FROST INVESTIGATION 1944-1945

REPORT ON LABORATORY TESTS ON FROST PENETRATION AND THERMAL CONDUCTIVITY OF COHESIONLESS SOILS

CORPS OF ENGINEERS, U.S. ARMY
U.S. ENGINEER OFFICE, BOSTON, MASS.

JUNE 1945

APPENDIX 13
TO COMPREHENSIVE REPORT
DATED JUNE 1945

NOTICE TO USERS

Portions of this document have been judged by the Clearinghouse to be of poor reproduction quality and not fully legible. However, in an effort to make as much information as possible available to the public, the Clearinghouse sells this document with the understanding that if the user is not satisfied, the document may be returned for refund.

If you return this document, please include this notice together with the IBM order card (label) to:

Clearinghouse
Attn: 152.12
Springfield, Va. 22151

WAR DEPARTMENT
U. S. ENGINEER OFFICE
BOSTON, MASSACHUSETTS

APPENDIX 13

REPORT ON LABORATORY TESTS ON FROST PENETRATION AND THERMAL CONDUCTIVITY OF COHESIONLESS SOILS

FROST INVESTIGATION
1944 - 1945

JUNE, 1945

FROST INVESTIGATION

TABLE OF CONTENTS

FROST INVESTIGATION

LIST OF PLATES

LABORATORY TESTS ON FROST PENETRATION AND THERMAL CONDUCTIVITY OF COHESIONLESS SOILS

1. Purpose. The purpose of this investigation has been to study (1) temperature changes within laboratory specimens of sand due to suddenly impressed surface temperatures and (2) the thermal conductivity of several representative materials commonly used for base course construction beneath pavements and one sample of bituminous concrete.

2. Scope. The materials selected for testing were limited to those which are non-frost susceptible, that is materials in which frost action is not possible. In connection with the analysis of test results it was necessary to utilize and develop theoretical solutions for temperature changes under ideal conditions. These studies are included in this report. Also included is a brief summary of the work accomplished by H. E. Patten on thermal conductivity and the results of his investigations are compared with those reported herein. All tests for thermal conductivity were limited to the material in the unfrozen state.

3. Acknowledgement. The tests reported herein were conducted in the Soil Mechanics Laboratory, Harvard University. The use of the facilities of the Soil Mechanics Laboratory including the cold room was made available through the cooperation of Harvard University by Dr. Arthur Casagrande. Dr. Casagrande made frequent suggestions and assisted greatly in these tests by giving freely of his own time for consultation. In addition members of the Staff of the Graduate School of Engineering furnished the temperature measuring equipment and valuable advice on its

use. Mr. Reginald Barron, Engineer, U. S. Engineer Office, Providence, R. I., accomplished, through a cooperative agreement, the theoretical mathematical studies utilized in the analysis of results. In addition he furnished valuable advice on test apparatus for determining the coefficient of thermal conductivity.

4. Definitions.

a. Non-Frost Susceptible Materials are crushed rock, sand, sand and gravel, gravel, slag, cinders or any other cohesionless material in which frost action is not possible.

b. Frost Action is the accumulation of water in the form of ice lenses in the soil or base materials under natural freezing conditions.

c. Density is the unit dry weight in pounds per cubic foot.

d. Water Content is the ratio expressed as a percentage of the weight of water in a given soil to the weight of solid particles.

e. Specific Heat, c_1, of any substance is defined as the calories of heat required to raise one gram one degree Centigrade.

f. Volumetric Heat Capacity, C, is defined as the heat in Btu required to raise one cubic foot of soil one degree Fahrenheit.

g. British Thermal Unit, Btu, is the heat required to raise the temperature of water one degree Fahrenheit at its maximum density. It is equal to 252 calories.

h. Latent Heat of Fusion, L, is the quantity of heat required to change unit mass of ice to water with no temperature change.

i. Thermal Conductivity, k, is the quantity of heat that will pass through a unit area of unit thickness in unit time under a unit temperature gradient.

5. Description of Laboratory Cold Room and Equipment. The investigations were carried out in the cold room laboratory, at Harvard University Graduate School of Engineering. General layout of the cold room and equipment is shown on Plate 1.

a. Cold Room. The cold room is a walk-in refrigerator with inside dimensions 6 feet 9-1/2 inches long by 6 feet 9-1/2 inches wide and 6 feet 5 inches high. It is insulated on all 6 sides with 4 inches of cork. A pressure controlled unit cold blower and an externally located freon compressor cool the room to any desired air temperature within a range of 30° to 50°F and to an accuracy of 1.0°F.

b. Freezing Cabinet. Within the cold room is a freezing cabinet located as shown on Plate 1. This cabinet consists of an air space at the top cooled by longitudinal coils, hung from the top of the cabinet, using a second compressor with sulphur dioxide refrigerant. Beneath this air space are 4 drawers arranged side by side as shown on photograph, Plate 2. The temperature at the top of each drawer may be fixed at any desired temperature with an accuracy of ± 0.8°F and equal to or less than that in the cold room by adjustment of a bimetalic De-Khotinsky type temperature control located in the air space above the drawers. With the cold room at approximately 40°F, the top of the freezing cabinet can be lowered to a temperature of -10°F. A small fan in the air space at the top aids in maintaining a uniform temperature throughout the air space. The bottom of the drawers consist of a 24 gage galvanized iron sample tray and is set 15 inches above the floor of the cold room. Detail of the trays is shown on Plate 1. The temperature of the bottom of the drawers is determined by the cold room temperature. Thus, test specimens may be placed in the drawers and subjected to any desired temperatures at the top and bottom within the temperature ranges of the two pieces of cooling equipment. Circulation of air between the air spaces at the top and bottom of drawers was prevented by inflating a tire inner tube installed in the air space between drawers until this space was sealed. Two of the drawers are equipped in such a manner that water may be supplied to the bottom of the test specimens.

c. Temperature Measurements. Temperature measurements in test specimens were made using 72 copper-constantan thermocouples and a Leeds and Northrop Potentiometer, type K. The thermocouples were arranged in groups of twelve. A switching arrangement permitted the rapid measurement of the temperature at individual thermocouples successively as desired. The constant temperature junction consisted of an ice water bath in a thermos bottle. The accuracy of a temperature determination was $\leq$ 0.1°F. Plate 3 illustrates the switches and temperature indicating apparatus. The cold temperature junction is shown on Plate 2.

6. Experiments to Measure Temperature Changes in Test Specimens.

a. Introduction. Two series of tests were conducted, each series consisting of tests on 12 test specimens compacted at various densities and water contents. All specimens consisted of a thoroughly mixed cohesionless, medium sand. The first series of tests was used primarily to familarize the technicians with the operation of the test equipment and to determine its accuracy and limitations.

b. Test Conditions. Each test consisted in permitting the 12 specimens to reach cold room temperature of approximately 40°F, suddenly applying at the top of the specimen a freezing temperature, maintaining the bottom of the specimen at cold room temperature and recording the temperature changes in the specimen vs. time.

c. Test Specimen. Each test specimen was a cylinder 3.36 inches in diameter and 6.5 inches high contained in a cardboard ice cream container. To measure temperature changes, several thermocouples were placed along the axis of the cylinder. Detail of sample cylinder and location of thermocouples are shown on Plate 1. From 2 to 4 specimens were placed in each drawer of the cold cabinet. The top of each specimen, except those which were saturated, was sealed with paraffin about 2 mm in thickness to prevent evaporation from the surface. The space between specimens and the sides of the drawer was filled, from drawer bottom to top of specimens, with the same sand, as the specimens, placed dry.

d. Material Tested. The material tested consisted of a cohesionless, siliceous, medium sand obtained from a glacial outwash deposit at South Lowell, Mass. The grain size and specific gravity of the material (Lowell Sand) as used for tests, after thorough mixing and removal of sizes larger than 2 mm and smaller than 0.07 mm, are shown on Figure 5, Plate 4. This material is considered not susceptible to frost action and contains particle sizes that were very small in proportion to the size of test specimen.

c. Sample Preparation. The quart ice cream container, with top and bottom removed, forming the sides of a test specimen, was placed into a split forming jacket, illustrated on Plate 5. The split forming jacket had holes through which thermocouples could be inserted into the specimen during compaction. Placement and compaction of the material in a dense state was accomplished by using a device and procedure developed by Dr. Yen Chan in connection with his work on a thesis for the degree of Doctor of Engineering at Harvard University. For the dense state, material having the desired water content was placed in ten equal layers and each layer compacted by an increasing number of blows in a sequence which resulted in a uniform degree of compaction throughout the specimen. Thermocouples were inserted as the placement progressed. After removal from forming jacket the thermocouple lead wires were cemented with paraffin to the ice cream container. Loose samples were constructed by first cementing the thermocouples at the desired positions, then carefully placing material having the desired water content around the thermocouples. At the same time the side of the container was lightly tapped to obtain a small amount of compaction to minimize shrinkage during testing. To obtain saturated samples in either loose or dense state, the material was placed dry in containers which were equipped with screen bottoms. These specimens were then placed in the drawers, fitted with pans for water supply, and saturated by forcing water upward through the specimens until free water appeared on the surface.

f. Test Procedure. Two different series of tests, numbered 1 and 2 were performed. Each series consisted in applying to the top of the specimens three different freezing cabinet temperatures, approximately 30°F, 20°F and 10°F. In the application of the 3 freezing temperatures to the top of the test specimens, a time lag to reach the desired temperature was evident. The time lag for the 30°F and the 20°F temperatures was small. For the 10°F temperature the time lag was greater, about 1 hour, and cork insulation was used as described below. For the 30°F tests of Series 1, the loaded drawers were left open until the compressor had cooled the coils of the freezing cabinet. The drawers were then closed and the time of closing was assumed as the starting time of the test. For 20°F and 10°F tests, the drawers were sealed, freezing cabinet compressor was started and time vs. temperature data of cabinet air temperature was observed until the test temperature was reached. For these tests the starting time was assumed to be the time at which the cabinet temperature had reached the average between the test temperature and the cold room temperature. The same procedure was followed for Series 2, except for the 10°F tests where sheet cork insulation was placed over the top of the samples, the drawers closed and the cabinet temperature lowered to 10 degrees. The cork sheet was then removed, the cabinet sealed and the starting time for test was assumed as the latter closing time.

g. Data Obtained. The data obtained from Series 1 is not included in this report for the reason that this series was performed primarily to train and familiarize the test operators in the use and operation of the equipment and the preparation and testing of specimens. The results of tests from this series are erratic and certain of the results are inconsistant with Series 2. The data is on file at the Boston District Office.

The data obtained from Series 2 are summarized on Plate 4. Table A summarizes the principal test conditions for each test performed. Figure 1 is a typical set of time vs. temperature curves for each of the thermocouples in a selected test. Figure 2 is a typical set of temperature gradients at selected times after a suddenly impressed surface temperature had been applied. Figure 3 presents representative data showing the penetration of the 32°F temperature vs. time into test specimens at different water contents and unit dry weights and with 2 different, suddenly impressed, surface temperatures. For 4 tests, conditions were such that equilibrium was reached with the 32°F temperature approximately at the midpoint of the specimen and equilibrium temperature gradients for these 4 tests are shown in Figure 4, Plate 4.

h. <u>Analysis and Conclusions.</u> From the tests described it is possible to investigate the effect of the surface boundary upon temperature conditions in the test specimens. The temperature gradients at equilibrium were plotted for all tests, similar to the typical equilibrium temperature gradients shown on Figure 4, Plate 4. These temperature gradients were then extrapolated to the top and bottom surfaces of the samples. The specimen temperatures at the top and bottom were then determined and are recorded on Table A, Plate 4. The difference between the temperature of the specimen at the top or bottom and the air temperature at the top or bottom respectively is termed the "boundary temperature difference".

why the wide variation between air at top and extrapolated temp. at top (See Table A Plate 4 for 9.?)

Further the equilibrium temperature gradients of each specimen, expressed in degrees F per foot, have been computed and are recorded on Table A, Plate 4. Plates 6, 7 and 8 are plots of equilibrium temperature gradients vs. boundary temperature differences for the 3 different water contents tested. The scattering of the test data is rather wide, however, it will be noted that small increases in the equilibrium temperature gradient produce substantial increases in the boundary temperature difference for all water contents and in general, the greater the water content the greater the boundary temperature difference for a given temperature gradient. Field observations indicate that equilibrium temperature gradients at one foot depth below the ground surface as large as 6°F per foot may be expected at Bedford, Massachusetts, and 10°F per foot at Presque Isle, Maine. For gradients of these magnitudes, the boundary temperature difference is approximately 1°F and 2°F respectively as indicated by the test results on specimens at 2.8 percent water content (Plate 7). It is interesting to note on Plates 6, 7 and 8 that the boundary temperature difference at the bottom of the specimens is approximately the same as the boundary temperature difference at top of the specimens even though the water content and the condition of the top and bottom of the specimens varied.

The importance of the evaluation of the boundary temperature difference lies in its relation to the prediction of frost penetration. Knowledge of the magnitude of the boundary temperature difference may permit refinements in theoretical methods for frost prediction and a more exact analysis of observed frost penetrations.

A study of Table A, Plate 4 indicates that the time for temperature equilibrium to be reached within a given test specimen is dependent upon the magnitude of the suddenly impressed temperature difference between top and bottom of specimen and the density and water content of the specimen. This is as expected for the density and water content of the specimens influence the thermal properties of the material. Specimens at very low water content reached equilibrium temperature quickly because of the small latent heat of fusion and volumetric heat capacity. Saturated specimens reached equilibrium more slowly because of the greater latent heat of fusion and volumetric heat capacity. The same results are illustrated by Figure 3, Plate 4 in which the penetration of the 32°F temperature is a function of the magnitude of temperature difference between top and bottom of a specimen, and its density and water content.

From Figure 4, Plate 4 the ratios of the thermal conductivity in the frozen to the unfrozen state can be determined. It may be shown that this ratio is equal to the ratio of the slopes of the equilibrium temperature gradient in the unfrozen zone to that in the frozen zone. These ratios have been determined for the four tests plotted and indicate that for the material tested and the density and water contents tested the coefficient of thermal conductivity in the unfrozen state is approximately 52 to 85 percent of that in the frozen state.

7. Experiments to Measure Thermal Conductivity in Unfrozen State.

a. Introduction. Five different base course materials were tested for thermal conductivity in the unfrozen state. Each material was tested at maximum density except one which was tested at several densities between maximum and minimum. Tests were performed on specimens at water contents ranging from almost dry to the saturated condition.

b. Test Conditions. Each test consisted of subjecting a cylindrical test specimen immersed in a bath, located outside the cold room, to a constant temperature of approximately 75°F. The specimen was then suddendly immersed in a second bath, located in cold room, to a constant temperature of approximately 40°F. The resulting temperature changes were measured at the midpoint of the specimen. Baths consisted of circulating water maintained at constant temperature by addition of hot or cold water or ice as required. Plate 1 shows details of constant temperature bath and Plate 9 shows photograph of bath with test specimens immersed.

c. Test Specimen. Each test specimen was of cylindrical shape, 5.36 inches in diameter and 10.68 inches in height, and was contained in a brass cylinder of 1/16 inch wall thickness. Brass was used because of its high thermal conductivity in comparison with soil. A thermocouple was placed at the exact midpoint of the cylinder as shown on Plate 1. Cylinder ends were 1/16 inch brass and were sealed to prevent leakage and changes in water content of specimen during test. Plate 10 shows photograph of brass cylinder and cover.

d. Materials Tested. The following materials were tested and gradation and specific gravity of all the materials are shown on Figure 3 and Table A, Plate 11 respectively:

(1) Sand (Lowell Sand) consisted of a cohesionless, siliceous sand from a glacial outwash deposit at South Lowell, Mass.

(2) Crushed Rock (Winchester Crushed Rock) consisted of a fine grained quartz diorite obtained from quarry at Winchester, Mass.

(3) Slag (Mystic Slag) consisted of basic residue from blast furnace located at Everett, Mass.

(4) Cinders (Somerville Cinders) consisted of commercial grade cinders obtained locally as a result of burning bituminous coal.

(5) Sand and Gravel (Bangor Sand and Gravel) consisted of a well graded sand and gravel of glacial origin obtained from Bangor, Maine.

(6) Blended Bituminous Concrete Aggregate consisted of locally processed aggregates of sand and partially crushed gravel obtained from bins at plant at Cambridge, Mass.

(7) Asphaltic Bituminous Concrete consisted of the blended bituminous concrete aggregate and 4.5% bitumen.

e. Sample Preparation. The selected test material was placed in approximately five equal layers and compacted using the device and procedure described in paragraph 6 e. Care was taken not to injure or displace the thermocouple during compaction. A template was used to center the thermocouple accurately in the cylinder. After the cylinder was full the cover was put on and sealed first with glyptal, then paraffin.

f. Test Data and Results. The data obtained from the thermal conductivity tests are summarized on Plate 11. Figure 3, consists of two plots showing grain size curves of materials tested. Table A is a summary of all test data in tabular form. Figure 2 is a plot of typical curves of the temperatures at the thermocouple located at the midpoint of the test specimen vs. time. Figure 4 is a summary plot showing the relation of thermal conductivity to water content and density of the several materials tested. The results of tests for the blended bituminous concrete aggregate and asphaltic bituminous concrete have not been plotted.

g. Method of Computing Thermal Conductivity. The equation used for computing the thermal conductivity from the data obtained together with the nomenclature is contained on Figure 1, Plate 11. This equation, designated (b) was derived for the following assumptions:

(1) The temperature of the exterior boundary of the soil is equal to the temperature of the liquid bath into which the container is immersed.

(2) The range of temperature change during a test was either above or below the freezing point of water, hence latent heat of fusion was not a factor.

h. Computation for Thermal Conductivity. From the test data the thermal conductivity, k, may be computed if the volumetric heat capacity is known. It may be assumed that the volumetric heat capacity can be computed for a given soil using equation (a) Figure 1, Plate 11. This equation is based upon the assumption that the volumetric heat capacity is equal to the sum of the volumetric heat capacities of the dry soil and of the water present in the soil. The value for the specific heat, c_1, of dry soil is a variable depending upon the mineral and chemical constitutents of the soil. Reference to the tabulations of specific heat for various minerals, rocks, and dry soils based upon tests by various investigators will show that the specific heat of dry soil, minerals, and rocks varies within narrow limits and that a value of approximately 0.2 Btu/(lb) (degF) is a good average value. The value of the specific heat of water is 1 Btu/(lb) (degF) and of ice is 0.5 Btu/(lb) (degF). Hence, using equation (a), the volumetric heat capacity of each test may be computed using the assumed value for specific heat of dry soil shown in Table A, Plate 11 and the determined water content and density. Substituting the computed value for volumetric heat capacity, the thermal conductivity, k, may be computed using equation (b). An example for the determination the thermal conductivity, k, is presented on Plate 11.

i. Tests by Other Investigators. A comprehensive investigation of the thermal conductivity of ten different soils was performed by Harrison E. Patten (1). The results of his investigations upon eight soils are presented on Plate 12 in a form similar to tests conducted by Boston District as summarized on Plate 11. Tests on the remaining two soils were incomplete and are not included. On Plate 12, Table A is a summary of test data, Figure 2 contains reported grain size curves, and Figure 1 is a summary plot of thermal conductivity vs. water content for the densities tested. It will be noted that densities of test specimen were very low and generally much less than that at which the soils would normally be found in their natural state.

j. Analysis and Conclusions. The tests performed by the Boston

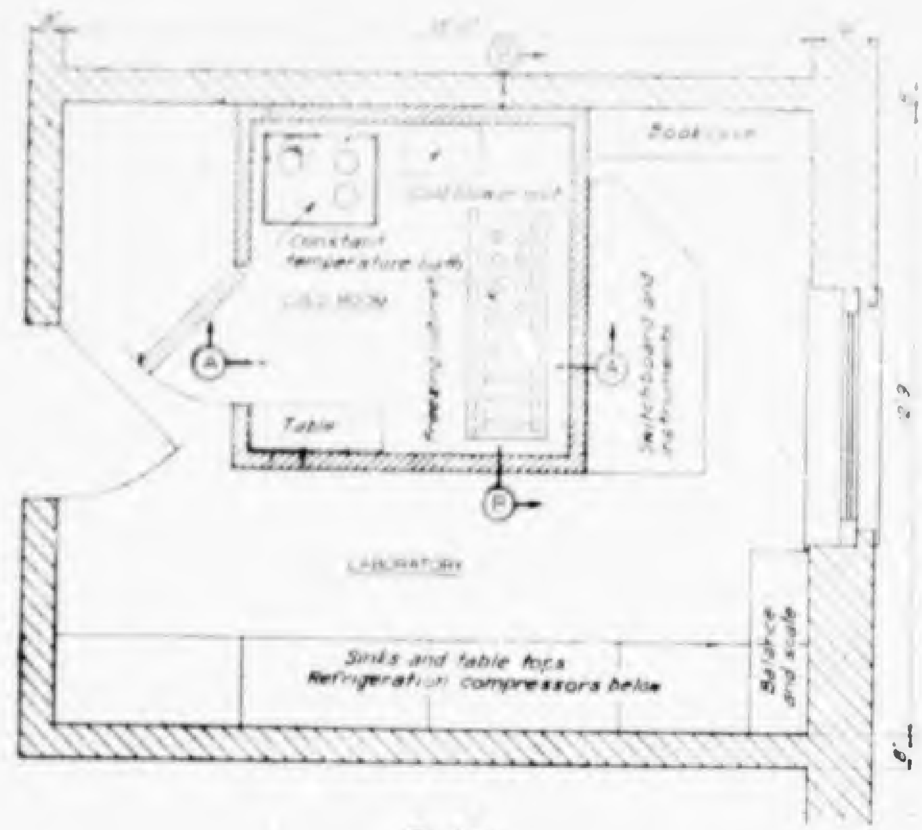
---

(1) Patten, Harrison E. "Heat Transference in Soils", U. S. Dept. of Agriculture, Bulletin No. 59, September 1909.

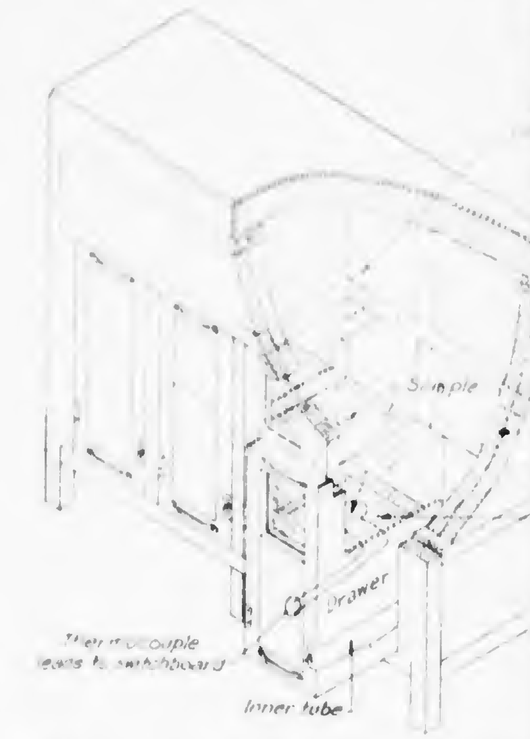
District and summarized on Plate 11 may be compared with those performed by H. E. Patton as summarized on Plate 12. It will be noted that the sample of coarse quartz tested by Patten approaches in grain size distribution that of Lowell Sand, and further that the thermal conductivities of these two soils are approximately the same at equal water contents. The tests on the Hudson River Sand are quite different from all other materials tested. The finer grained soils, Podunk fine sandy loam, Leonardtown silt loam, Hagerstown loam, Galveston clay and fine quartz flour all have approximately the same thermal conductivity at equal water contents. The thermal conductivity of the muck soil is much less than that of the Somerville cinders and Mystic slag tested.

The tests upon the Lowell sand indicate that the influence of water content upon thermal conductivity is much greater than density.

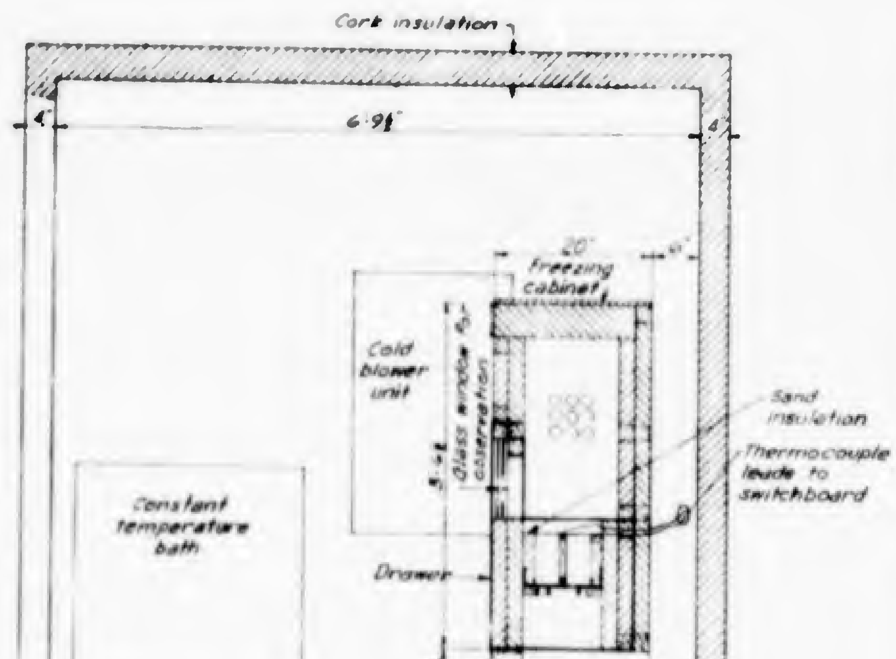
There is no apparent relation between grain size or other characteristics of the various soils tested which may be correlated with thermal conductivity. To satisfactorily determine the thermal conductivity of a given soil, tests are required at several different moisture contents. The test procedure herein described is considered a satisfactory method for the rapid determination of the coefficient of heat conductivity.



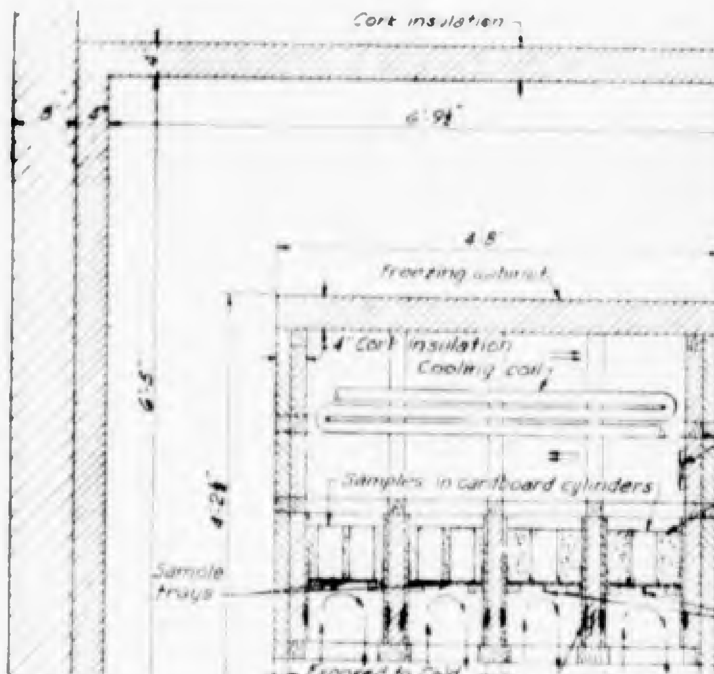
PLAN



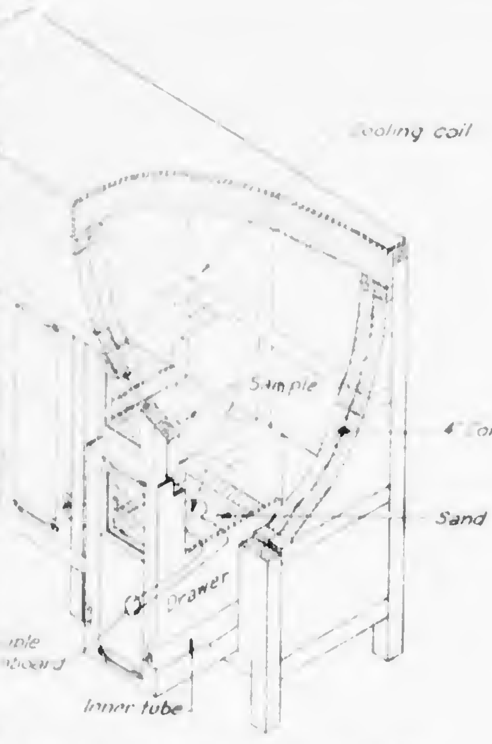
ISOMETRIC VIEW OF FREEZING CABIN



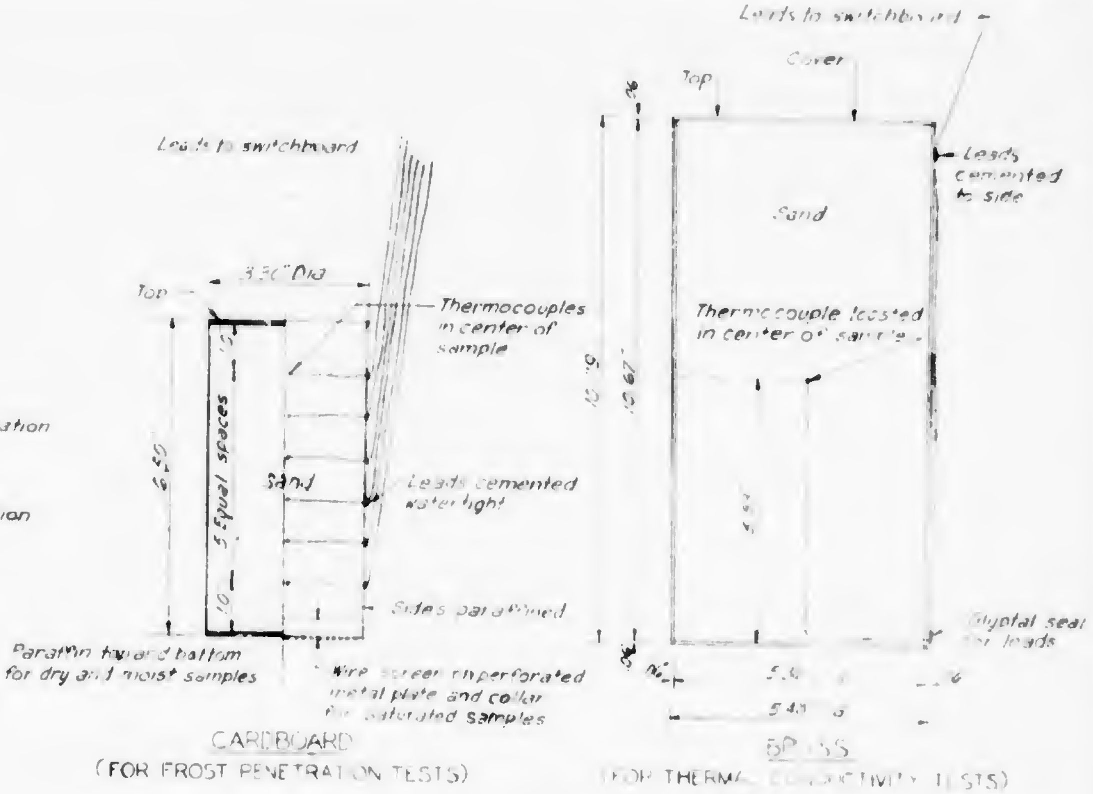
SECTION A-A



SECTION B-B

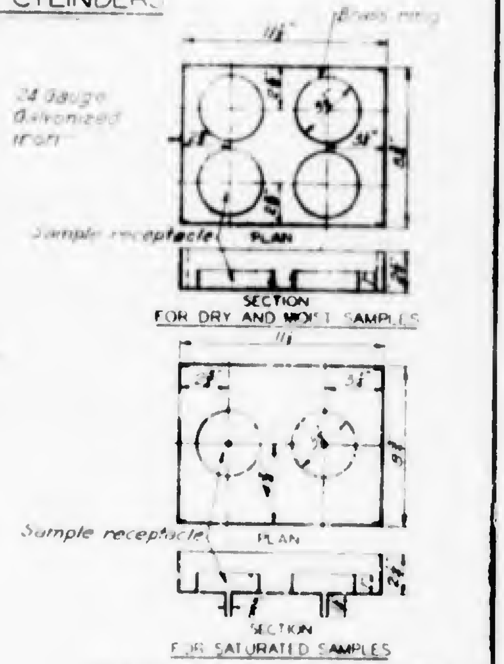


VIEW OF FREEZING CABINET

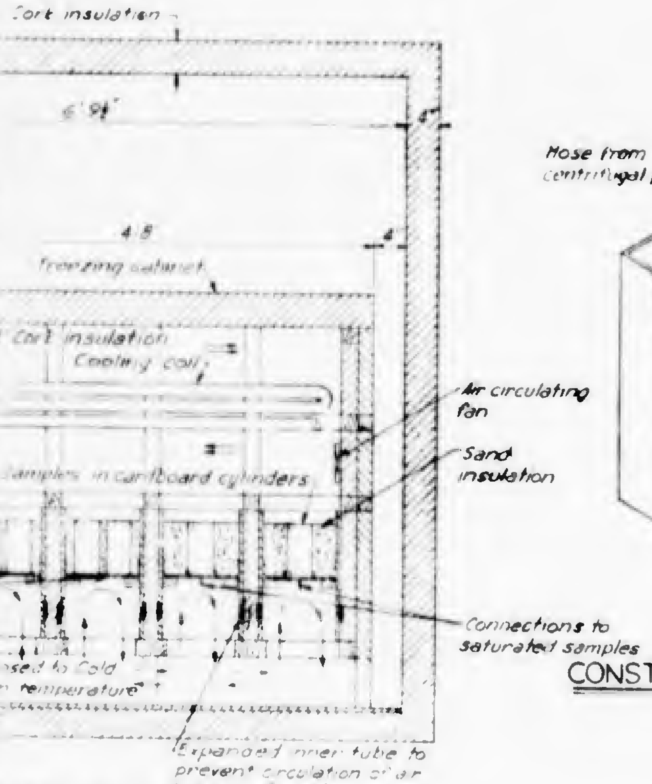


SECTIONS OF SAMPLE CYLINDERS

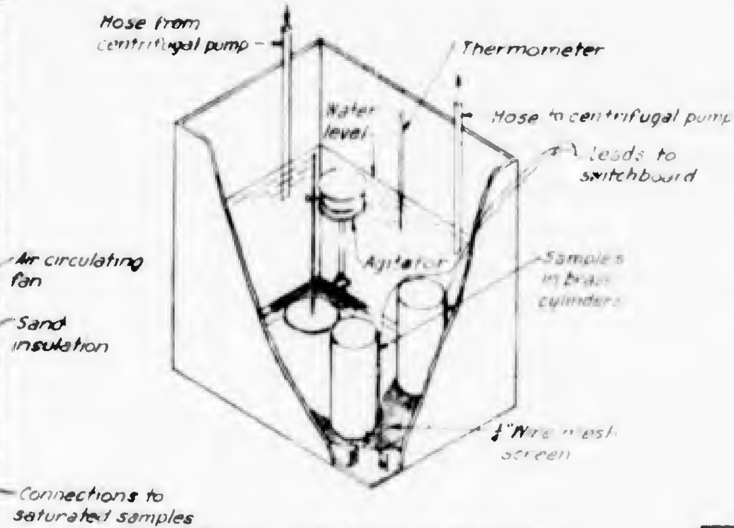
SCALE HALF SIZE



DETAILS OF SAMPLE TRAYS



CTION B-B

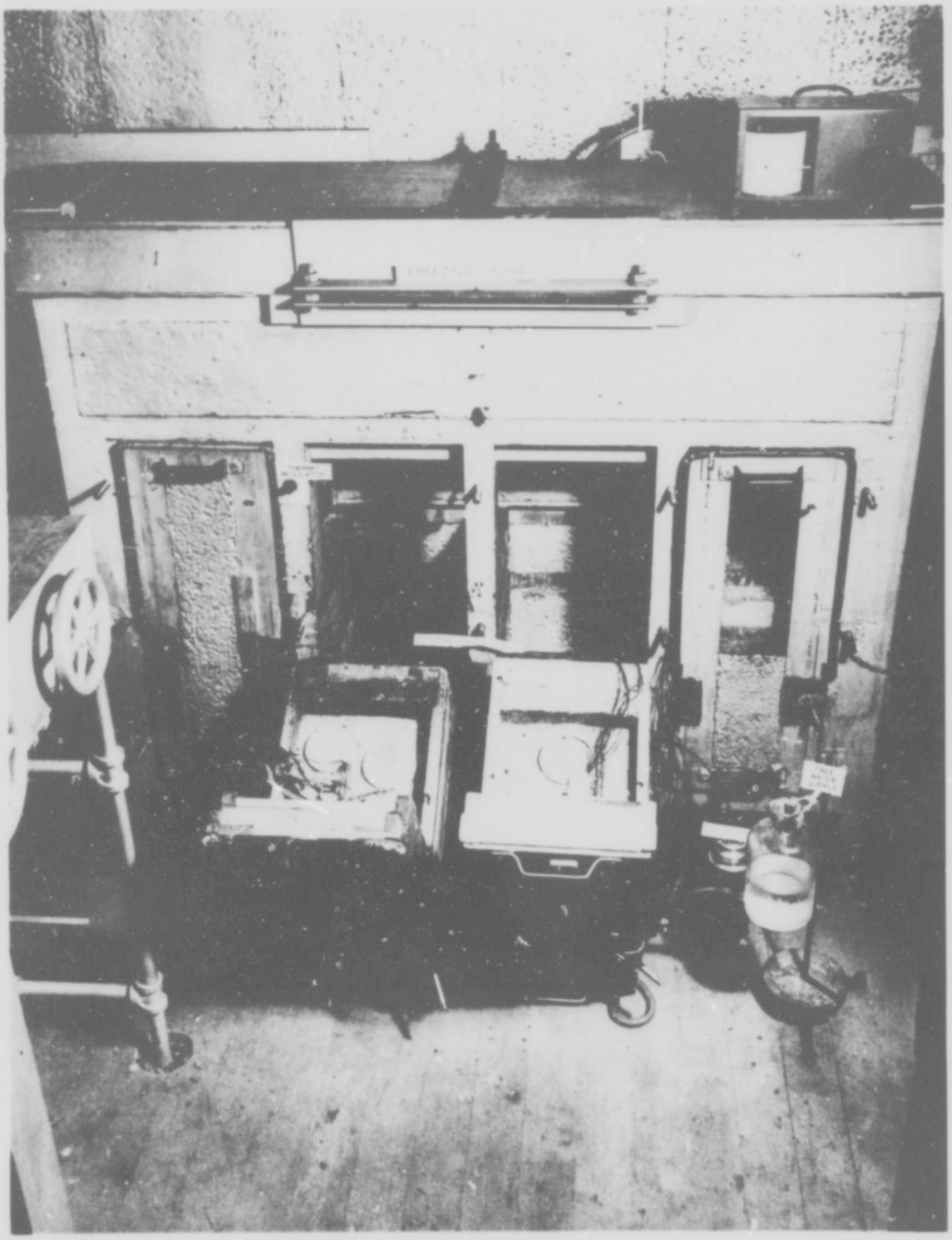


CONSTANT TEMPERATURE BATH

FROST INVESTIGATION

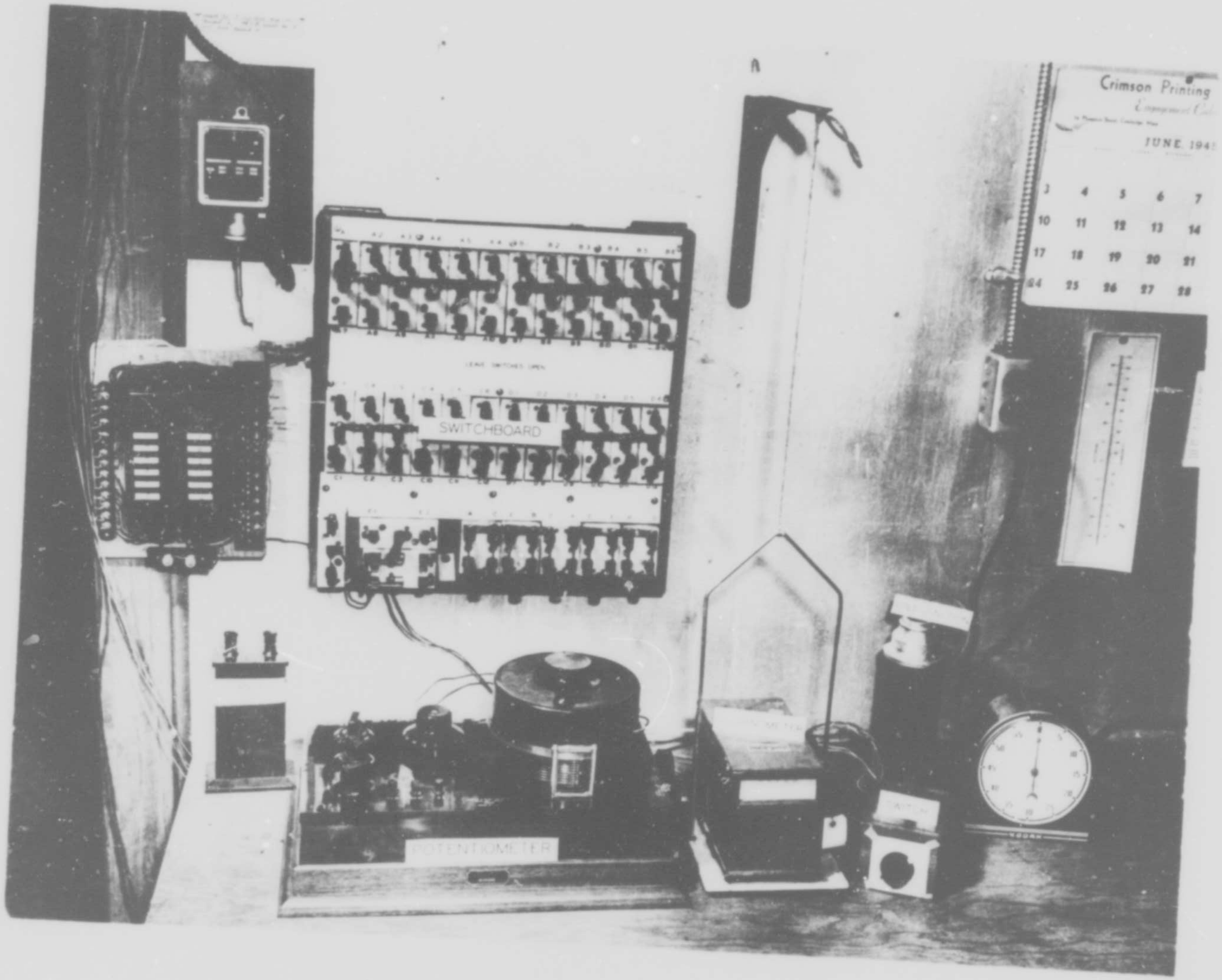
DETAILS OF COLD ROOM AND TEST APPARATUS

FROST EFFECTS LABORATORY BOSTON MASS. JUNE 1945



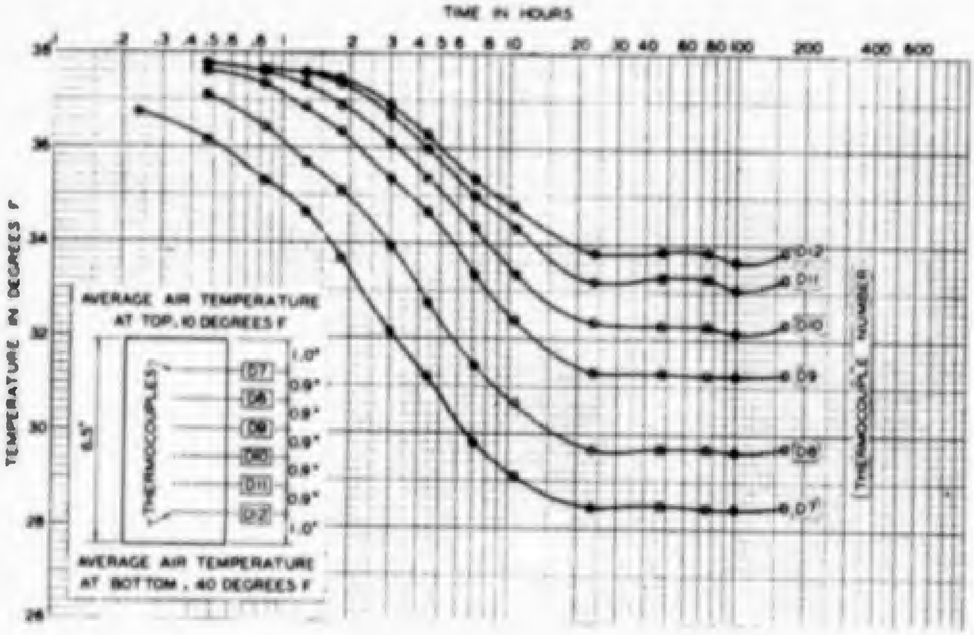
View of Freezing Cabinet

PLATE 7



Temperature indicating apparatus

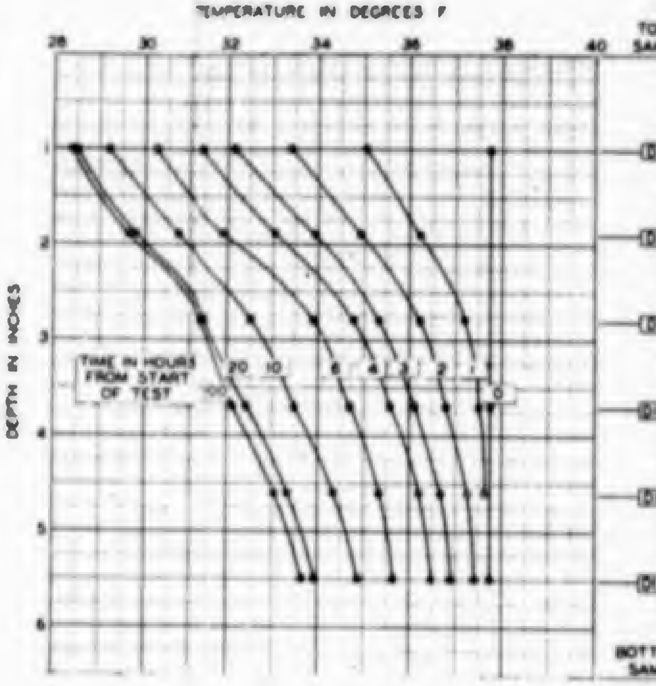
PLATE 5



SAMPLE 2C-8

TYPICAL SET OF TIME TEMPERATURE CURVES

FIG. 1



SAMPLE 2C-8

TYPICAL SET OF TEMPERATURE GRADIENTS

FIG. 2

Sample No.	Unit Dry Weight	Water Content	Run A: Average Air Temperature, Top of Specimen a	Run A: Average Air Temperature, Bottom of Specimen b	Run A: Time for Equilibrium Conditions to be Reached, Hours	Run A: Extrapolated Sample Temperature, Top c	Run A: Extrapolated Sample Temperature, Bottom d	Run A: Equilibrium Temperature Gradient in Specimen °F/Ft.	Run A: [illegible] c - a	Run A: [illegible] b - d
1	98.3	0.2	50.0	58.5	20	52.1	55.2	5.7	2.1	3.1
2	99.3	0.2	50.0	58.5	25	51.5	55.4	7.2	1.5	2.9
3	104.7	0.2	50.0	58.5	30	50.0	55.3	6.1	0.6	3.0
4	104.5	0.2	50.0	58.5	30	51.6	55.2	4.7	1.6	3.1
5	81.8	2.6	50.0	58.5	30	52.5	55.4	6.1	2.5	2.7
6	86.0	2.6	50.0	58.5	30	51.0	56.5	9.4	1.0	2.0
7	102.4	2.6	50.0	58.5	40	51.1	56.4	7.9	1.1	2.9
8	105.6	2.7	50.0	58.5	50	51.5	56.5	9.8	1.5	3.5
9	101.5	23.8	50.0	58.5	50	51.5	55.5	6.8	1.5	3.5
10	101.0	23.8	50.0	58.5	100	53.1	56.4	6.8	1.1	2.5
11	106.0	21.0	50.0	58.5	150	50.4	55.4	5.5	0.8	4.5
12	106.8	20.7	50.5	58.5	50	51.1	56.4	6.1	1.1	5.0

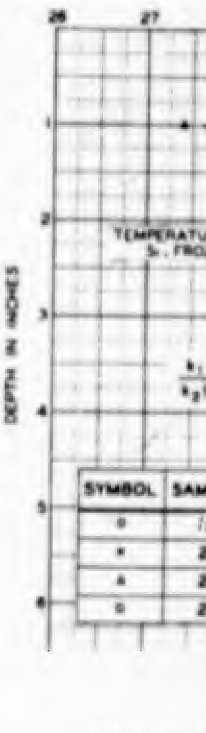
Sample No.	Run B: Average Air Temperature, Top of Specimen a	Run B: Average Air Temperature, Bottom of Specimen b	Run B: Time for Equilibrium Conditions to be Reached, Hours	Run B: Extrapolated Sample Temperature, Top c	Run B: Extrapolated Sample Temperature, Bottom d	Run B: Equilibrium Temperature Gradient in Specimen °F/Ft.	Run B: [illegible] c - a	Run B: [illegible] b - d
1	20.5	58.5	30	26.5	55.5	12.0	6.0	5.0
2	20.5	58.5	25	25.6	55.5	12.8	5.5	5.6
3	20.5	58.5	30	26.5	55.5	17.5	5.7	6.6
4	20.5	58.5	30	25.1	55.0	16.5	5.8	6.4
5	20.5	58.5	30	25.1	56.7	15.9	5.8	6.5
6	20.5	58.5	30	26.2	56.5	16.5	5.9	6.5
7	20.5	58.5	50	26.5	56.5	21.4	2.0	6.5
8	20.5	58.5	50	26.7	55.7	16.6	4.4	6.4
9	20.5	58.5	30	25.5	55.5	16.6	4.4	6.8
10	20.5	58.5	100	25.5	56.5	15.5	5.7	6.6
11	20.5	58.5	100	25.1	50.1	12.0	2.8	6.8
12	20.5	58.5	70	25.0	50.0	12.0	5.6	7.4

Sample No.	Unit Dry Weight	Water Content	Run C: Average Air Temperature, Top of Specimen a	Run C: Average Air Temperature, Bottom of Specimen b	Run C: Time for Equilibrium Conditions to be Reached, Hours	Run C: Extrapolated Sample Temperature, Top c	Run C: Extrapolated Sample Temperature, Bottom d	Run C: Equilibrium Temperature Gradient in Specimen °F/Ft.	Run C: [illegible] c - a	Run C: [illegible] b - d
1	98.3	0.2	9.7	58.5	20	19.6	51.0	21.1	9.5	7.5
2	99.3	0.2	9.7	58.5	20	18.7	50.6	20.3	9.5	7.5
3	104.7	0.2	9.7	58.5	25	16.5	51.4	27.5	6.6	6.0
4	104.5	0.2	9.7	58.5	25	18.1	51.0	26.3	8.4	7.1
5	81.8	2.8	9.7	58.5	25	18.6	52.0	28.4	8.0	5.6
6	86.0	2.8	9.7	58.5	25	17.0	50.4	28.4	7.3	5.6
7	102.4	2.8	9.7	58.5	25	15.5	50.1	31.0	7.6	6.9
8	105.6	2.7	9.7	58.5	50	17.7	50.3	27.5	8.0	6.0
9	101.5	23.8	3.7	58.5	100	16.3	50.5	23.6	6.4	10.3
10	101.0	23.8	9.7	58.5	100	16.1	50.7	20.6	6.4	12.6
11	106.0	21.0	9.7	58.5	50	15.5	50.4	15.5	8.6	12.0
12	106.8	20.7	9.7	58.5	50	19.5	27.2	16.6	9.6	11.1

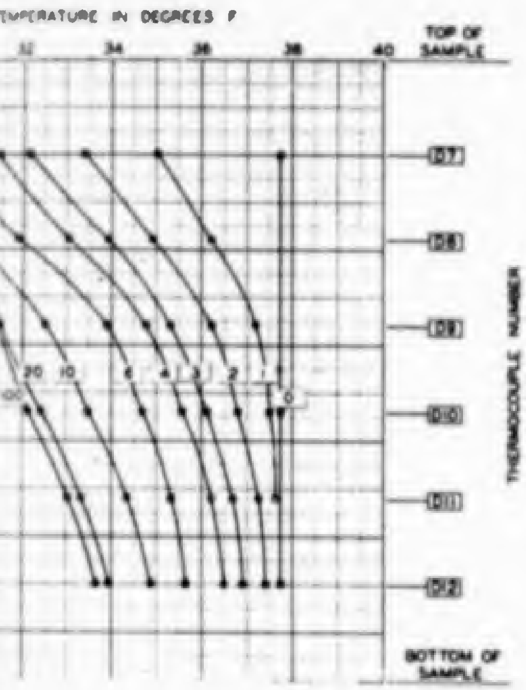
Sample No.	Run D: Average Air Temperature, Top of Specimen a	Run D: Average Air Temperature, Bottom of Specimen b	Run D: Time for Equilibrium Conditions to be Reached, Hours	Run D: Extrapolated Sample Temperature, Top c	Run D: Extrapolated Sample Temperature, Bottom d	Run D: Equilibrium Temperature Gradient in Specimen °F/Ft.	Run D: [illegible] c - a	Run D: [illegible] b - d
1	25.0	37.0	80	27.6	33.3	10.0	2.6	3.7
2	25.0	37.0	50	27.5	33.6	11.6	8.5	5.8
3	25.0	37.0	50	26.6	36.3	13.6	3.4	8.7
4	25.0	37.0	50	27.5	35.4	12.7	4.5	8.6
5	25.0	37.0	50	26.4	36.4	11.6	5.5	5.8
6	25.0	37.0	50	26.9	36.0	16.6	1.0	6.6
7	25.0	37.0	50	27.4	36.5	13.1	4.6	6.6
8	25.0	37.0	50	27.5	36.5	12.6	5.3	6.7
9	25.0	37.0	100	26.6	33.4	8.5	5.6	5.6
10	25.0	37.0	100	26.5	33.5	8.3	5.5	6.6
11	25.0	37.0	100	27.1	33.6	6.7	2.1	5.8
12	25.0	37.0	100	26.9	33.4	9.0	1.8	5.6

SUMMARY OF TEST CONDITIONS

TABLE A



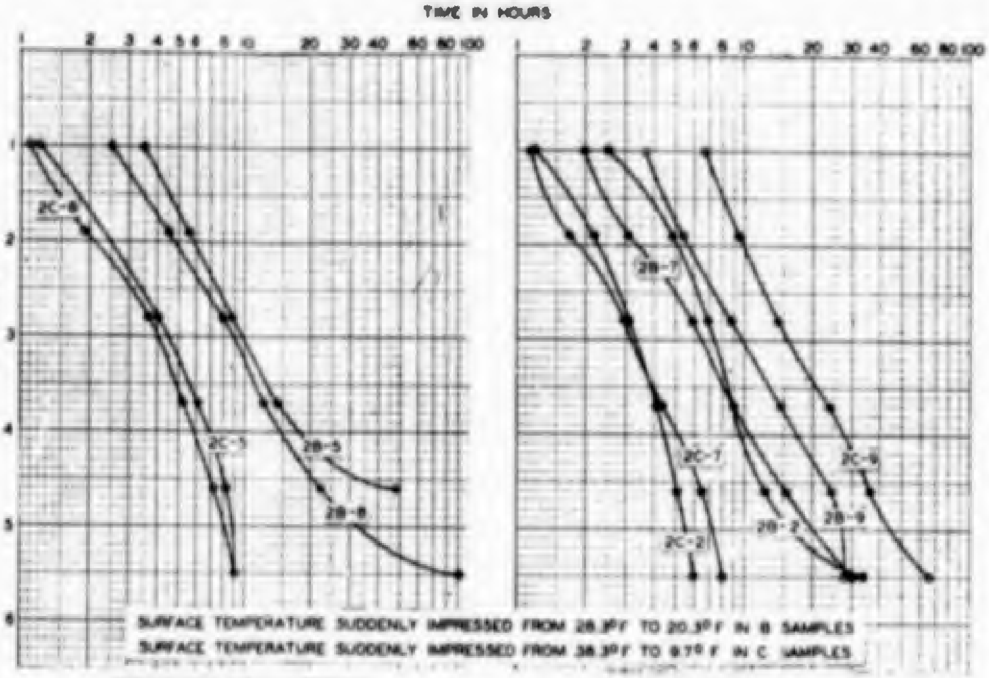
EQUILI



SAMPLE 2C-8

OF TEMPERATURE GRADIENTS

FIG. 2



SAMPLE NO.	w	r
2B-5, 2C-5	2.8	81.8
2B-8, 2C-8	2.7	103.6

FIG. 3a

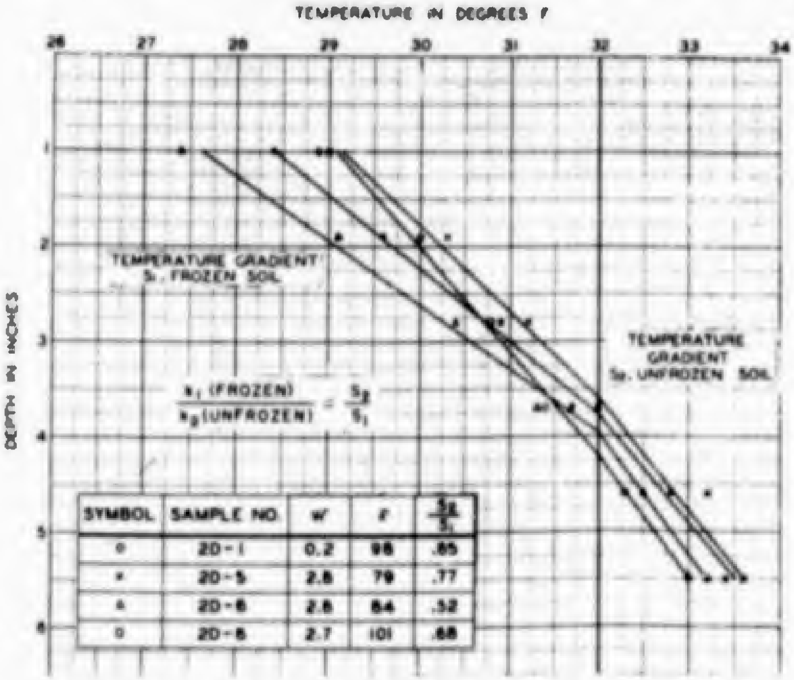
SAMPLE NO.	w	r
2B-2, 2C-2	0.2	99.3
2B-7, 2C-7	2.8	102.6
2B-9, 2C-9	23.8	101.0

FIG. 3b

PENETRATION OF 32 DEGREES F TEMPERATURE VS TIME

FIG. 3

EQUILIBRIUM TEMPERATURE GRADIENT IN SPECIMEN °F/FT.	[illegible] C-8	[illegible] D-8
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

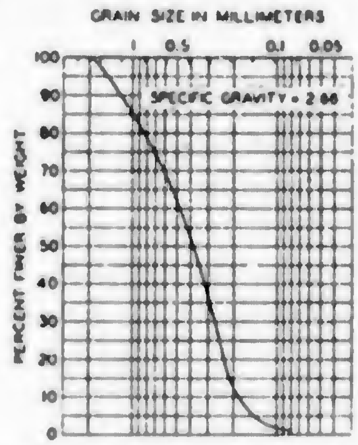


SYMBOL	SAMPLE NO.	w	r	$\frac{S_2}{S_1}$
○	2D-1	0.2	98	.85
×	2D-5	2.8	79	.77
▲	2D-6	2.8	84	.52
●	2D-8	2.7	101	.68

SAMPLES 2D-1, 2D-5, 2D-6, 2D-8

EQUILIBRIUM TEMPERATURE GRADIENTS

FIG. 4



GRAIN SIZE GRADATION CURVE

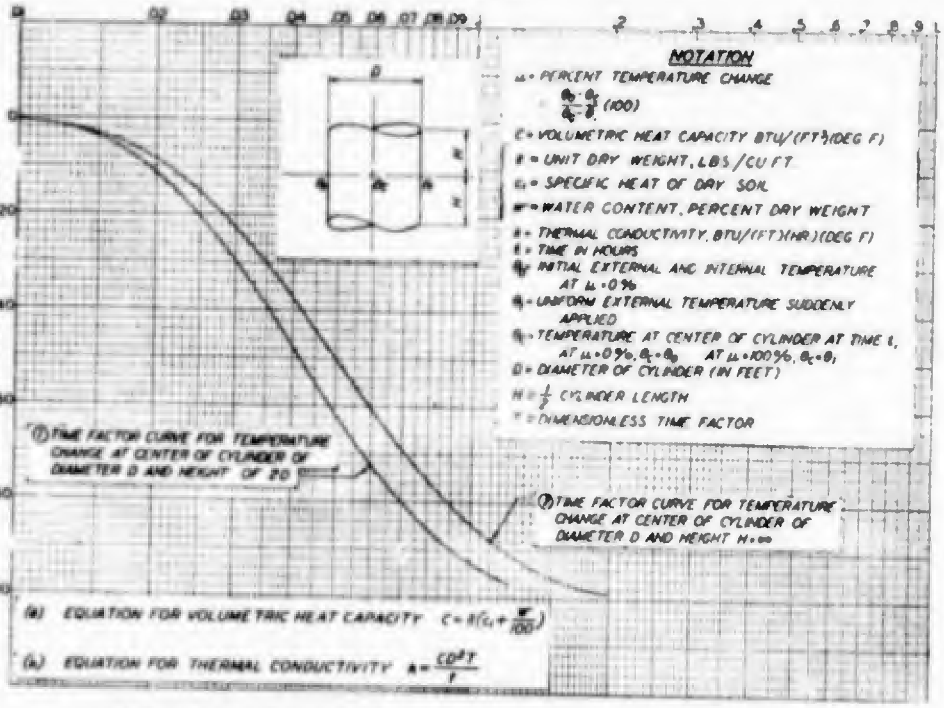
FIG. 5

REVISED FEBRUARY, 1947

FROST INVESTIGATION

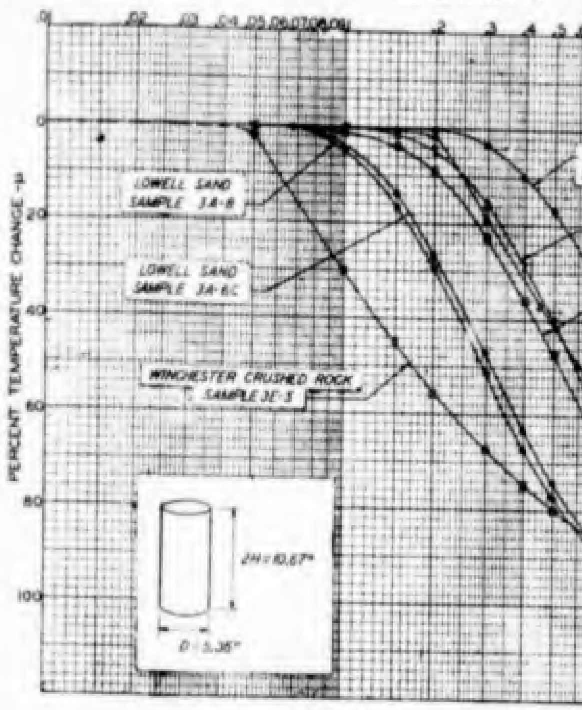
SERIES 2 TESTS INVESTIGATION OF TEMPERATURE CONDITIONS IN LABORATORY SPECIMENS

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE, 1945



TIME FACTOR CURVES FOR TEMPERATURE CHANGE AT CENTER OF A CYLINDER

FIG 1



TYPICAL TIME CURVE[S FOR] THERMAL CONDUCTIVITY DETE[RMINATION]

FIG.2

TABLE A — SUMMARY OF TEST DATA

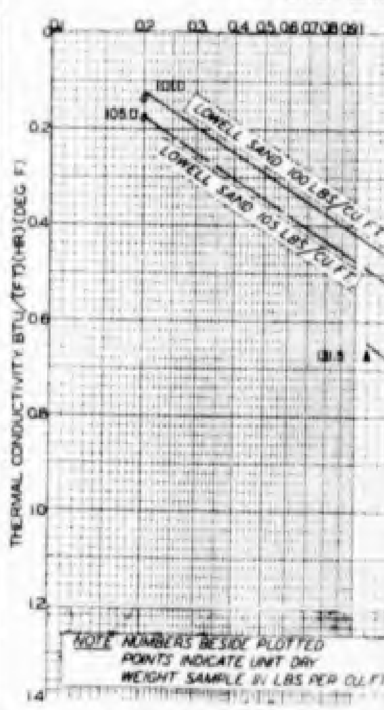
Series No.	Laboratory Sample No.	Material	Unit Dry Weight lbs/cu. ft. γ	Water Content Percent Dry Weight w	Specific Gravity G	Specific Heat(1) Dry Soil Btu/(lb)(deg F) c_0	Volumetric Heat Capacity Total Sample Btu/(ft³)(deg F) C	Thermal Conductivity Btu/(ft)(hr)(deg F) k
5A	5A-4	Lowell Sand (well-graded medium to coarse sand) (2)	105.0	0.2	2.66	0.20	21.2	0.188
	5A-4a		105.0	0.2	2.66	0.20	21.2	0.188
	5A-5(3)		101.0	0.2	2.66	0.20	20.4	0.180
	5A-6		106.5	16.4	2.66	0.20	38.8	1.089
	5A-7		101.0	20.5	2.66	0.20	41.3	1.009
	5A-8		105.0	4.5	2.66	0.20	25.3	0.718
	5A-9		85.5	4.9	2.66	0.20	20.8	0.607
	5A-10(3)		86.5	2.3	2.66	0.20	18.8	0.555
	5A-11(3)		91.1	1.9	2.66	0.20	19.9	0.558
	5A-12		109.0	2.2	2.66	0.20	24.3	0.592
	5A-13		105.0	2.0	2.66	0.20	22.7	0.785
	5A-15		89.5	2.1	2.66	0.20	19.7	0.668
	5A-16		105.0	5.1	2.66	0.20	26.4	0.777
	5A-17		90.8	2.1	2.66	0.20	20.1	0.437
5B	5B-1	Bangor Sand and Gravel	177.0	5.4	2.70	0.20	29.8	0.890
	5B-2		151.5	1.1	2.70	0.20	27.7	0.675
	5B-3		127.0	9.3	2.70	0.20	36.3	1.125
5C	5C-1	Somerville Cinders (1-inch maximum)	60.9	20.7(5)	2.27	0.18	23.6	0.303
	5C-2		60.0	56.6	2.27	0.18	32.8	0.462
	5C-3		60.8	21.2(6)	2.27	0.18	23.9	[illegible]
	5C-4		61.7	11.3	2.27	0.18	18.1	0.297
5D	5D-1	Mystic Slag (1½-inch maximum)	79.1	9.1	[illegible]	0.17	17.5	0.189
	5D-2(4)		81.2	33.5	[illegible]	0.17	40.9	[illegible]
5E	5E-1	Winchester Crushed Trap Rock (3/4-inch maximum)	90.2	1.9	2.91	0.20	21.7	0.350
	5E-2		100.0	2.1	2.91	0.20	22.1	0.571
	5E-3		98.5	4.4	2.91	0.20	23.6	[illegible]
	5E-4		98.6	27.2	2.91	0.20	46.5	[illegible]
	5E-5(4)		99.5	28.4	2.91	0.20	48.0	[illegible]
	5E-6a(4)		100.0	27.7	2.91	0.20	47.7	[illegible]
	5E-7		102.0	2.5	2.91	0.20	23.0	0.571
	5E-8		102.0	26.7	2.91	0.20	47.7	[illegible]
5F	5F-1(8)	Asphaltic Bituminous Concrete	150.0(7)	0.0	2.60	0.20	30.3	[illegible]
	5F-2(9)		150.0(7)	0.0	2.60	0.20	30.3	[illegible]
5G	5G-1(9)	Blended Bituminous Concrete Aggregate	135.5	0.0	2.81	0.20	26.7	0.503

REMARKS

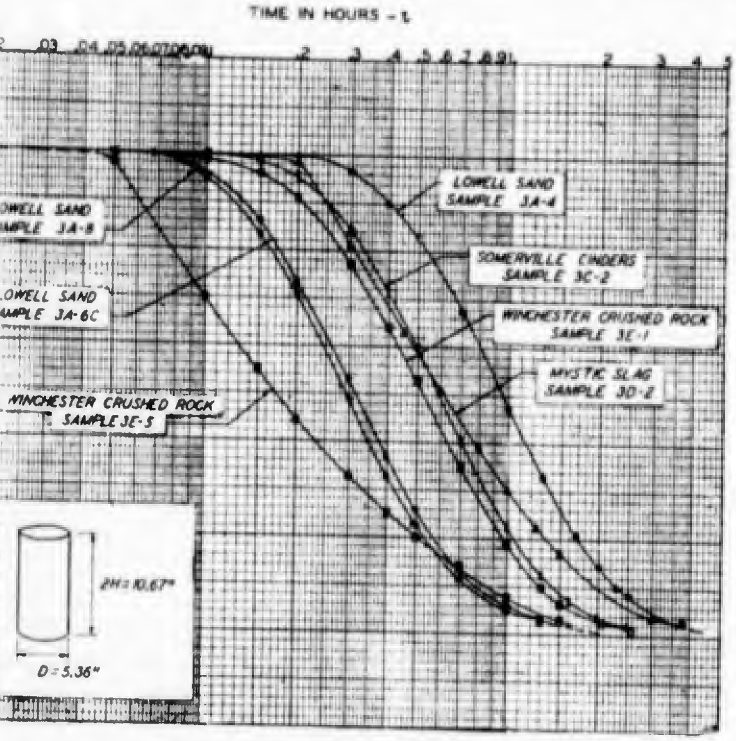
(1) Assumed
(2) Minimum dry density 92.9 lbs/cu. ft. Maximum dry density 110.9 lbs/cu. ft.
(3) Sample not properly sealed; some water leaked into sample during test
(4) Test results are not consistent with results of other tests
(5) Average— w = 14.2% top of sample; w = 27.5% bottom of sample
(6) Non-uniform water content
(7) Percent bitumen 6.5%. Specific heat of bitumen = 0.22 Btu/lb deg F
(8) Diameter of cylinder = [illegible] Length = [illegible]
(9) Diameter of cylinder = [illegible] Length = [illegible]

SUMMARY OF TEST DATA

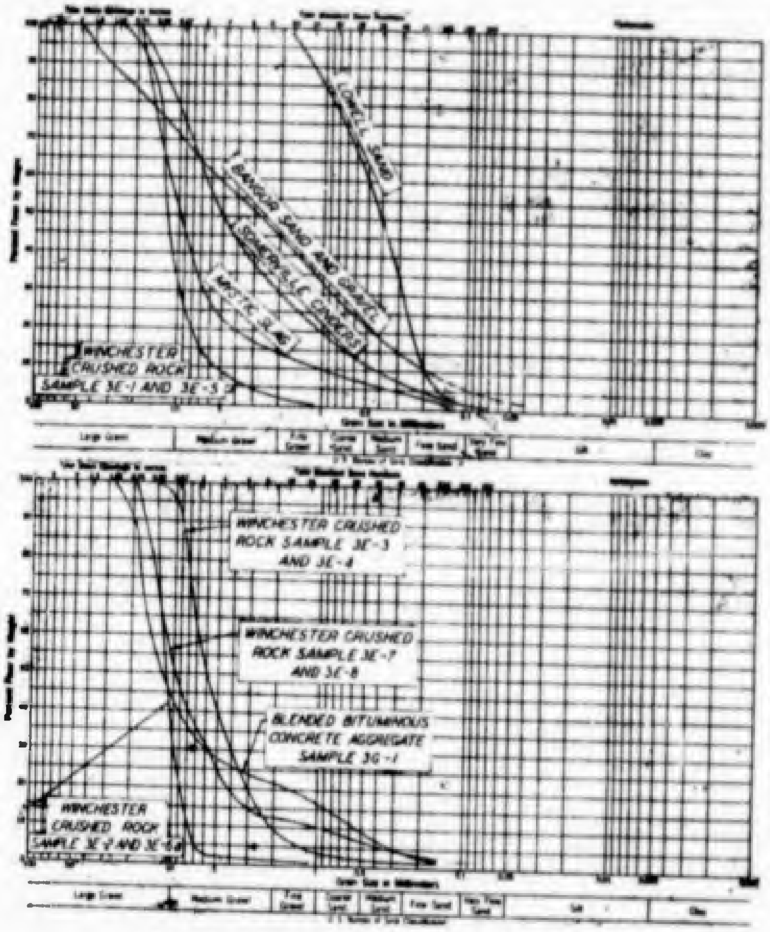
TABLE A



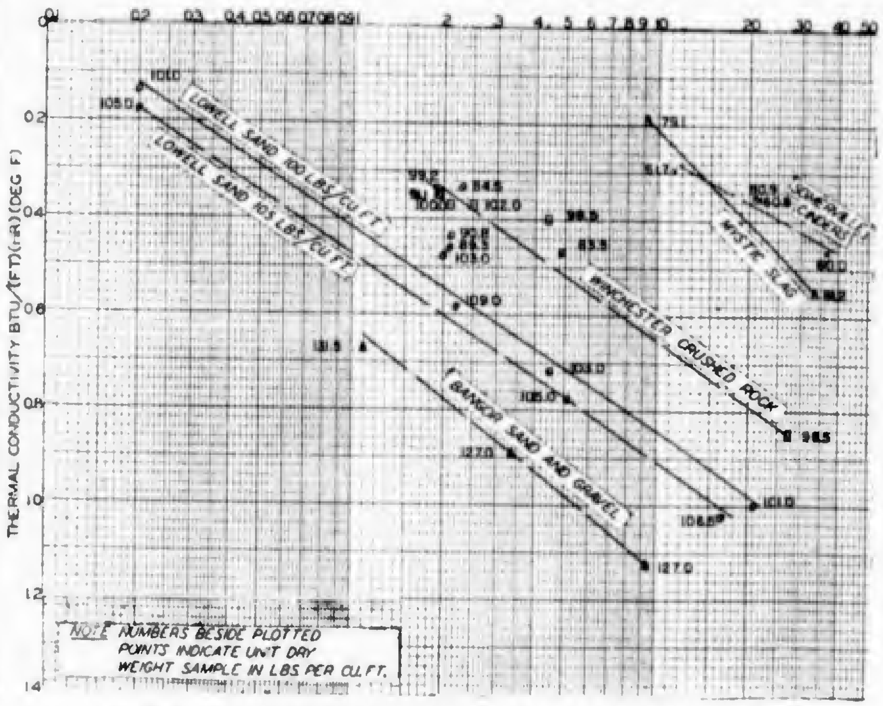
THERMAL CONDUC[TIVITY] OF VARIOU[S]



TYPICAL TIME CURVES
THERMAL CONDUCTIVITY DETERMINATIONS
FIG.2



GRADATION OF BASE MATERIALS
FIG.3



THERMAL CONDUCTIVITY VS WATER CONTENT OF VARIOUS BASE MATERIALS
FIG. 4

EXAMPLE FOR DETERMINATION OF k

EQUATION $k = \frac{C D^2 T}{t}$

TEST DATA FROM TABLE 4, SAMPLE 3A-8 ARE USED

$c = 0.20$

$\gamma = 103$ LBS/CU. FT.

$w = 4.5\%$

$C = \gamma\left(c + \frac{w}{100}\right) = 103\left(0.20 + \frac{4.5}{100}\right) = 25.3$ BTU/(FT³)(DEG. F)

FROM FIG. 2

$D^2 = (5.36")^2 = (0.446')^2 = 0.1995$ FT.²

FOR $\mu = 50\%$, $t = 0.295$ HOURS

(50% TEMPERATURE CHANGE IS ARBITRARILY TAKEN. ANY VALUE OF μ ON THE STRAIGHT PORTION OF THE CURVE MAY BE USED)

FROM FIG 1 CURVE ①

FOR $\mu = 50\%$, $T = 0.042$

SUBSTITUTING IN EQUATION

$k = \frac{C D^2 T}{t} = \frac{(25.3)(0.1995)(0.042)}{(0.295)}$

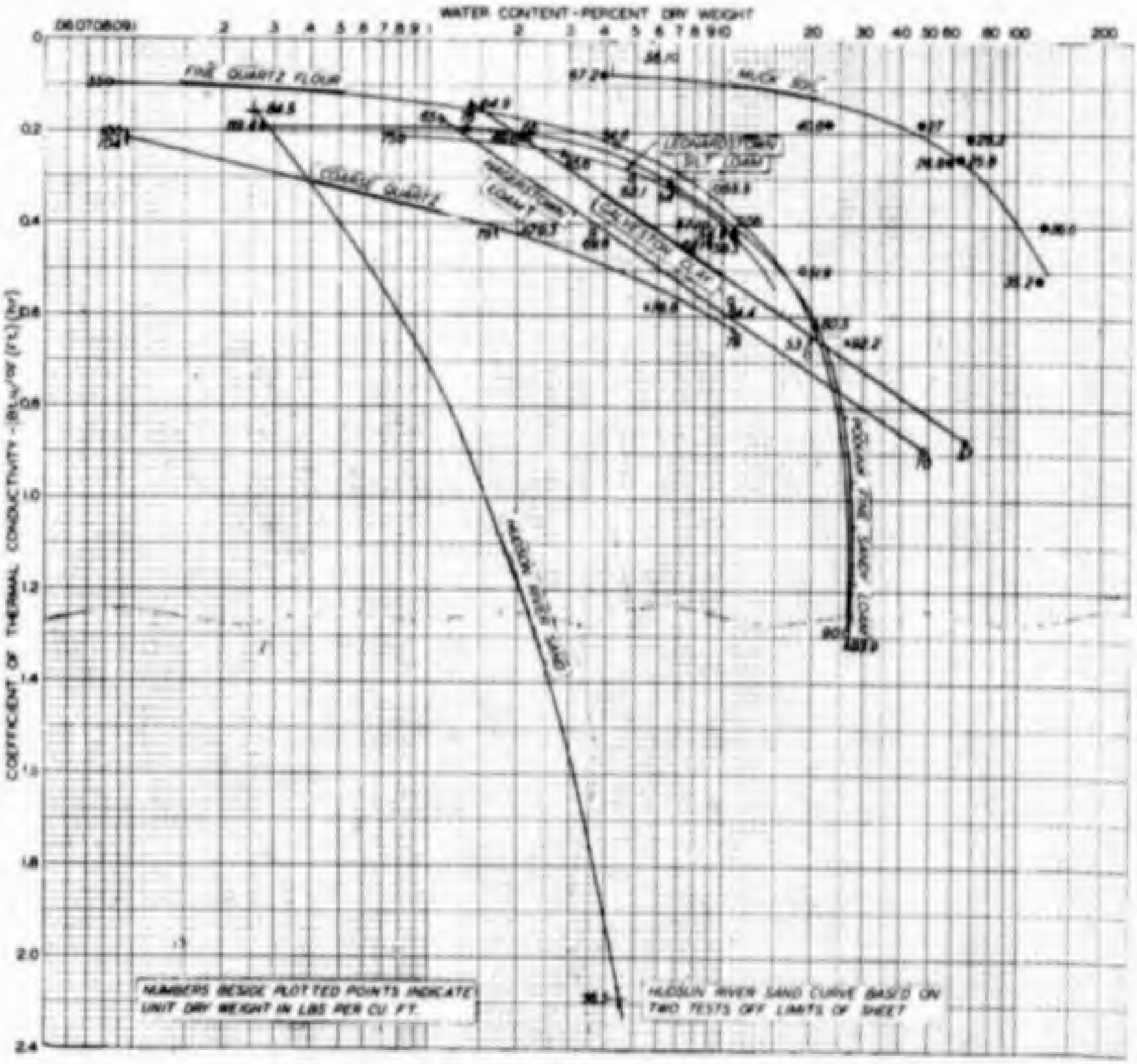
$k = 0.718$ BTU/(FT)(HR)(DEG. F)

FROST INVESTIGATION

THERMAL CONDUCTIVITY DETERMINATIONS COHESIONLESS BASE MATERIALS

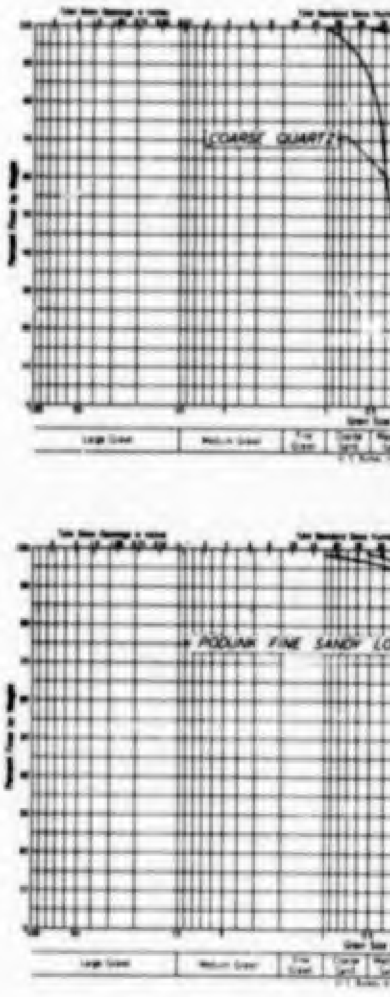
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1945

REVISED FEBRUARY, 1947



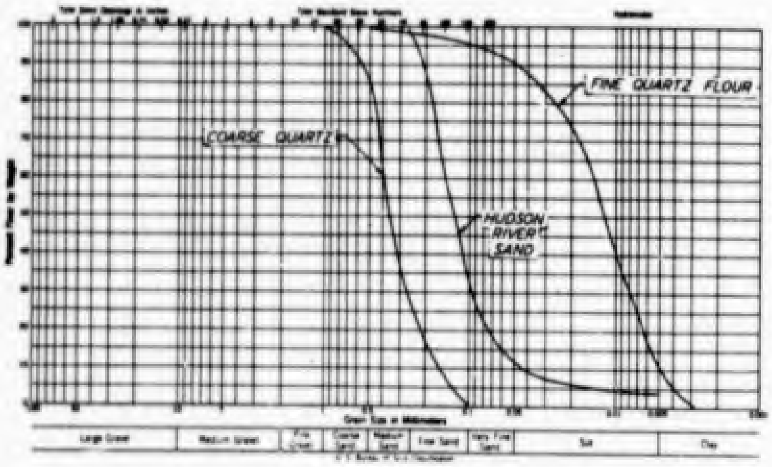
THERMAL CONDUCTIVITY VS WATER CONTENT

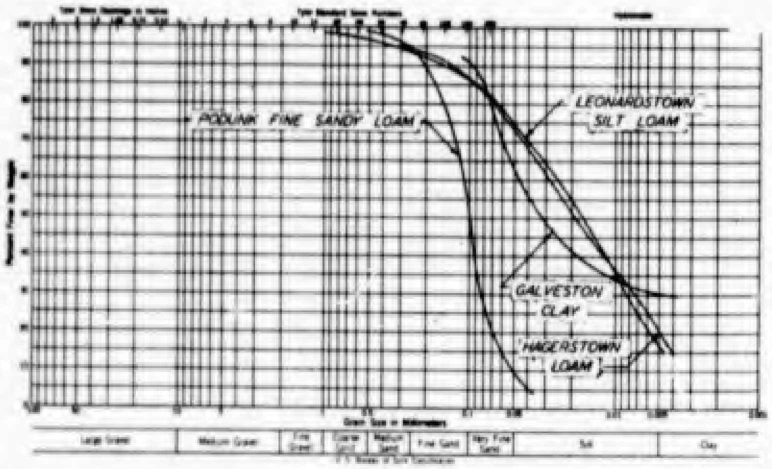
FIG 1



GRAIN SIZE GRA

FI





GRAIN SIZE GRADATION CURVES

FIG. 2

Material	Unit Dry Weight	Water Content	Specific Heat	Volumetric Heat Capacity	Thermal Conductivity
	lbs/c.f.	% Dry Wt.		Btu/(°F)(cf)	Btu/°F (ft)(hr)
COARSE QUARTZ	104	0.095	0.1900	19.3	0.221
	100	0.095	0.1900	[illegible]	0.206
	79	1.710	0.1900	16.3	0.423
	79.3	2.160	0.1900	16.7	0.415
	76.8	5.520	0.1900	[illegible]	0.581
	78.0	10.910	0.1900	23.3	0.630
	92.2	26.700	0.1900	42.1	0.653
FINE QUARTZ FLOUR	55	0.0833	0.1900	[illegible]	0.0981
	54.6	4.280	0.1900	[illegible]	0.232
	56.1	6.930	0.1900	[illegible]	[illegible]
	57.1	8.720	0.1900	[illegible]	0.403
	55.5	9.530	0.1900	[illegible]	0.323
	58.3	10.920	0.1900	17.4	0.427
	53.7	19.670	0.1900	[illegible]	0.680
	90.0	26.650	0.1900	[illegible]	1.290
HUDSON RIVER SAND	84.5	0.257	0.1900	[illegible]	0.1575
	86.5	4.500	0.1900	13.3	2.19
	58.8	18.120	0.1900	21.	7.20
	88.5	30.760	0.1900	43.	9.53
PODUNK FINE SANDY LOAM	89.4	0.268	0.1900	17.2	0.191
	76.0	1.330	0.1900	15.5	0.191
	66.0	2.140	0.1900	[illegible]	0.209
	60.7	2.830	0.1900	13.2	0.244
	54.0	6.601	0.1900	13.8	0.302
	54.9	10.080	0.1900	[illegible]	0.416
	60.5	20.250	0.1900	23.7	0.623
	93.9	26.930	0.1900	43.0	1.32
LEONARDSTOWN SILT LOAM	75.0	0.806	0.1900	14.9	0.214
	69.6	2.127	0.1900	14.7	0.210
	69.8	3.580	0.1900	15.7	0.422
	62.1	4.690	0.1900	14.7	0.299
	62.1	8.980	0.1900	17.3	0.443
	64.4	10.650	0.1900	[illegible]	0.562
	56.0	11.570	0.1900	17.1	0.388
	51.9	18.350	0.1900	[illegible]	0.500
HAGERSTOWN LOAM	65.0	1.12	0.1914	13.2	0.1686
	70.0	48.06	0.1914	47.0	0.993
GALVESTON CLAY	64.9	1.41	0.2097	[illegible]	0.139
	57.0	67.55	0.2097	[illegible]	0.868
MUCK SOIL	67.2	3.93	0.1900	15.4	0.0842
	40.6	22.95	0.1900	[illegible]	0.144
	27.0	47.06	0.1900	17.3	0.180
	26.8	58.98	0.1900	[illegible]	0.260
	25.8	62.53	0.1900	21.1	0.257
	26.2	69.42	0.1900	23.1	0.208
	35.2	119.20	0.1900	49.6	0.519
	36.6	123.00	0.1900	51.9	0.402

DATA SUMMARY TABULATION

TABLE A

NOTE

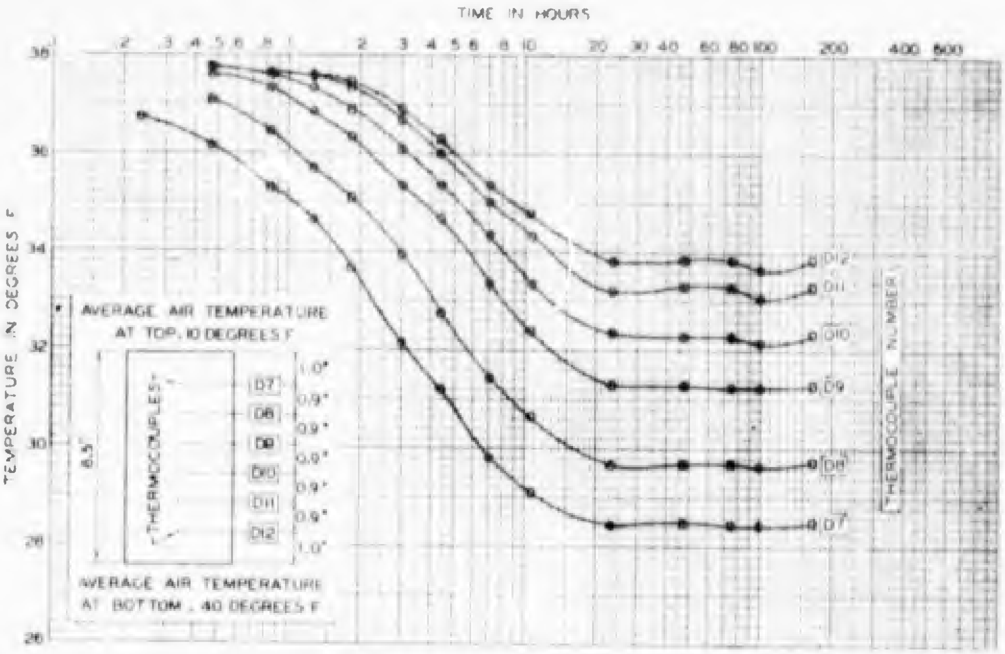
(1) H.E. PATTEN "HEAT TRANSFERENCE IN SOILS" U.S. DEPARTMENT OF AGRICULTURE BULLETIN NO. 59 SEPTEMBER 1909.

FROST INVESTIGATION

SUMMARY OF THERMAL CONDUCTIVITY TESTS BY H. E. PATTEN (1)

REVISED FEBRUARY, 1947

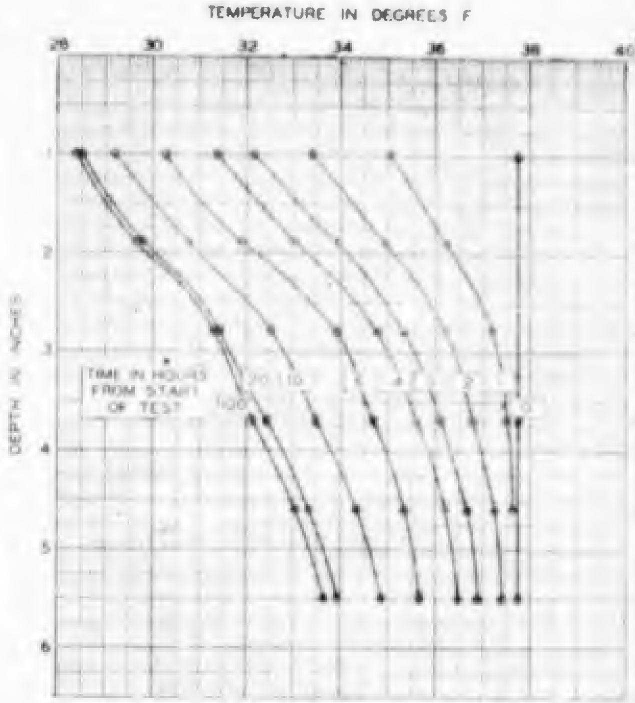
FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1945



SAMPLE 2C-8

TYPICAL SET OF TIME TEMPERATURE CURVES

FIG. 1



SAMPLE 2C-8

TYPICAL SET OF TEMPERATURE GRADIEN

FIG. 2

Sample No.	Unit Dry Weight	Water Content	Run	Average Air Temperature: Top of Specimen a	Average Air Temperature: Bottom of Specimen b	Time for Equilibrium Conditions to be Reached, Hours	Extrapolated Sample Temperature: Top c	Extrapolated Sample Temperature: Bottom d	Equilibrium Temperature Gradient in Specimen °F/FT.	[illegible]: Top c-a	[illegible]: Bottom b-d
			RUN A								
1	98.3	0.2	A	30.0	38.5	20	32.1	35.2	5.7	2.1	3.1
2	99.3	0.2	A	30.0	38.5	25	31.5	35.4	7.2	1.5	2.9
3	104.7	0.2	A	30.0	38.5	30	30.9	35.3	8.1	0.9	3.0
4	106.0	0.2	A	30.0	38.5	30	31.6	35.2	6.7	1.6	3.1
5	81.8	2.8	A	30.0	38.5	30	32.3	35.6	6.1	2.3	2.7
6	86.2	2.8	A	30.0	38.5	30	31.0	36.3	9.8	1.0	2.0
7	102.6	2.8	A	30.0	38.5	40	31.1	35.4	7.9	1.1	2.9
8	105.6	2.7	A	30.0	38.5	30	31.5	36.8	9.8	1.5	1.5
9	101.0	23.8	A	30.0	38.5	50	31.3	35.0	6.8	1.3	3.3
10	101.0	23.8	A	30.0	38.5	100	31.1	34.8	6.8	1.1	3.5
11	106.0	21.0	A	30.0	38.5	150	30.8	33.8	5.5	0.8	4.5
12	106.8	20.7	A	30.0	38.5	50	31.1	34.4	6.1	1.1	3.9
			RUN C								
1	98.3	0.2	C	9.7	38.5	20	19.6	31.0	21.1	9.9	7.3
2	99.3	0.2	C	9.7	38.5	20	18.7	30.8	22.3	9.0	7.5
3	104.7	0.2	C	9.7	38.5	25	16.5	31.4	27.5	6.8	6.9
4	106.0	0.2	C	9.7	38.5	25	18.1	31.2	24.2	8.4	7.1
5	81.8	2.8	C	9.7	38.5	25	18.6	32.9	26.4	8.0	5.4
6	86.2	2.8	C	9.7	38.5	25	17.0	32.4	28.4	7.3	5.9
7	102.6	2.8	C	9.7	38.5	30	15.3	32.1	31.0	5.6	6.2
8	105.6	2.7	C	9.7	38.5	30	17.7	32.3	27.0	8.0	6.0
9	101.0	23.8	C	9.7	38.5	100	14.3	26.0	21.6	4.6	12.3
10	101.0	23.8	C	9.7	38.5	100	16.1	26.7	19.6	6.4	11.6
11	106.0	21.0	C	9.7	38.5	50	14.[illegible]	26.4	15.0	6.6	11.9
12	106.8	20.7	C	9.7	38.5	50	19.3	27.2	16.6	9.6	11.1

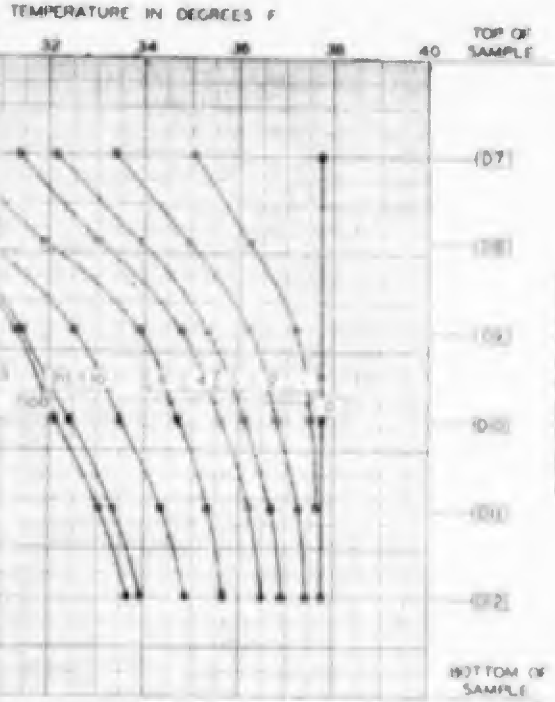
Sample No.	Run	Average Air Temperature: Top of Specimen a	Average Air Temperature: Bottom of Specimen b	Time for Equilibrium Conditions to be Reached, Hours	Extrapolated Sample Temperature: Top c	Extrapolated Sample Temperature: Bottom d	Equilibrium Temperature Gradient in Specimen °F/FT.	[illegible]: Top c-a	[illegible]: Bottom b-d
	RUN B								
1	B	20.5	38.5	50	26.5	33.5	12.9	6.0	5.0
2	B	20.5	38.5	60	25.6	33.5	14.8	5.3	5.0
3	B	20.5	38.5	50	24.0	33.5	17.5	3.7	4.8
4	B	20.5	38.5	50	25.1	33.6	16.5	4.6	4.4
5	B	20.5	38.5	60	26.3	34.7	15.9	5.8	3.6
6	B	20.5	38.5	50	24.2	34.3	18.4	3.9	4.9
7	B	20.5	38.5	50	22.5	34.2	21.6	2.0	4.1
8	B	20.5	38.5	50	24.7	33.7	18.6	4.4	4.6
9	B	20.5	38.3	100	25.5	33.3	14.2	5.2	4.8
10	B	20.5	38.5	100	25.0	32.3	13.5	4.7	6.0
11	B	20.5	38.5	70	23.1	30.1	12.9	2.8	8.2
12	B	20.5	38.5	80	23.9	30.9	12.0	3.6	7.4
	RUN D								
1	D	25.0	37.0	80	27.8	33.5	10.0	2.9	3.7
2	D	25.0	37.0	50	27.5	33.8	11.6	2.5	3.2
3	D	25.0	37.0	50	26.8	34.3	13.8	1.8	2.7
4	D	25.0	37.0	50	27.5	34.4	12.7	2.5	2.6
5	D	25.0	37.0	50	29.4	34.8	11.9	4.4	1.2
6	D	25.0	37.0	50	26.3	34.0	14.0	1.0	3.0
7	D	25.0	37.0	50	27.4	34.5	13.1	2.4	2.5
8	D	25.0	37.0	50	27.3	34.7	12.0	2.3	2.7
9	D	25.0	37.0	100	28.[illegible]	33.4	8.5	3.5	3.6
10	D	25.0	37.0	100	25.5	33.0	8.5	1.5	4.0
11	D	25.0	37.0	100	27.1	31.0	8.7	2.3	5.0
12	D	25.0	37.0	100	26.[illegible]	31.4	9.0	1.0	5.6

SUMMARY OF TEST CONDITIONS

TABLE A

EQ

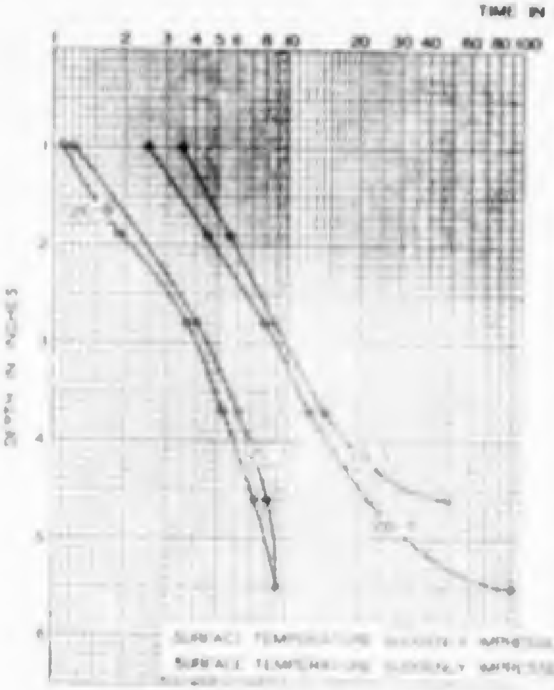
A



SAMPLE 2C-8

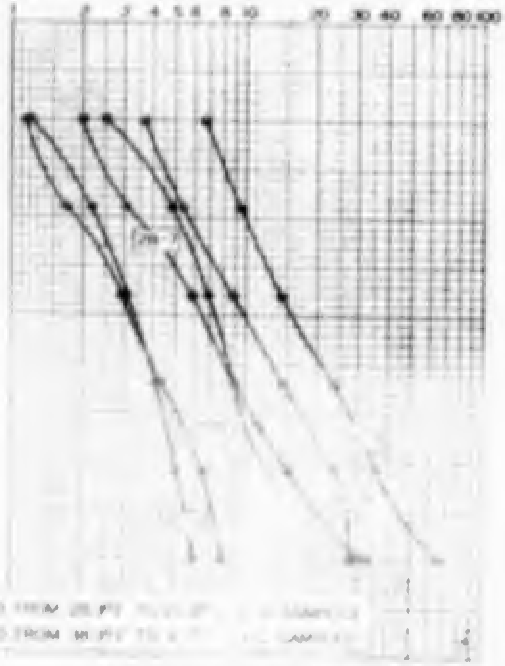
OF TEMPERATURE GRADIENTS

FIG. 2



SAMPLE NO.	W	γ
2B-5, 2C-5	2.6	81.8
2B-8, 2C-8	2.7	103.6

FIG. 3a



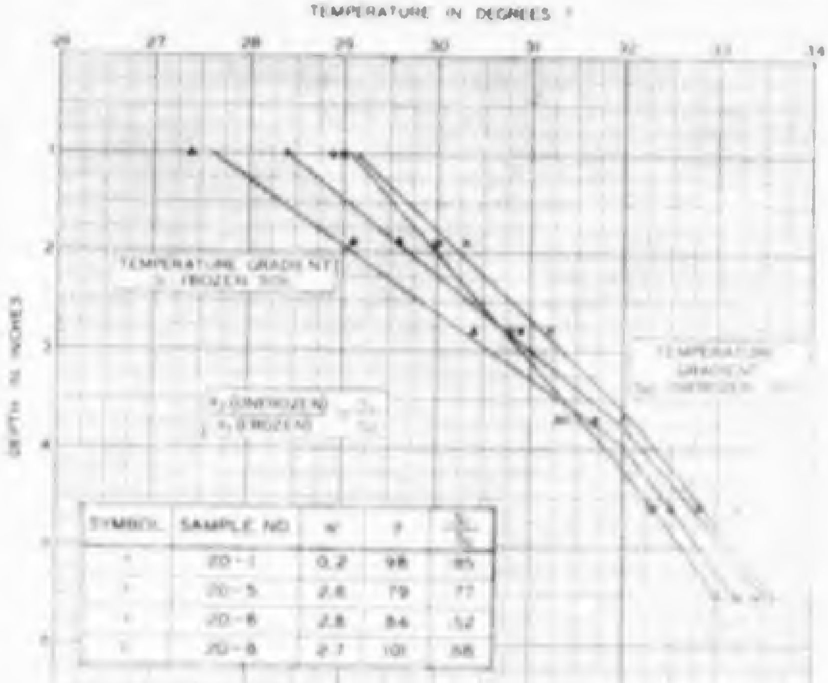
SAMPLE NO.	W	
2B-2 [illegible]	0.2	98.3
2B-[illegible]	2.4	102.6
2B-[illegible]	13.8	[illegible]0.0

FIG. 3b

PENETRATION OF 32 DEGREES F TEMPERATURE VS TIME

FIG. 3

EQUILIBRIUM TEMPERATURE GRADIENT IN SPECIMEN °F/FT.		
12.0	6.0	5.0
14.8	5.5	5.8
17.5	5.7	6.0
16.5	6.0	6.5
15.0	5.8	5.8
18.0	7.0	6.0
21.0	7.0	6.1
16.0	6.6	6.6
14.0	5.8	6.8
13.5	6.7	8.0
12.0	7.8	8.2
12.5	5.0	7.6
15.0	2.0	5.7
13.6	2.5	5.0
13.8	1.8	8.7
10.7	2.5	2.4
11.5	6.6	4.0
16.0	2.0	5.0
17.1	2.6	2.5
12.0	2.7	2.5
8.5	2.5	2.5
8.5	2.5	2.5
5.7	2.5	2.2
5.0	1.0	5.5

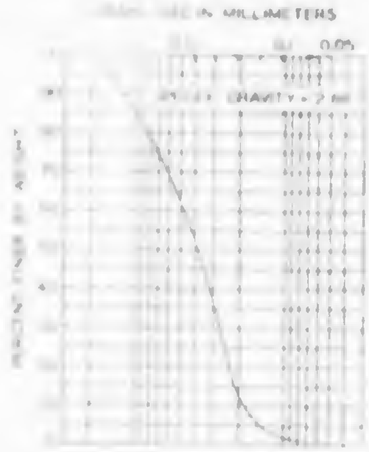


SYMBOL	SAMPLE NO.	W	γ	
	2D-1	0.2	98	95
	2D-5	2.6	79	77
	2D-6	2.8	84	52
	2D-8	2.7	101	88

SAMPLES 2D-1, 2D-5, 2D-6, 2D-8

EQUILIBRIUM TEMPERATURE GRADIENTS

FIG. 4



GRAIN SIZE GRADATION CURVE

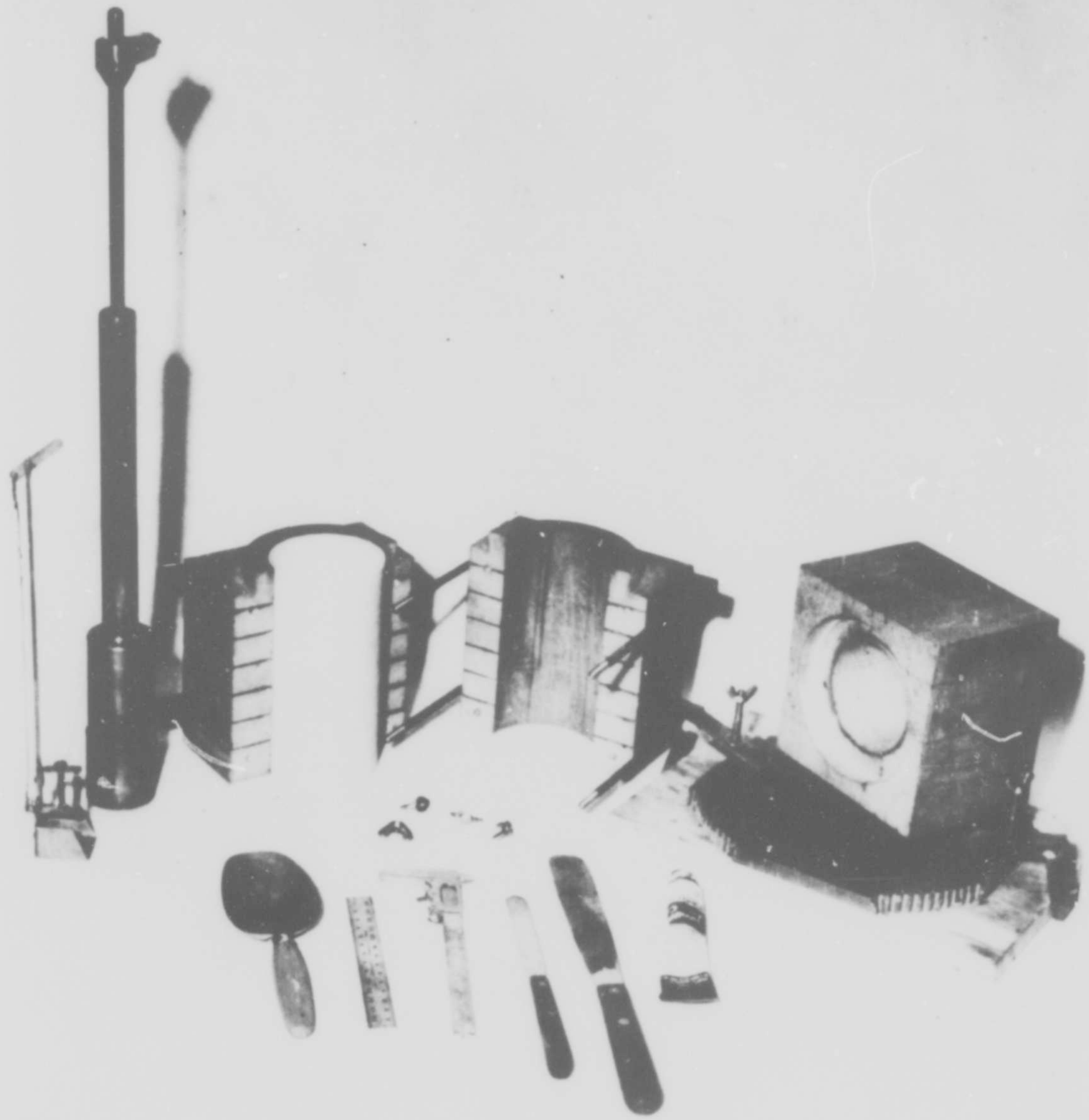
FIG. 5

FROST INVESTIGATION

SERIES 2 TESTS
INVESTIGATION OF
TEMPERATURE CONDITIONS
IN LABORATORY SPECIMENS

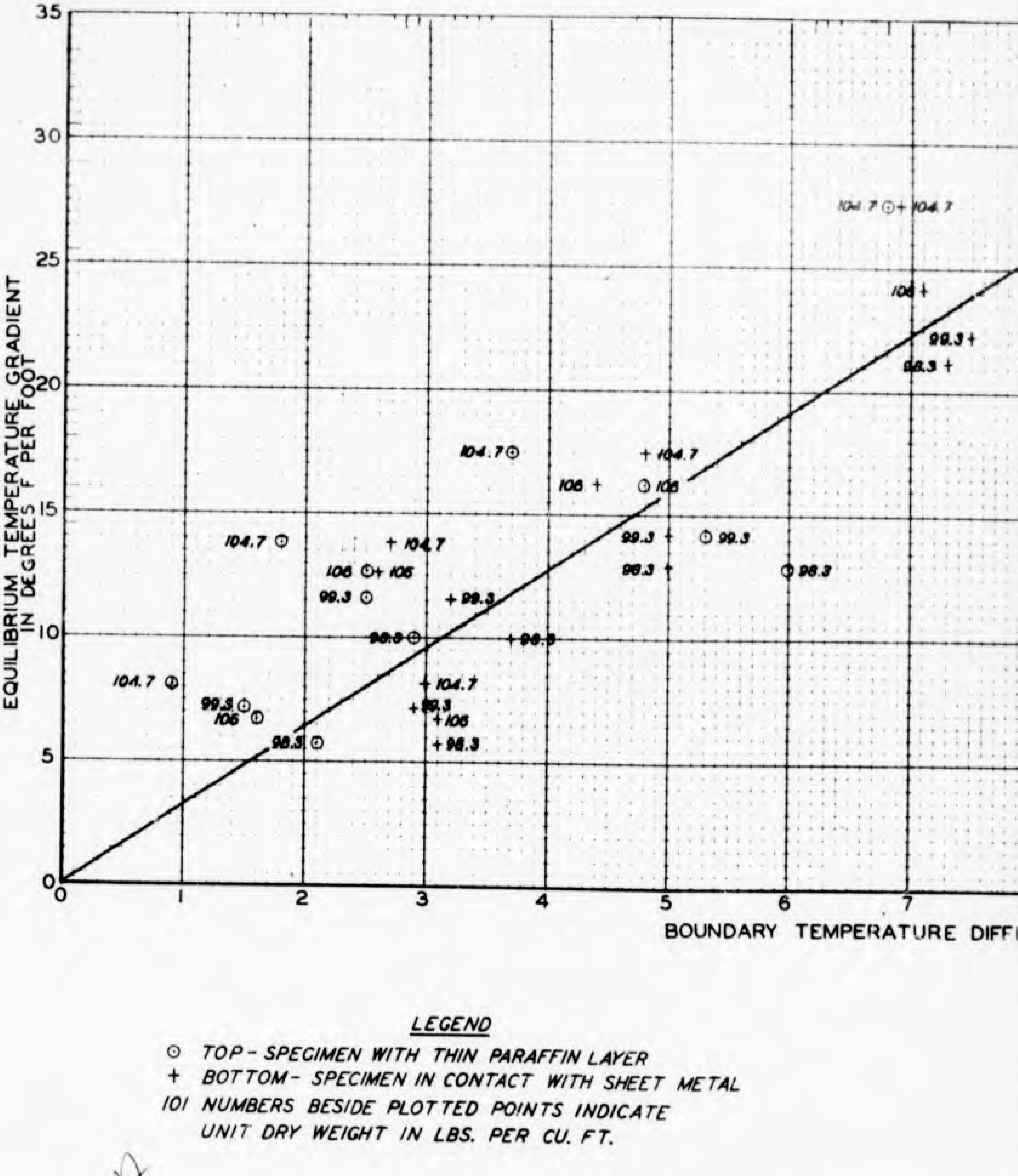
FROST EFFECTS LABORATORY BOSTON, MASS. JUNE 1945

B

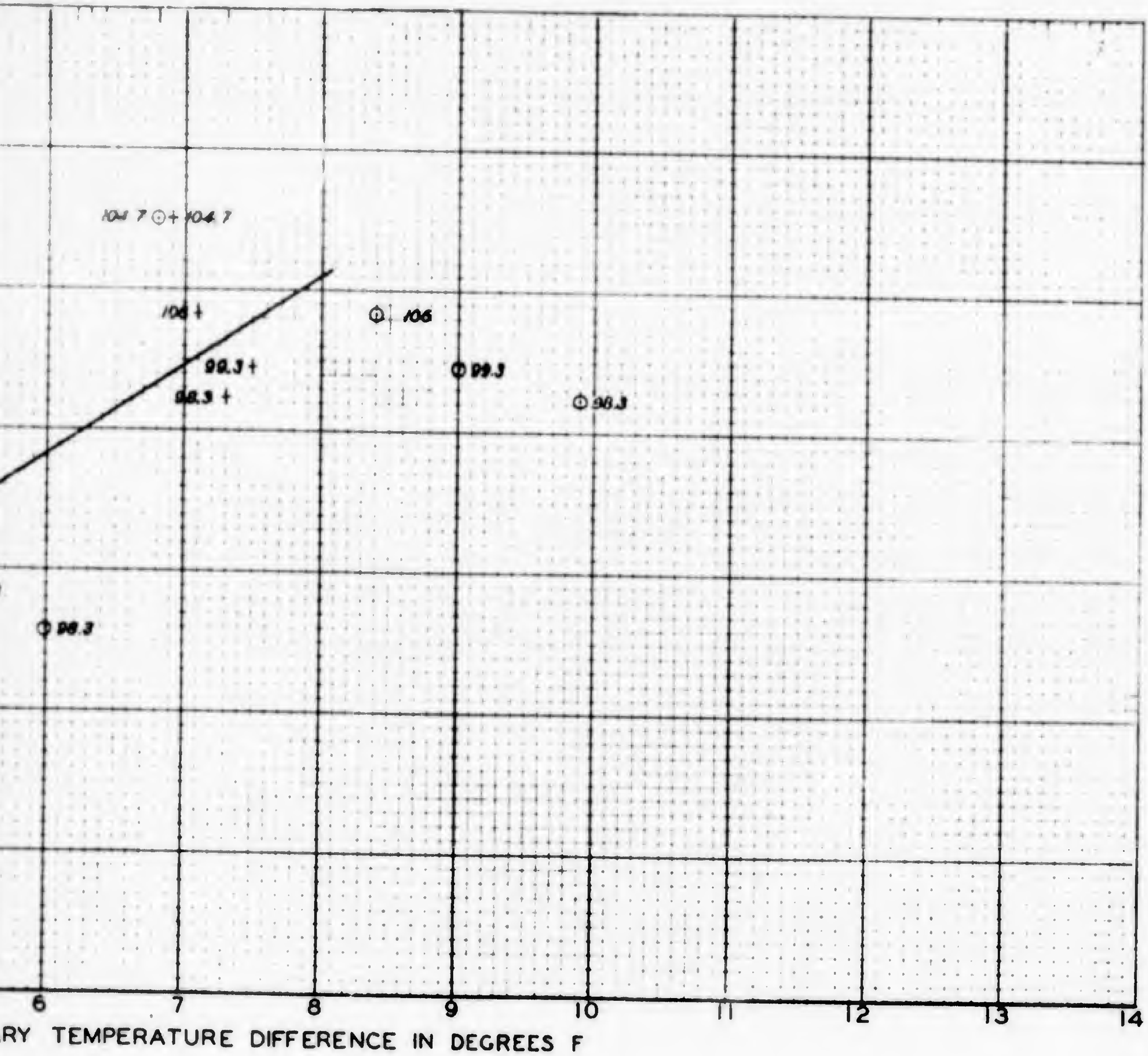


Laboratory equipment for compacting samples
in cardboard cylinders

PLATE 5



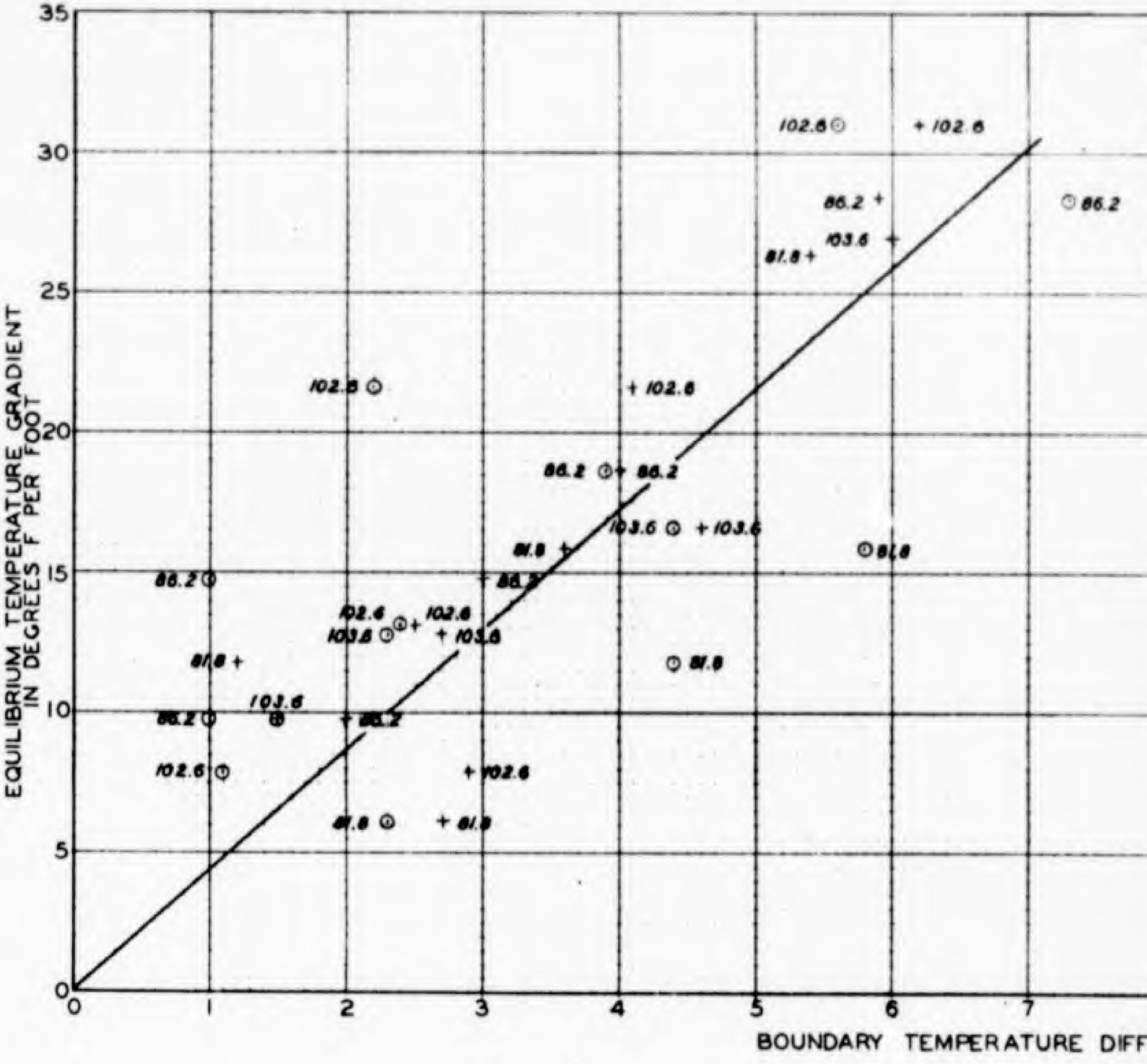
EQUILIBRIUM TEMPERATURE GRADIENT IN DEGREES F PER FOOT
BOUNDARY TEMPERATURE DIFF
LEGEND
⊙ TOP - SPECIMEN WITH THIN PARAFFIN LAYER
+ BOTTOM - SPECIMEN IN CONTACT WITH SHEET METAL
101 NUMBERS BESIDE PLOTTED POINTS INDICATE UNIT DRY WEIGHT IN LBS. PER CU. FT.



FROST INVESTIGATION

BOUNDARY TEMPERATURE DIFFERENCE
0.2 PERCENT WATER CONTENT

JUNE 1945
FROST EFFECTS LABORATORY BOSTON, MASS.



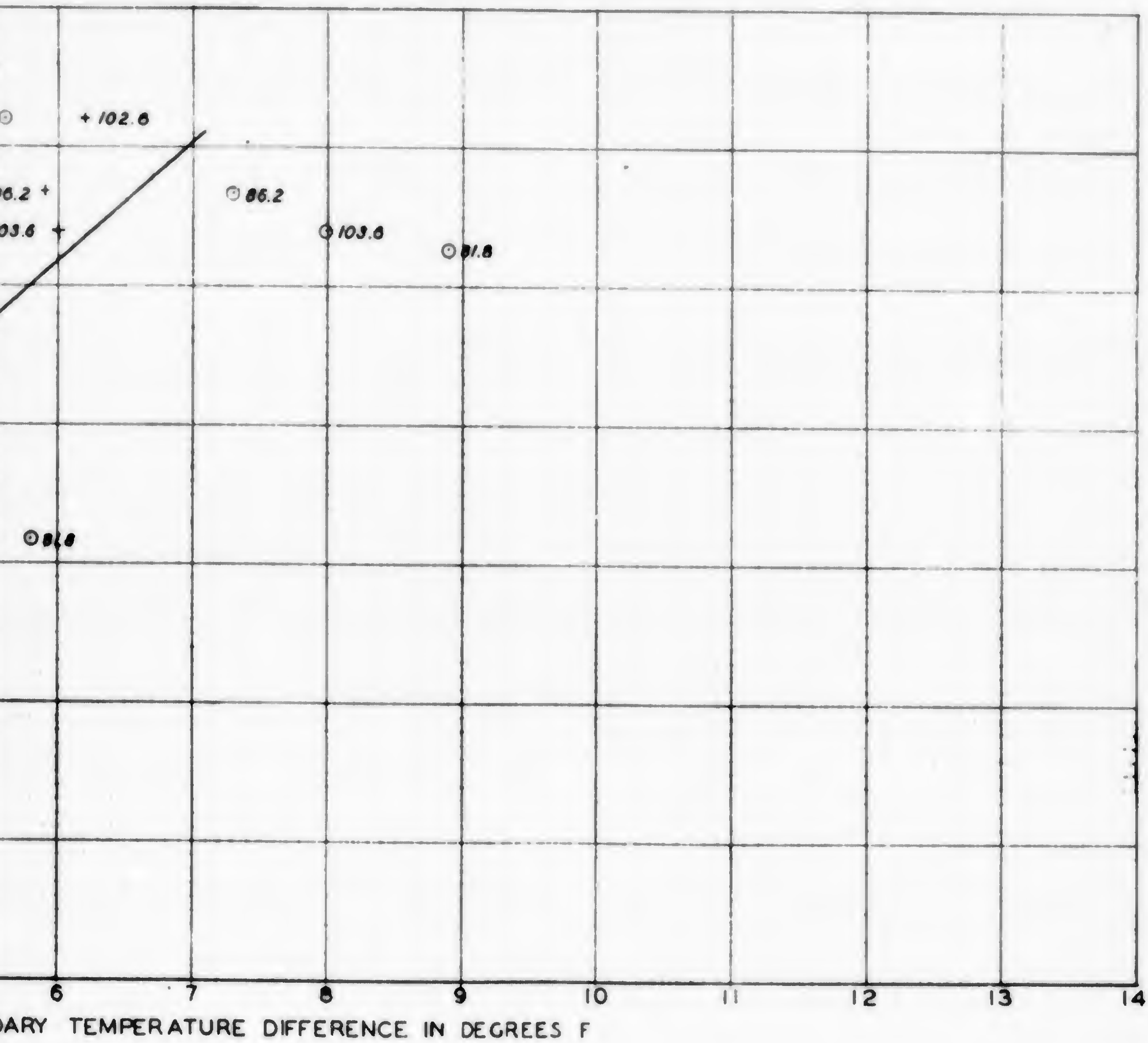
LEGEND

⊙ TOP - SPECIMEN WITH THIN PARAFFIN LAYER

\+ BOTTOM - SPECIMEN IN CONTACT WITH SHEET METAL

101 NUMBERS BESIDE PLOTTED POINTS INDICATE UNIT DRY WEIGHT IN LBS. PER CU. FT.

CORPS OF ENGINEERS, U.S. ARMY



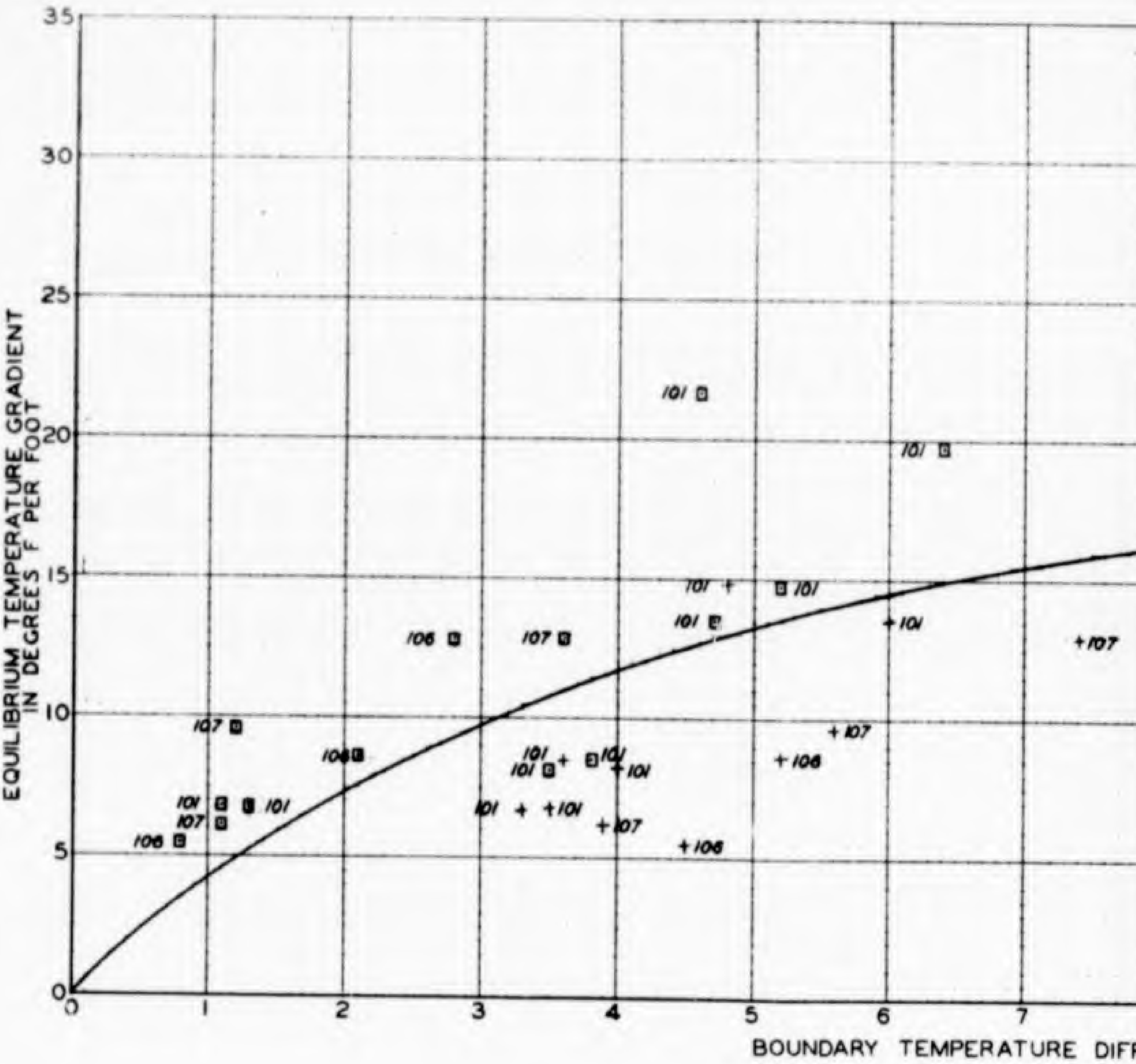
FROST INVESTIGATION

BOUNDARY TEMPERATURE DIFFERENCE
2.8 PERCENT WATER CONTENT

JUNE 1945

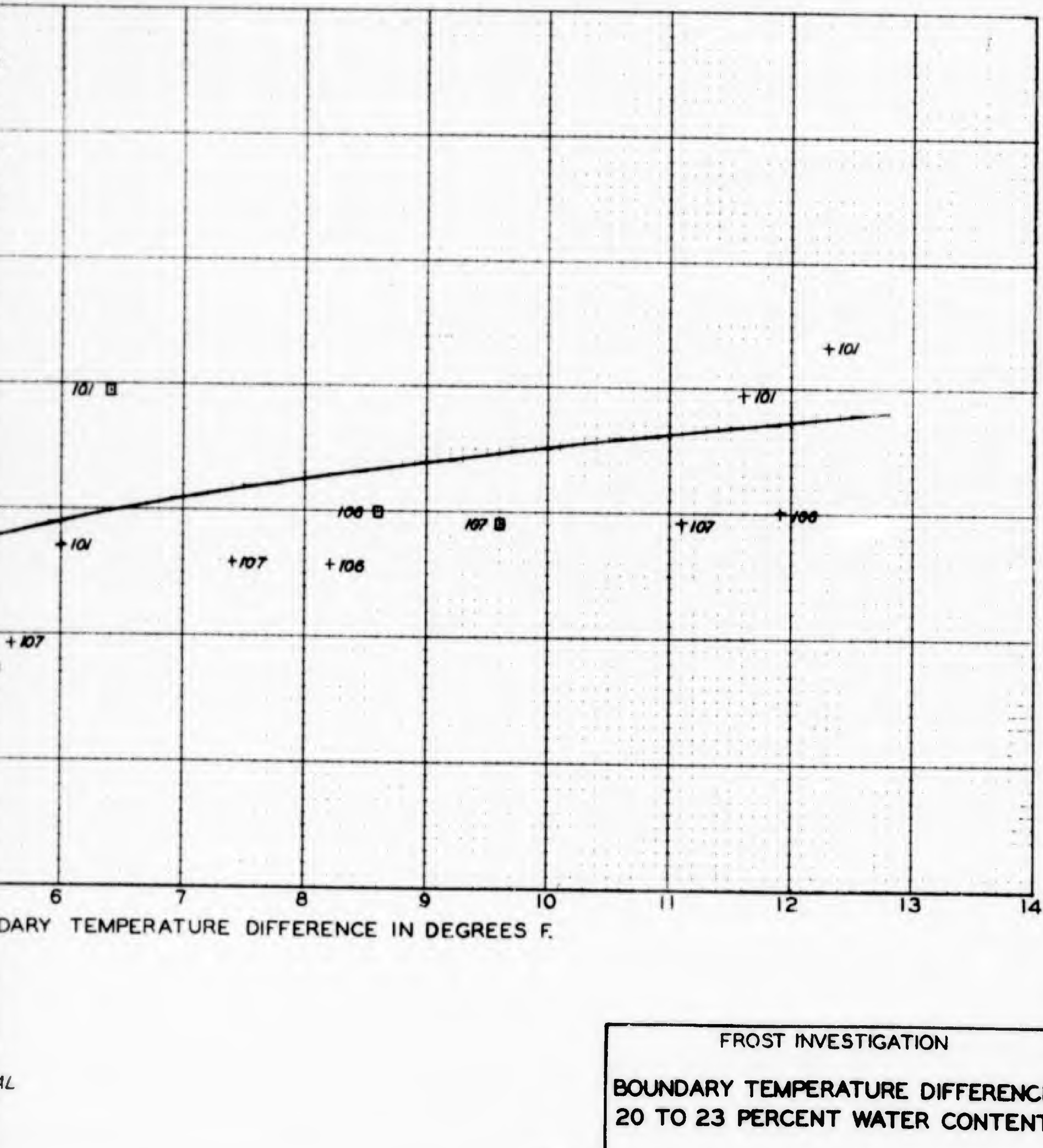
FROST EFFECTS LABORATORY BOSTON, MASS.

PLATE 7



LEGEND

- ▣ TOP - SPECIMEN WITH NO PROTECTION
- \+ BOTTOM - SPECIMEN IN CONTACT WITH SHEET METAL
- 101 NUMBERS BESIDE PLOTTED POINTS INDICATE UNIT DRY WEIGHT IN LBS. PER CU. FT.



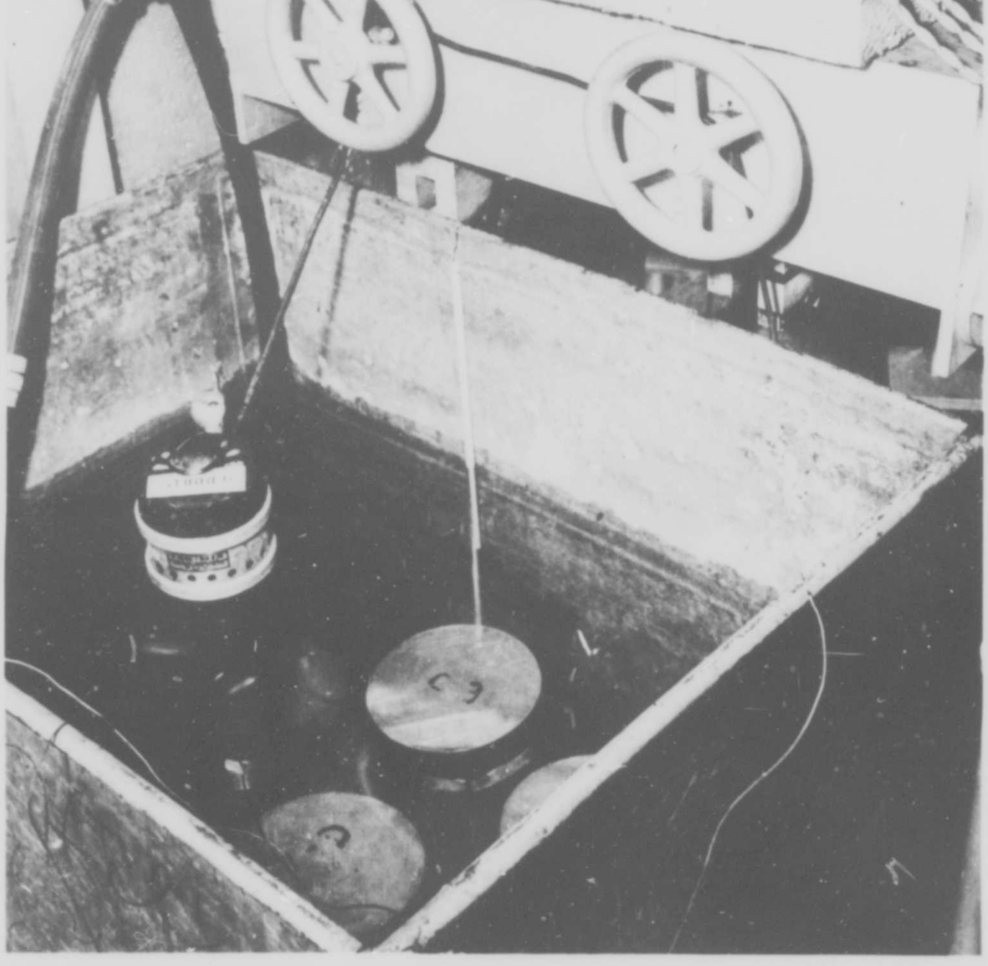
FROST INVESTIGATION

BOUNDARY TEMPERATURE DIFFERENCE
20 TO 23 PERCENT WATER CONTENT

JUNE 1945

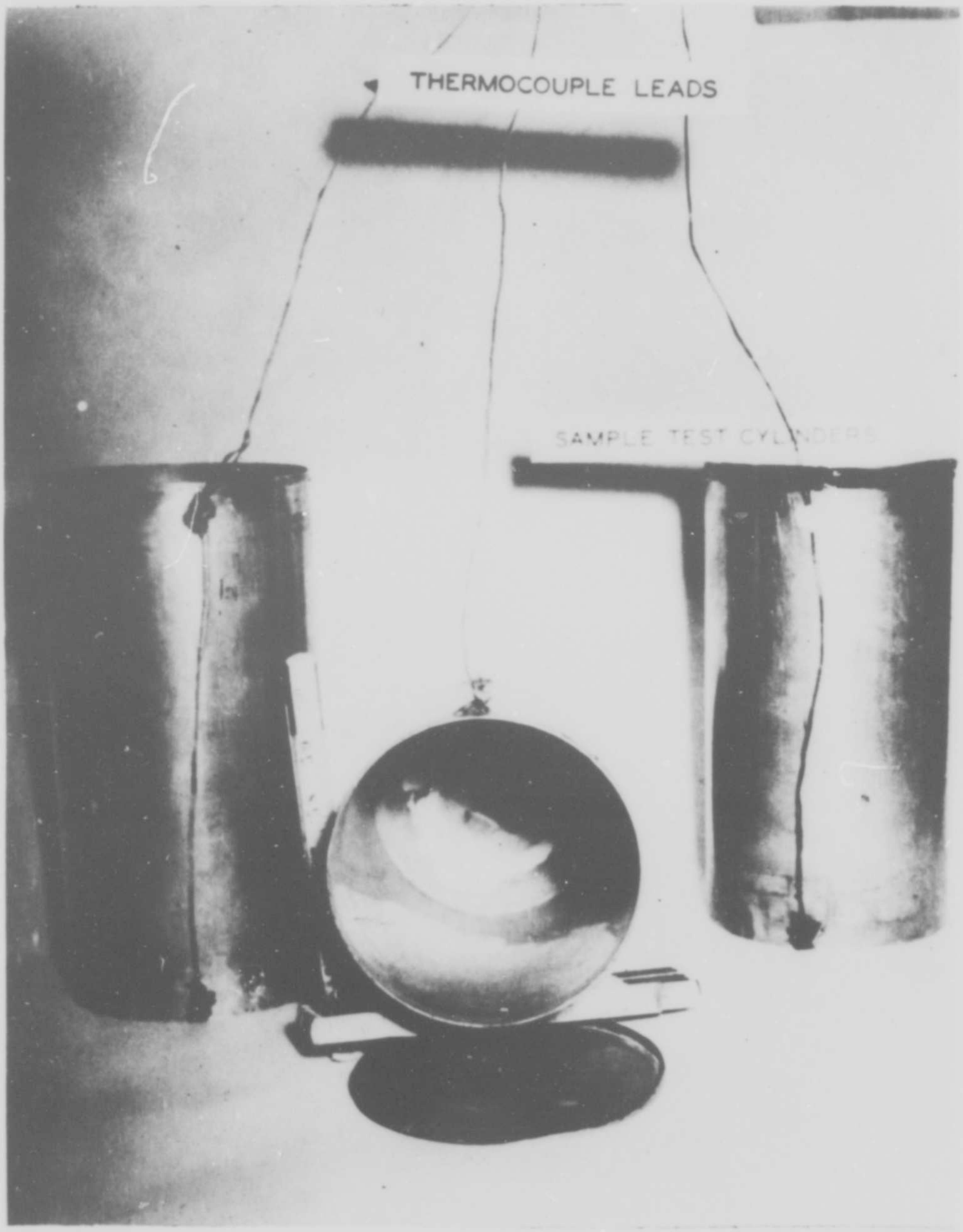
FROST EFFECTS LABORATORY BOSTON, MASS.

PLATE 8



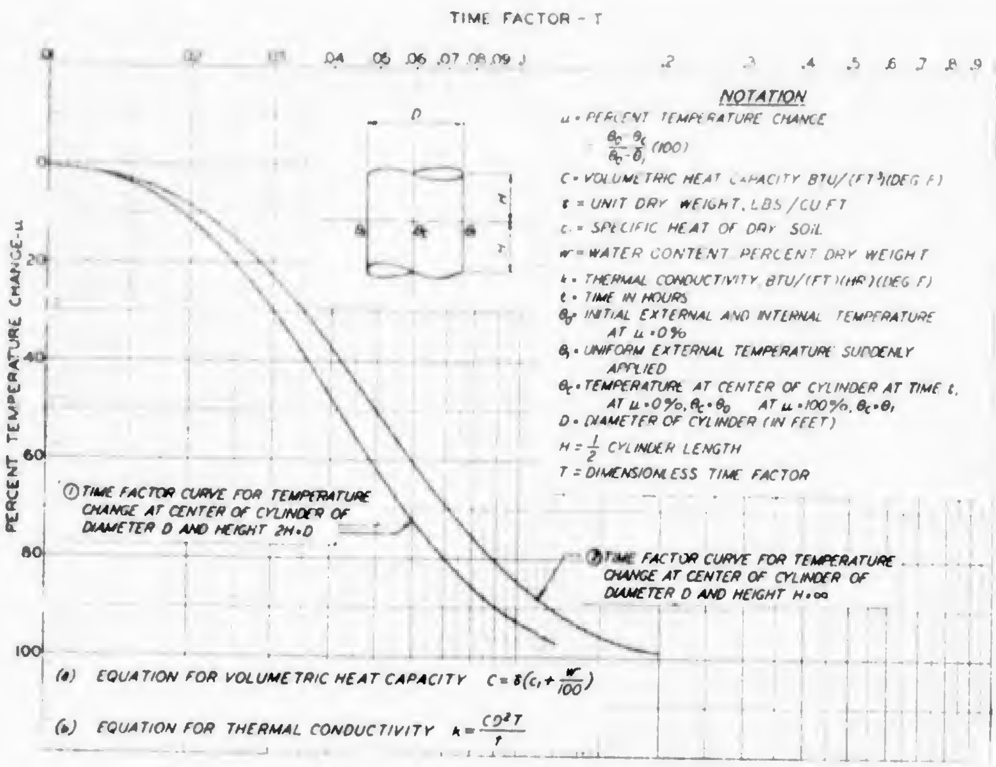
Constant Temperature Bath with Test Specimens Immersed

PLATE 9



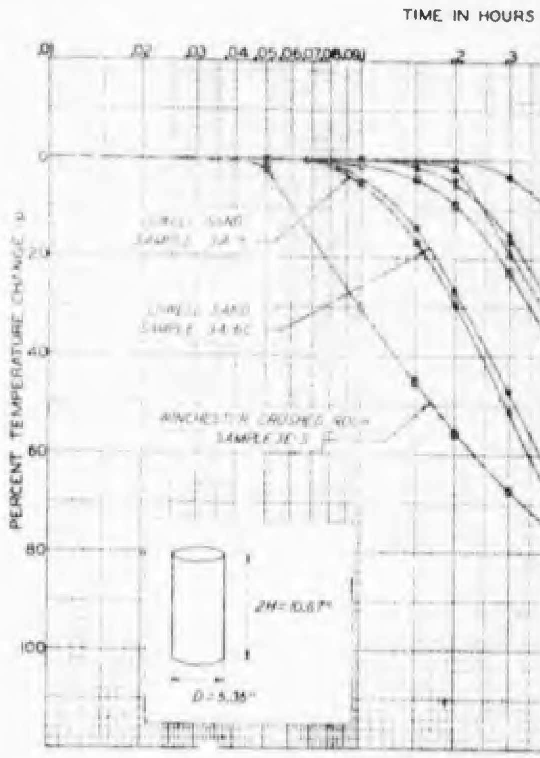
Cylinders used for thermo-conductivity tests

PLATE 10



TIME FACTOR CURVES FOR TEMPERATURE CHANGE AT CENTER OF A CYLINDER

FIG.1



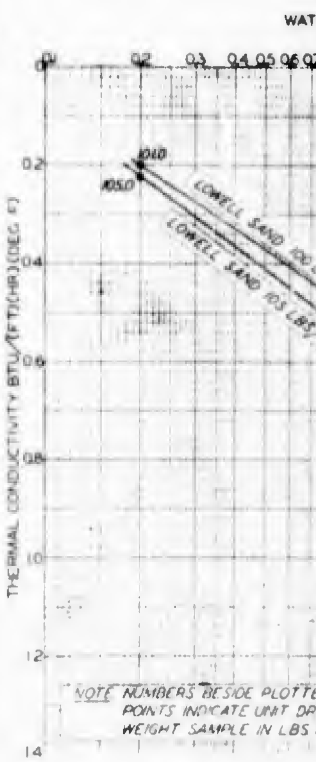
TYPICAL TIME C
THERMAL CONDUCTIVITY D

FIG.2

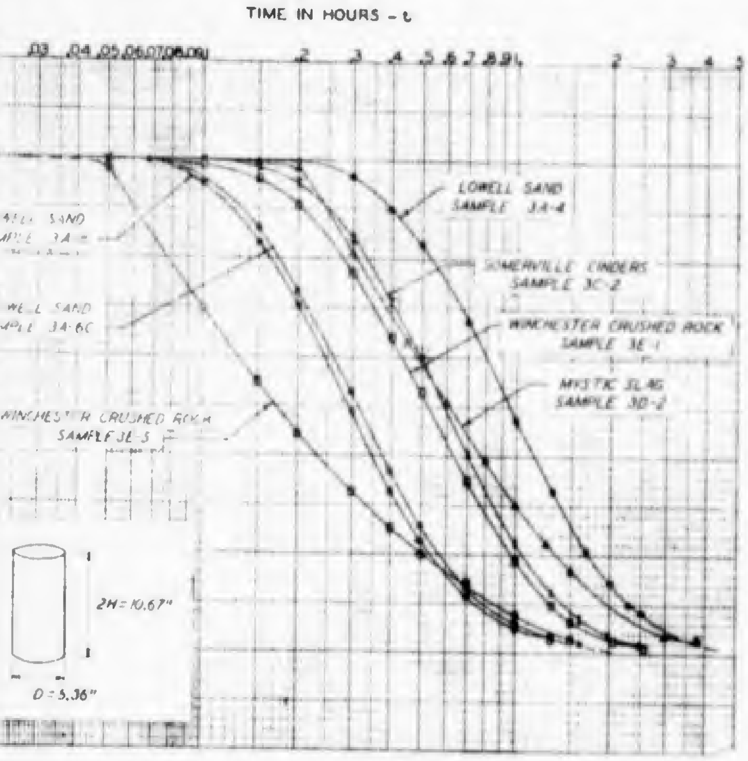
Series No.	Laboratory Sample No.	Material	Unit Dry Weight Lbs/cu. ft. γ	Water Content Percent Dry Weight w	Specific Gravity g	Specific Heat(1) Dry Soil Btu/(lb)(deg F) c	Volumetric Heat Capacity Total Sample Btu/(ft³)(deg F) C	Thermal Conductivity Btu/(ft)(hr)(deg F) k	REMARKS
3A	3A-4	Lowell Sand (well-graded medium to coarse sand) (2)	105.0	0.2	2.66	0.20	21.2	0.224	(1) Assumed (2) Minimum dry density 92.9 lbs/cu. ft. Maximum dry density 110.9 lbs/cu. ft. (3) Sample not properly sealed, some water leaked into sample during test. (4) Test results are not consistent with results of other tests. (5) Average-- w = 14.2% top of sample w = 27.5% bottom of sample (6) Non-uniform water content (7) Percent Bitumen 4.5%
	3A-4a		105.0	0.2	2.66	0.20	21.2	0.224	
	3A-5(3)		101.0	0.2	2.66	0.20	20.4	0.201	
	3A-6a		106.5	16.4	2.66	0.20	38.8	1.22	
	3A-7		101.0	20.9	[illegible]	0.20	41.3	1.19	
	3A-8		103.0	4.5	2.66	0.20	25.3	~~0.855~~	
	3A-9		83.5	4.9	2.66	0.20	20.8	0.559	
	3A-10(3)		84.5	2.3	2.66	0.20	18.8	0.399	
	3A-11(3)		91.1	1.9	2.66	0.20	19.9	0.418	
	3A-12		109.0	2.2	2.66	0.20	24.3	0.693	
	3A-13		103.0	2.0	2.66	0.20	22.7	0.566	
	3A-15		89.3	2.1	2.66	0.20	19.7	0.552	
	3A-16		105.0	5.1	2.66	0.20	26.4	0.925	
	3A-17		90.8	2.1	2.66	0.20	20.1	0.520	
3B	3B-1	Bangor Sand and Gravel	127.0	3.4	2.70	0.20	29.8	1.06	
	3B-2		131.5	1.1	2.70	0.20	27.7	0.801	
	3B-3		127.0	9.3	2.70	0.20	36.3	1.34	
3C	3C-1	Somerville Cinders (1-inch maximum)	60.9	20.7(5)	1.28	0.18	23.6	0.420	
	3C-2		60.0	36.6	1.28	0.18	32.8	0.550	
	3C-3		60.8	21.2(6)	1.28	0.18	23.9	0.422	
	3C-4		61.7	11.3	1.28	0.18	18.1	0.354	
3D	3D-1	Mystic Slag (1½-inch maximum)	79.1	9.1	2.18	0.17	17.5	0.224	
	3D-2(4)		81.2	33.5	2.18	0.17	40.9	0.658	
3E	3E-1	Winchester Crushed Trap Rock (3/4-inch maximum)	99.2	1.9	2.91	0.20	21.7	0.416	
	3E-2		100.0	2.1	2.91	0.20	22.1	0.441	
	3E-3		98.5	4.4	2.91	0.20	23.6	0.480	
	3E-4		98.5	27.2	2.91	0.20	46.5	1.01	
	3E-5(4)		99.3	28.4	2.91	0.20	48.0	2.76	
	3E-6a(4)		100.0	27.7	2.91	0.20	47.7	2.20	
	3E-7		102.0	2.5	2.91	0.20	23.0	0.441	
	3E-8		102.0	26.7	2.91	0.20	47.7	1.76	
3F	3F-1	Asphaltic Bituminous Concrete	150.0(7)	0.0	2.60	0.20	30.3	0.820	
	3F-2		150.0(7)	0.0	2.60	0.20	30.3	0.815	
3G	3G-1(3)	Blended Bituminous Concrete Aggregate	133.5	0.0	2.81	0.20	26.7	0.372	

SUMMARY OF TEST DATA

TABLE A

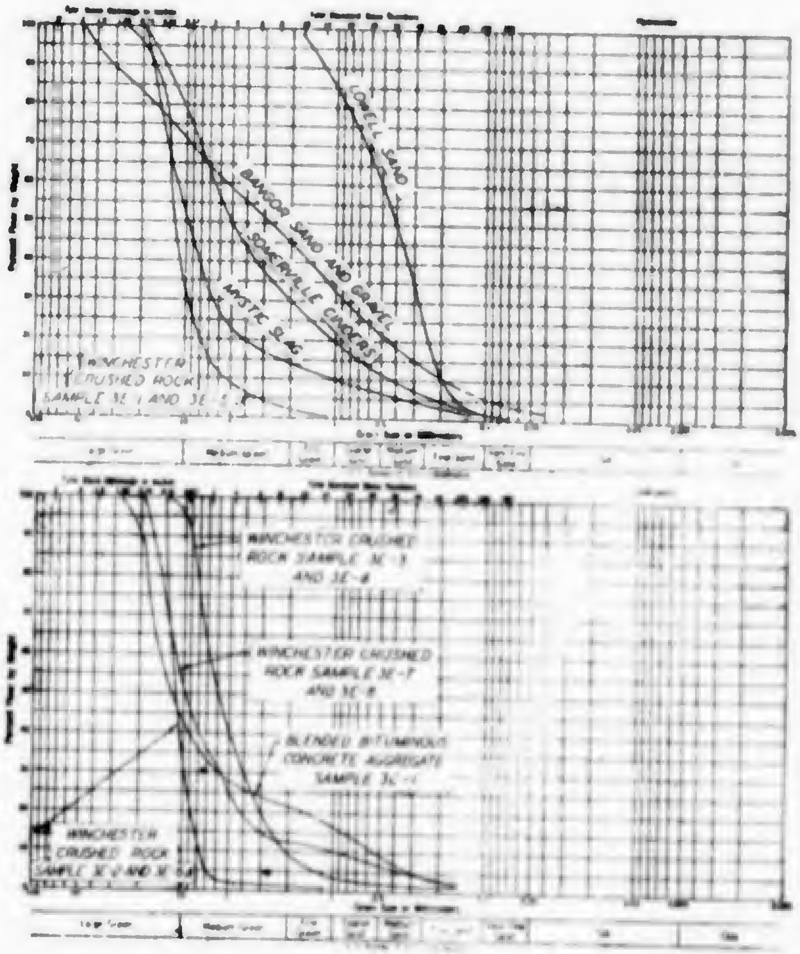


THERMAL CON
OF VA



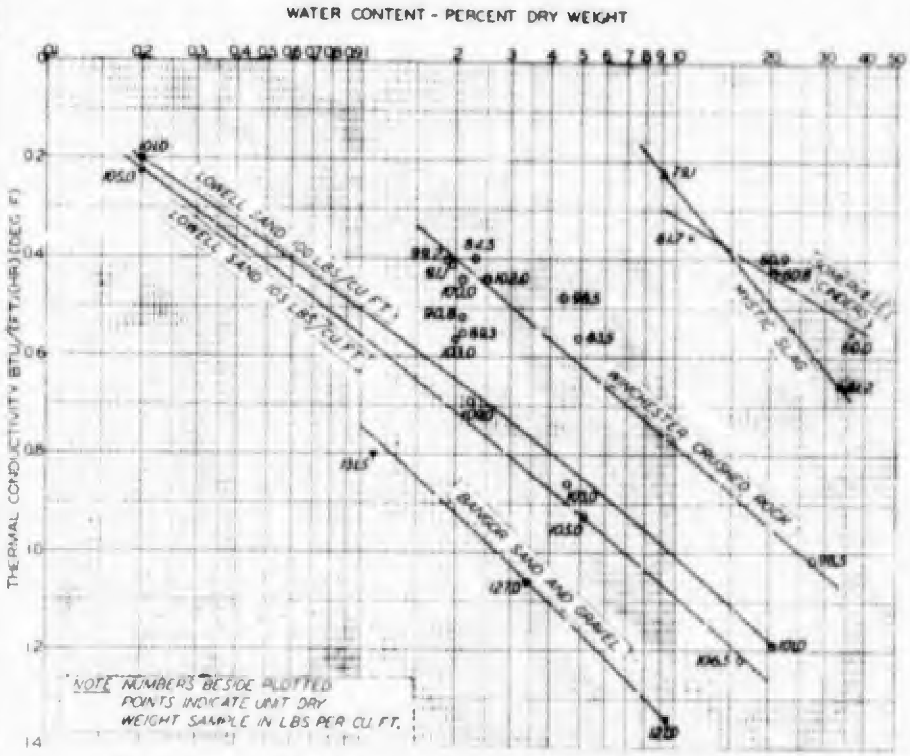
TYPICAL TIME CURVES
THERMAL CONDUCTIVITY DETERMINATIONS

FIG.2



GRADATION OF BASE MATERIALS

FIG.3



THERMAL CONDUCTIVITY VS WATER CONTENT OF VARIOUS BASE MATERIALS

FIG 4

EXAMPLE FOR DETERMINATION OF k

EQUATION $k = \frac{C D^2 T}{t}$

TEST DATA FROM TABLE A, SAMPLE 3A-8 ARE USED

$c = 0.20$

$\gamma = 103$ LBS/CU FT

$w = 4.5\%$

$C = \gamma\left(c + \frac{w}{100}\right) = 103\left(0.20 + \frac{4.5}{100}\right) = 25.3$ BTU/(FT³)(DEG F)

FROM FIG 2

$D^2 = (5.36")^2 = (0.446')^2 = 0.1995$ FT²

FOR $\mu = 50\%$, $t = 0.295$ HOURS

(50% TEMPERATURE CHANGE IS ARBITRARILY TAKEN ANY VALUE OF μ ON THE STRAIGHT PORTION OF THE CURVE MAY BE USED)

FROM FIG 1 CURVE (2)

FOR $\mu = 50\%$, $T = 0.05$

SUBSTITUTING IN EQUATION

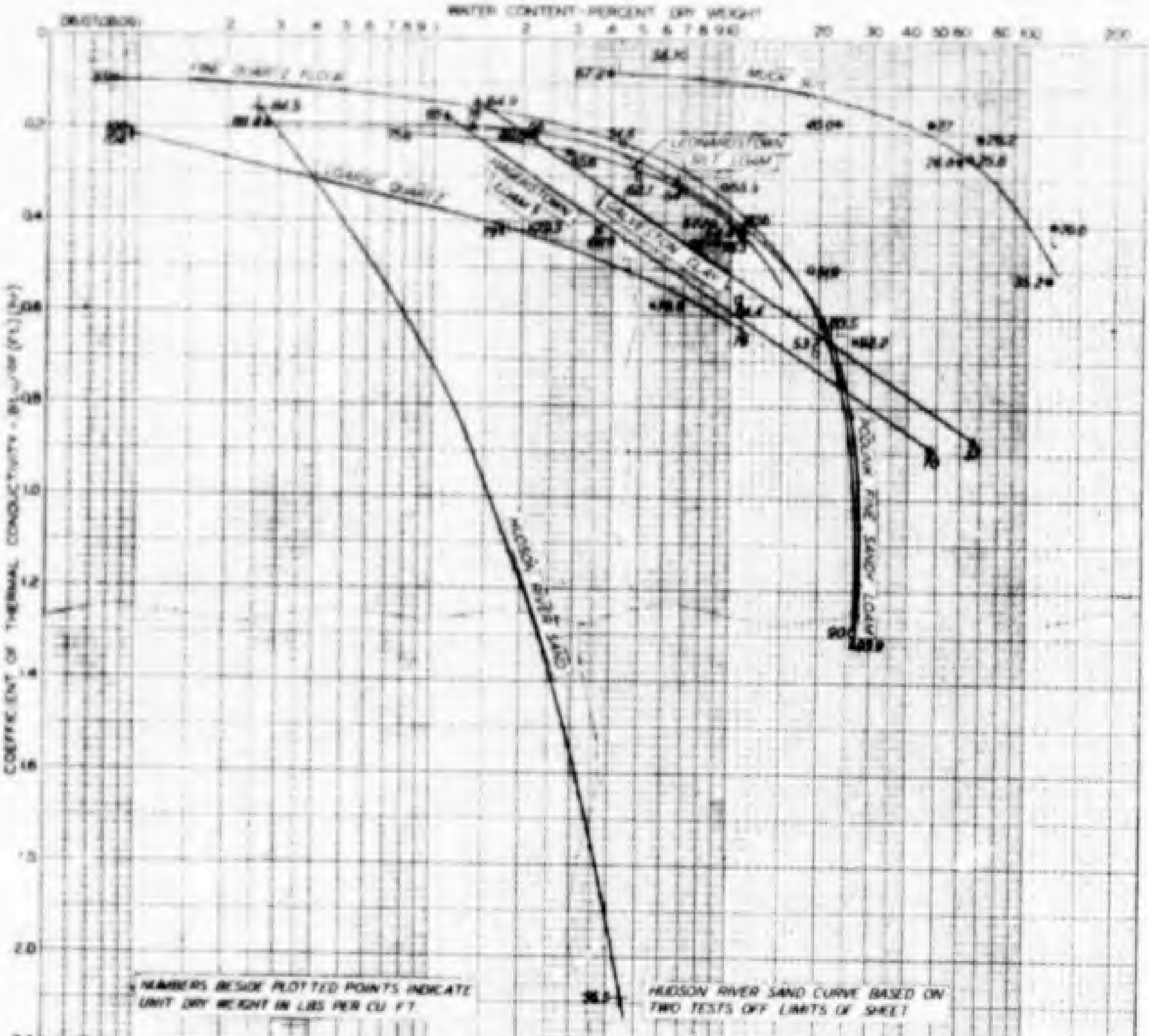
$k = \frac{C D^2 T}{t} = \frac{(25.3)(0.1995)(0.05)}{(0.295)}$

$k = 0.855$ BTU/(FT)(HR)(DEG. F)

FROST INVESTIGATION

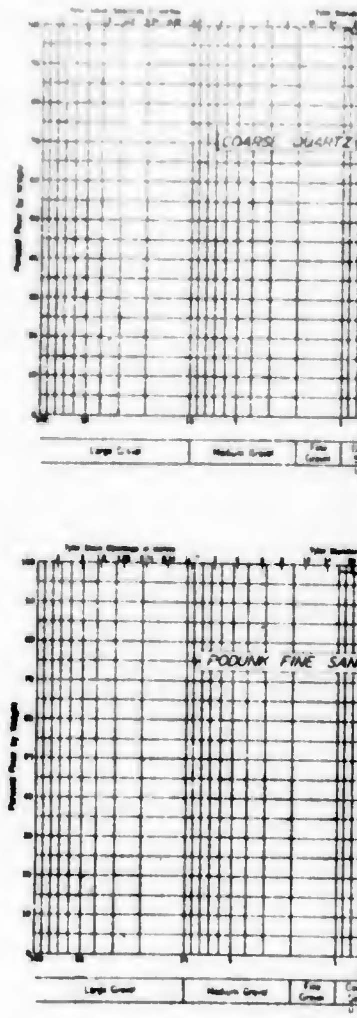
THERMAL CONDUCTIVITY DETERMINATIONS COHESIONLESS BASE MATERIALS

FROST EFFECTS LABORATORY BOSTON MASS JUNE 1945

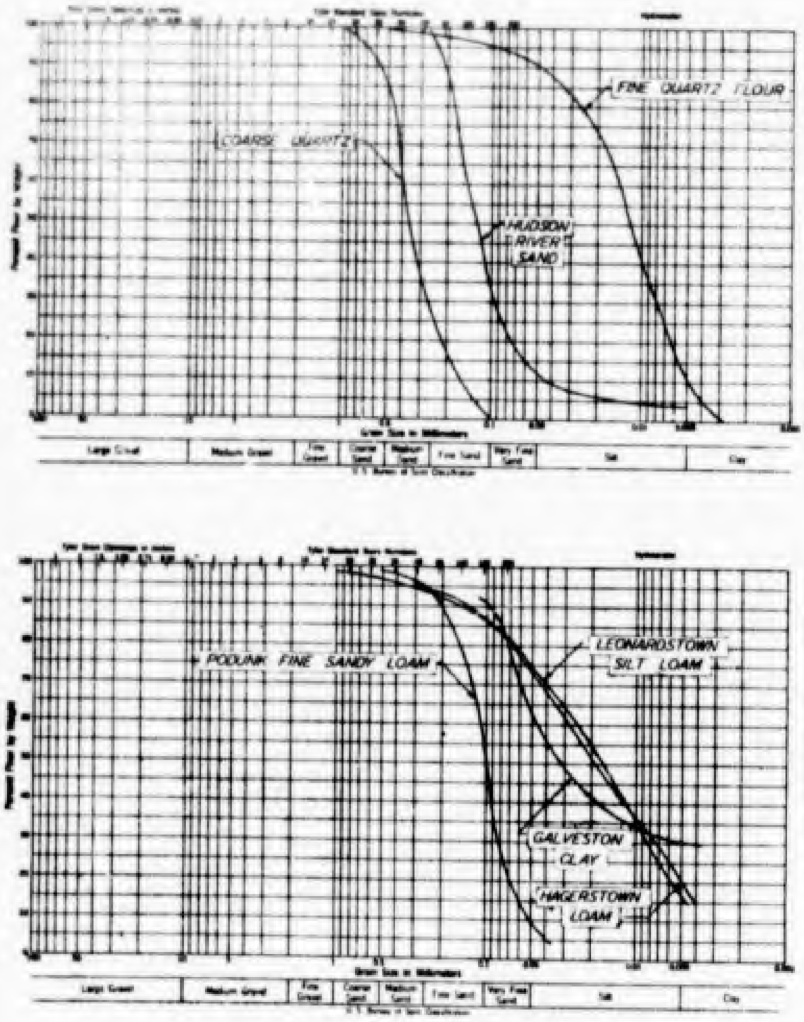


THERMAL CONDUCTIVITY VS WATER CONTENT

FIG. 1



GRAIN SIZE



GRAIN SIZE GRADATION CURVES

FIG. 2

Material	Unit Dry Weight	Water Content	Specific Heat	Volumetric Heat Capacity	Thermal Conductivity
	lbs/c.f.	% Dry Wt.		Btu/(°F)(cf)	Btu/°F (ft)(hr)
COARSE QUARTZ	104	0.095	0.1900	11.9059	0.221
	100	0.095	0.1900	11.9059	0.206
	79	1.710	0.1900	12.7046	0.[illegible]
	79.3	2.160	0.1900	12.9230	0.415
	76.8	5.520	0.1900	14.4768	0.581
	78.0	10.910	0.1900	16.8418	0.650
	92.2	26.700	0.1900	21.9274	0.655
FINE QUARTZ FLOUR	55	0.0833	0.1900	11.9059	0.0481
	54.6	4.280	0.1900	13.9539	0.232
	56.1	6.930	0.1900	15.0750	0.0499
	57.1	8.720	0.1900	15.9120	0.405
	55.5	9.530	0.1900	[illegible].2552	0.323
	58.3	10.920	0.1900	[illegible]	0.427
	53.7	19.670	0.1900	[illegible]	0.680
	90.0	26.650	0.1900	[illegible]	1.290
HUDSON RIVER SAND	84.5	0.257	0.1900	11.1690	0.1575
	56.5	4.500	0.1900	13.2538	2.19
	58.8	18.120	0.1900	18.9197	7.20
	88.5	30.760	0.1900	23.1192	9.53
PODUNK FINE SANDY LOAM	89.4	0.268	0.1900	11.5440	0.191
	76.0	1.330	0.1900	12.0744	0.191
	66.0	2.140	0.1900	12.4800	0.209
	65.6	2.830	0.1900	12.8107	0.244
	54.0	6.601	0.1900	14.5642	0.302
	54.9	10.080	0.1900	16.0680	0.418
	60.5	20.250	0.1900	19.9930	0.625
	93.9	26.930	0.1900	22.2269	1.32
LEONARDSTOWN SILT LOAM	75.0	0.806	0.1900	14.8138	0.214
	69.6	2.127	0.1900	15.3192	0.210
	69.8	3.580	0.1900	15.9951	0.422
	62.1	4.690	0.1900	14.8138	0.299
	62.1	8.980	0.1900	18.2770	0.443
	64.4	10.650	0.1900	18.9384	0.562
	56.0	11.570	0.1900	19.1256	0.388
	51.9	18.350	0.1900	21.6216	0.500
HAGERSTOWN LOAM	65.0	1.12	0.1914	12.5050	0.1686
	70.0	48.06	0.1914	[illegible].3171	0.895
GALVESTON CLAY	64.9	1.41	0.2097	13.7717	0.199
	57.0	67.55	0.2097	32.9659	0.868
MUCK SOIL	67.2	3.93	0.1900	11.7562	0.0842
	40.6	22.95	0.1900	19.5936	0.104
	27.0	47.06	0.1900	26.6136	0.180
	26.8	58.98	0.1900	29.2968	0.260
	25.8	62.83	0.1900	30.0893	0.257
	26.2	69.42	0.1900	31.3310	0.208
	35.2	119.20	0.1900	38.3448	0.519
	36.6	123.00	0.1900	38.8003	0.402

DATA SUMMARY TABULATION

TABLE A

NOTE

(1) H. E. PATTEN "HEAT TRANSFERENCE IN SOILS" U.S. DEPARTMENT OF AGRICULTURE BULLETIN NO. 59 SEPTEMBER 1909.

FROST INVESTIGATION

SUMMARY OF THERMAL CONDUCTIVITY TESTS BY H. E. PATTEN (1)

FROST EFFECTS LABORATORY, BOSTON, MASS. JUNE 1945