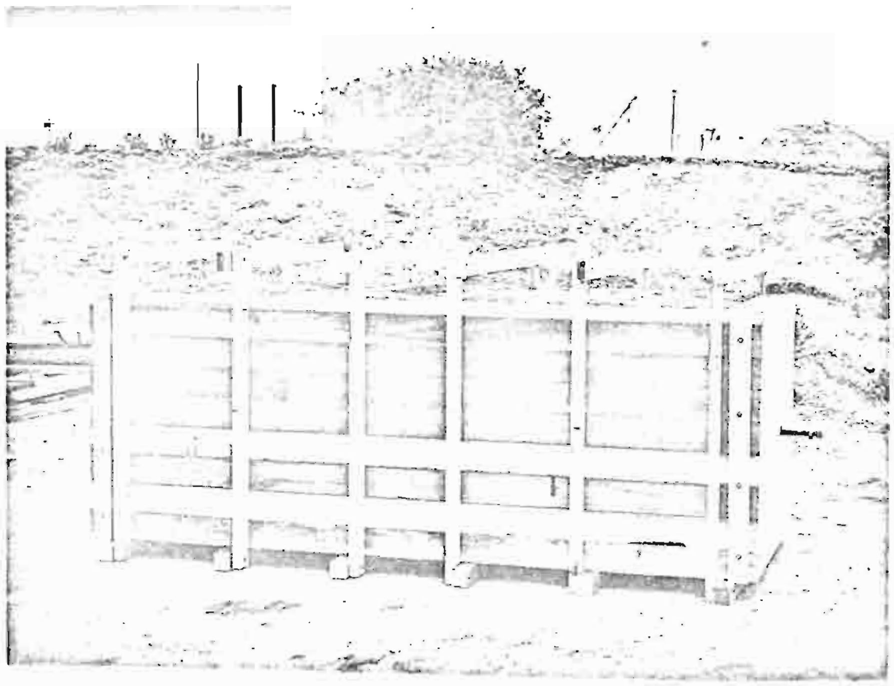


Figure 4. First test box filled with wet earth around insulation and piping. No tracers used. (See Figure 1 for results.)

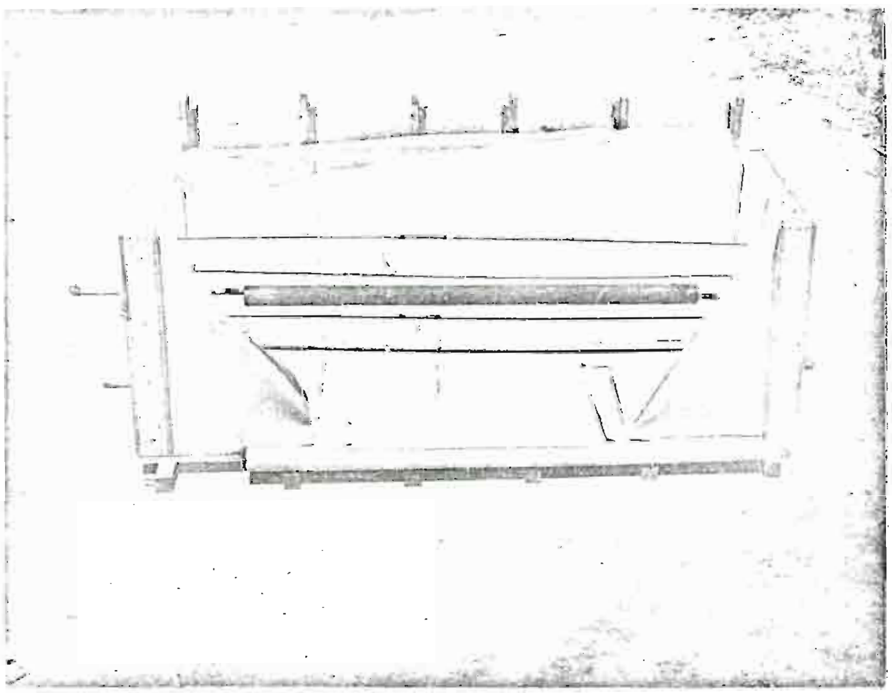
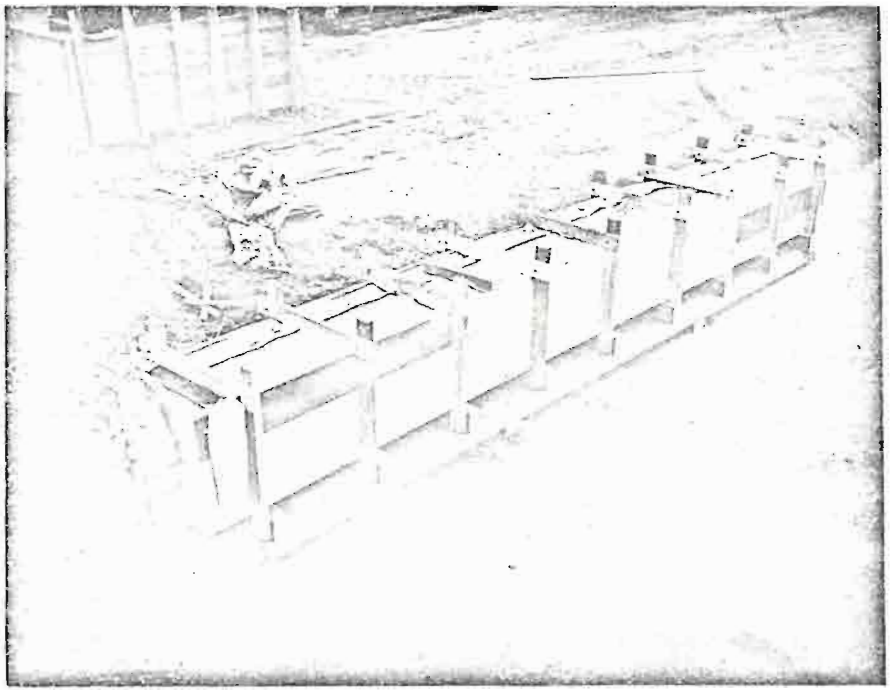


Figure 5. First test box used with Thermal Balance System for piping protection in permafrost. Box measures 4'x4'x8' inside.



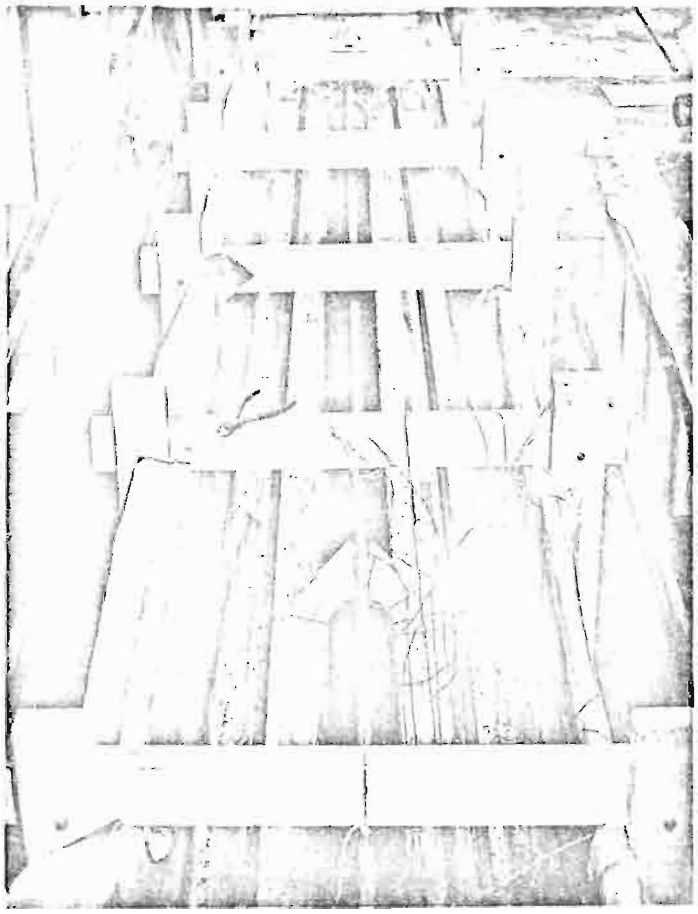
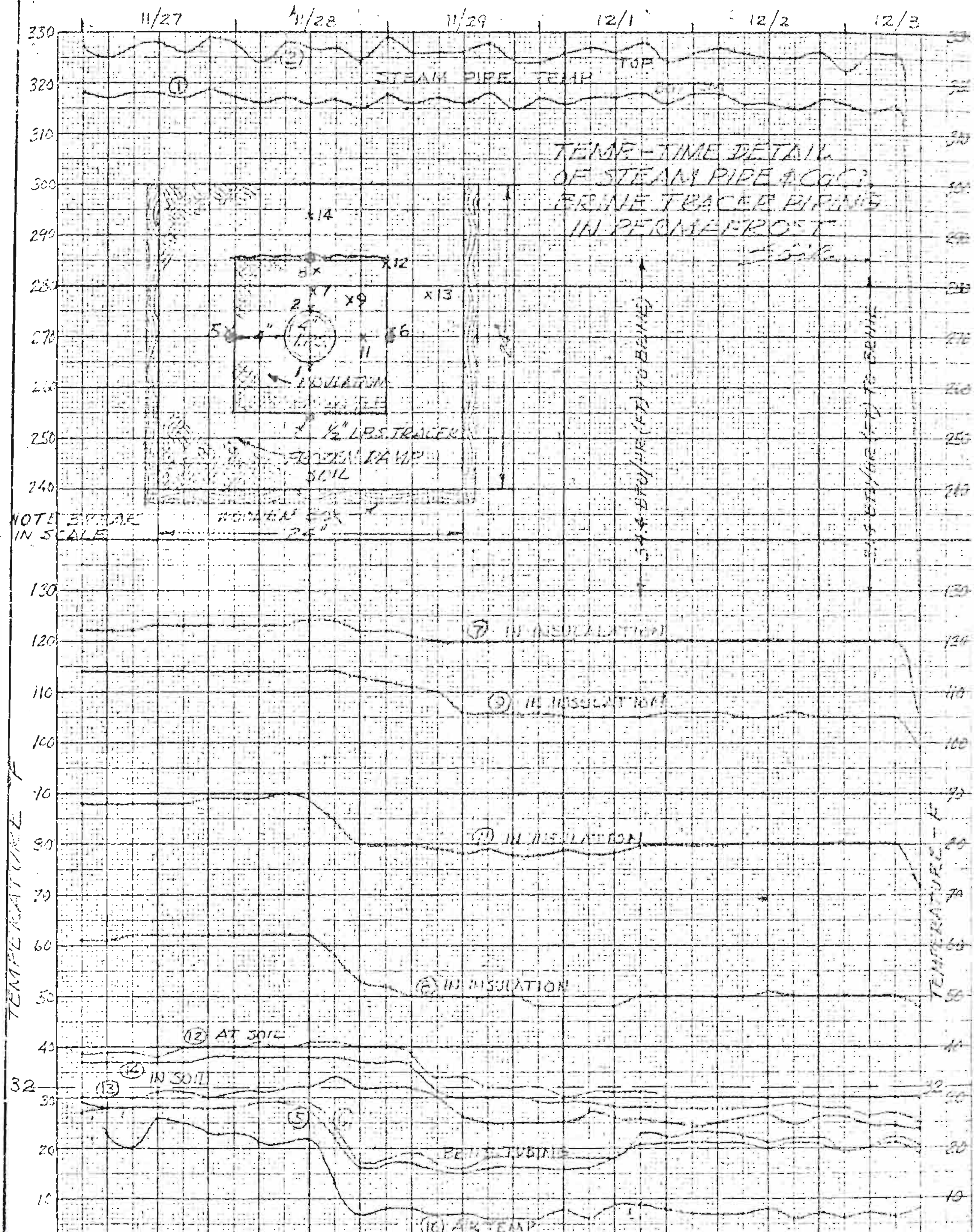
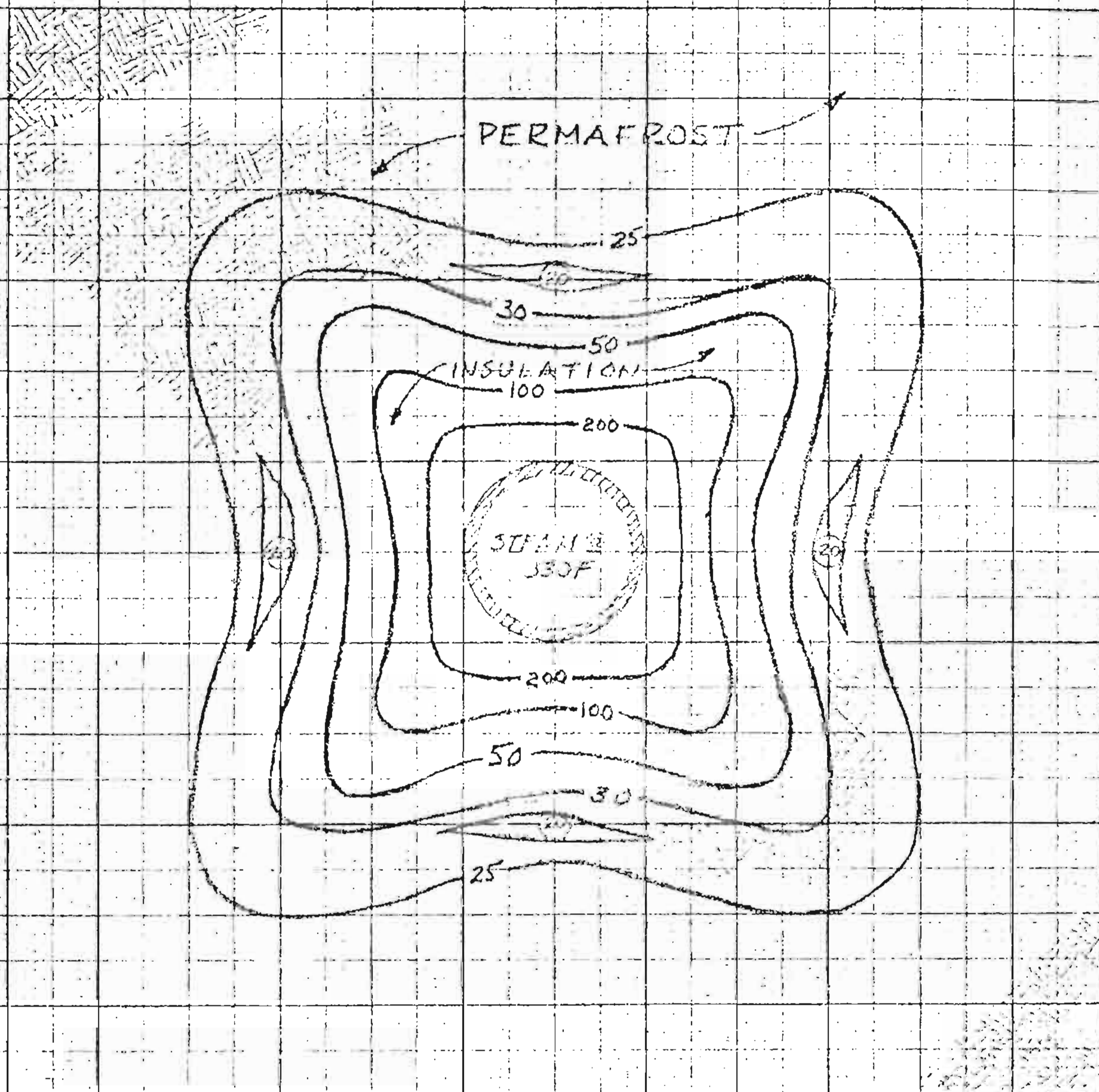


Figure 6. Second box used for test of Thermal Balance System for piping protection in permafrost. Box measures 2'x2'x20' inside. 4" of insulation around pipe. (See Figures 7 and 8.)



TEMP-TIME DETAIL OF STEAM PIPE & CaCl2 BRINE TRACER PIPING IN PERMAFROST
STEAM PIPE TEMP
TOP
11/27
11/28
11/29
12/1
12/2
12/3
TEMPERATURE °F
TEMPERATURE - °F
NOTE BREAK IN SCALE
WOODEN BOX
24"
1/2" I.P.S. TRACER
FROZEN DAMP SOIL
INSULATION
7 IN INSULATION
9 IN INSULATION
11 IN INSULATION
8 IN INSULATION
12 AT SOIL
14 IN SOIL
13
BRINE TUBING
10 AIR TEMP
27
28
29
1
2
3
NOVEMBER
1955
DECEMBER

FIGURE 7



ESTIMATED TEMPERATURE
GRADIENT IN INSULATION
AND PERMAFROST (FROM LAB TEST)
TEST OF STEAM PIPE WITH CHILLED
TRACER SYSTEM-4 PIPE SYST.

12-13-

FIGURE 8

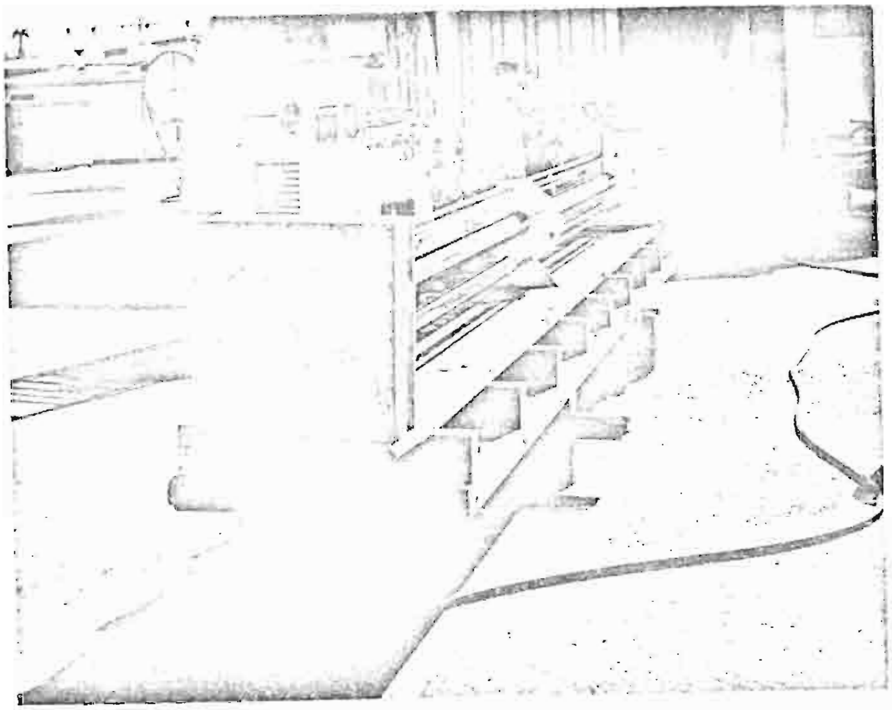
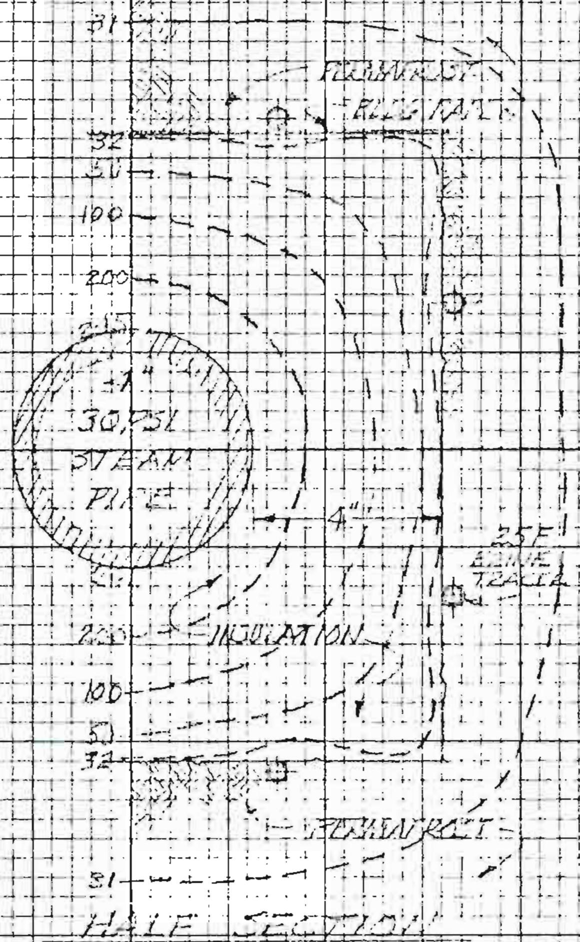
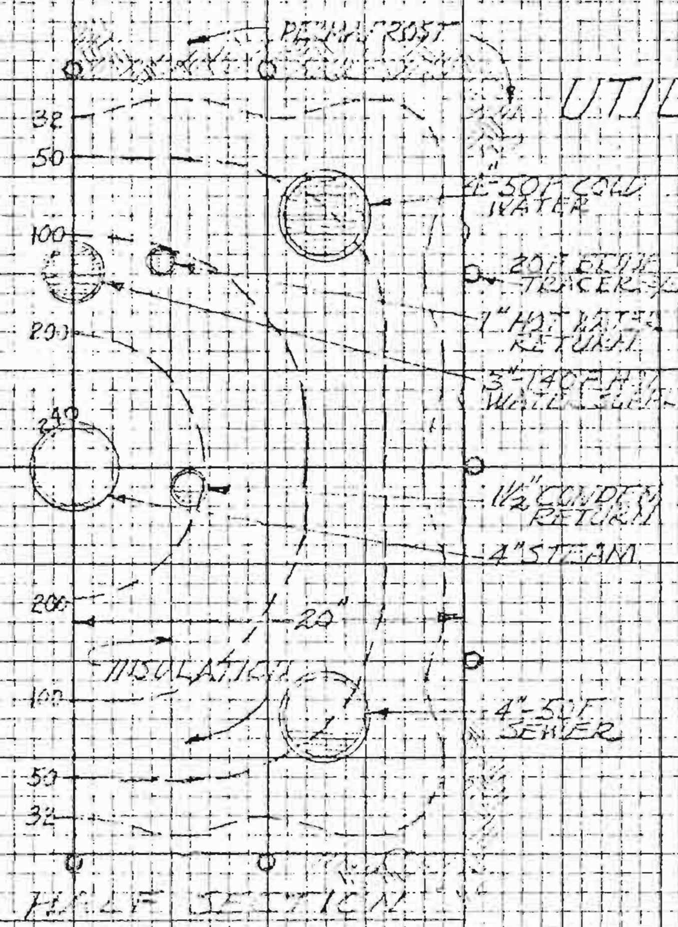


Figure 9. Test box being assembled with 8 tracer lines spaced 4" away from the steam pipe.

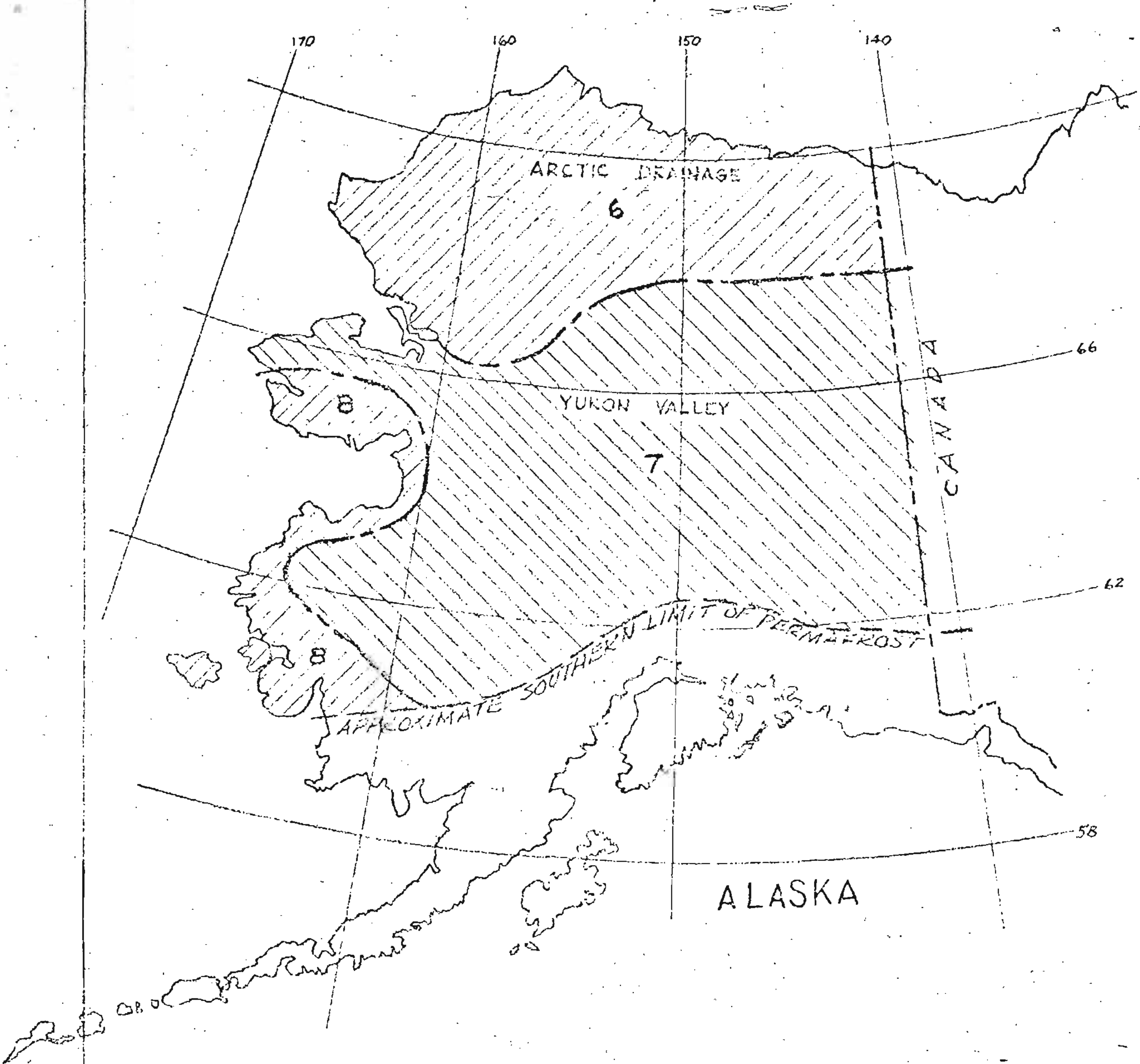


ISOTHERMS resulting from test of insulated steam pipe in permafrost with 8 refrigerated brine tracer lines. Brine in at 20 F, out at 25 F. Steam pipe test section length = 20 ft.



UTILITY SYSTEM using the Thermal Balance System to control the temperatures of water, condensate and sewage lines with a steam supply main and refrigerated brine tracer piping system.

THERMAL BALANCE SYSTEM FIGURE 1



THE THERMAL BALANCE SYSTEM

Map of Alaska showing the estimated months per year requiring mechanical refrigeration for chilling brine for the Thermal Balance System. During the remaining months of the year for the areas shown the air temperature will be low enough to chill the brine to the desired temperature. The numbers shown represent the number of months that the average air temperature is above +16 F and is based on U. S. Department of Commerce Weather Bureau data.

Figure 11