THERMAL PROPERTIES OF SOILS

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INTRODUCTION

This report presents the results of an investigation to determine the thermal properties of a variety of soils and insulating materials. The work has been performed by the Engineering Experiment Station of the University of Minnesota for the St. Paul District, Corps of Engineers, U. S. Department of the Army. This study represents only one phase of a comprehensive program of research which the Corps of Engineers is making on problems of construction in regions of permafrost. In planning the program, it was recognized that the interpretation of many observations made in the field and the correct solution of many design problems of structures in the field would be dependent upon a knowledge of the thermal properties of the soils.

The original instructions and outline prepared by the Corps of Engineers in November, 1945, gave as the objective and purpose of the study, "to determine under varying conditions of temperature, moisture, bulk density, and composition the thermal properties of representative soils and organic material from Alaska." The thermal properties which were to be studied were thermal conductivity, specific heat and diffusivity. The major part of the test work has been the determination of thermal conductivity values. Diffusivity may be determined by calculation if the thermal conductivity, specific heat, and density of a soil are known. It was originally intended to make some check tests for this constant, but it was later agreed to drop this item from the program. It was endeavored to make the thermal conductivity test program sufficiently comprehensive not only to give characteristic values for the typical soils but also to determine the effect and the relative importance of the many variables which affect the coefficients.

Most of the soils and materials tested have been furnished by the St. Paul District Corps of Engineers and are typical materials from regions of permafrost. Two graded soils from local sources were included since no soils of their particular textural class were obtained from Alaska. Also, to aid in the study of mineral composition, some crushed rock materials and pure quartz sands were obtained from various local sources.

In addition to the thermal tests on soils, the program was extended to include tests on pre-cast insulating slabs and an asphalt paving mixture. The insulating slabs were prepared from materials used in the foundations of some of the experimental field installations near Fairbanks, Alaska.

Since this is the final report on the investigation, the data are given in detail; the thermal conductivity test data on soils are tabulated in Appendix I. In the discussion of the effect of various factors, graphs for just one or two soils are given in the body of the report, and similar curves for the other soils are included in an appendix. This arrangement permits a more compact report and still makes available the relationships for all soils.

The research program was started in the fall of 1945, and the test work was completed in the spring of 1948. During this period, the following progress reports were submitted to the St. Paul District Corps of Engineers:

1. Laboratory Research for the Determination of the Thermal Properties of Soils. Quarterly Report, April 1, 1946.
2. Laboratory Research for the Determination of the Thermal Properties of Soils. Semi-Annual Report, October 1, 1946.
3. Laboratory Research for the Determination of the Thermal Properties of Soils. Semi-Annual Report, February 1, 1947.
4. Laboratory Research for the Determination of the Thermal Properties of Soils. Comprehensive Report, January, 1948.

Personnel

The investigation was conducted at the Oak Street Laboratories of the Engineering Experiment Station of the University of Minnesota for the St. Paul District, Corps of Engineers. The work was under the general direction of Frank B. Rowley, Director of the Engineering Experiment Station. Miles S. Kersten, Associate Professor of Civil Engineering was in immediate charge of the investigation. Axel B. Algren, Associate Professor of Mechanical Engineering was in charge of operations during the early stage of construction of the thermal conductivity apparatus. Specific heat tests were performed by O. M. Bjeldanes; the thermal conductivity tests on insulating concrete slabs by Robert Lander; and the minerological counts by Professor George Schwartz and G. E. Prichard. The operating staff included some full time workers as well as a number of students who worked on a part time basis.

The St. Paul District, Corps of Engineers planned the investigational program and cooperated closely in the procurement and construction of testing equipment and in providing some personnel for the testing work. Harry Carlson, engineer, coordinated the activities of the St. Paul District and the University of Minnesota under the general direction of H. J. Manger, Head of the Permafrost Division. E. J. Evans, engineer, was in charge of control tests on soils for the testing program. Walter K. Wilson, Jr. Colonel, Corps of Engineers, Department of the Army is District Engineer.

Authorization and funds for the investigation were provided through the Office, Chief of Engineers, Washington, D. C. Colonel L. C. Urquhart was Chief of the Engineering Division. Valuable suggestions on the program were given by Gayle McFadden, T. B. Pringle, and W. Marks Jaillite of the Office, Chief of Engineers, William L. Shannon and A. Casagrande of Harvard University; and Philip C. Rutledge of Northwestern University.

SUMMARY

Test Results

Thermal conductivity tests have been conducted on 19 soils at a number of different density and moisture content conditions. The tests have shown that the coefficient of thermal conductivity varies in the following ways:

1. Above freezing it increases with an increase in mean temperature.
2. Below freezing, for soils at low moisture contents, it shows very little change; for greater moisture contents, it shows an increase for a decrease in temperature.
3. For a change from unfrozen to frozen soil, it changes variably according to the moisture content. For dry soils it does not change; for soils of low moisture content, it decreases; and for soils of high moisture content, it increases.

4. At a constant moisture content, it increases with an increase in dry density. The rate of increase is fairly constant and is independent of the moisture content.

5. At a constant dry density, it increases with an increase in moisture content.

6. At a given density and moisture content, it varies in general with the texture of the soil, being high for gravels and sands, lower for the sandy loams, and lowest for the silt and clay soils.

7. It differs appreciably for different soil minerals.

The specific heats of a variety of soils are all approximately the same. The values decrease with a decrease in temperature. The specific heat of soil-water mixtures may be calculated by proportion according to the percentages of weight of soil and water and the respective specific heats.

The thermal conductivity of light-weight concrete slabs varies with the density.

Prediction of Thermal Properties

On the basis of the thermal conductivity tests, four charts are presented to aid in the prediction of conductivity values for any other soil. Separate charts are given for sands or sandy soils and for silt or clay soils; two of the charts are for frozen material and two for unfrozen.

Since the specific heat values were found to be quite similar for all soils tested, it appears to be reasonable to assume the same value for other soils.

The diffusivity of a soil may be computed if its coefficient of thermal conductivity, specific heat and density are known. Thus, the determinations of this research also serve as a basis for estimating diffusivity.

MATERIALS

Soils

Nineteen soils were included in the test program; five were sands or gravel, six were materials of heavier texture varying from sandy loam to clay, seven were minerals or crushed rocks, and one was an organic soil. For convenience in presentation, all the materials have been termed "soils" and have been given soil numbers. All are listed in Table I with their mechanical analyses and physical constants. This table is in approximate order of texture, with the coarser materials such as gravel, crushed rocks, and sands first, followed by soils of progressively finer texture. The peat soil is listed last. The textural class names given for the soils defined by the U. S. Bureau of Chemistry and Soils* are based on percentages of sand, silt, and clay in the soils. In this classification sand is considered as particles 2.0 to 0.05 mm. in size, silt as 0.05 to 0.005 mm., and clay below 0.005 mm. The Corps of Engineers classification symbols, which are given in the last column of the table, are defined in a report included herein as Appendix III. It will be noted in the Appendix that soil fines (silt and clay) are defined as minus No. 200 mesh material. This differs from the upper size limit of silt of 0.05 mm. used in this report.

*Davis, R. E. and H. H. Bennett, "Grouping of Soils on the Basis of Mechanical Analysis", U. S. Dept. Agr., Dept. Circ. 419, 1927.

TABLE I
GENERAL PHYSICAL PROPERTIES OF SOILS

		Mechanical Analysis				Physical Constants						Textural Class	
		Gravel	Sand	Silt	Clay								
Soil No.	Soil Designation	Over 2.00[1]	0.05 to 2.00	0.005 to 0.05	Under 0.005	Liquid[2] Limit	Plasticity[2] Index	Modified Optimum Moisture Content	Modified Maximum Density	Specific Gravity	Absorption (per cent)	U. S. Bur. of Chem. and Soils	Corps of Engin.[3]
P4601	Chena River Gravel	80.0	19.4	- 0.6-		-	N.P.[4]	-	-	2.70	0.75	Gravel	GP
P4703	Crushed Quartz	15.5	79.0	- 5.5-		-	N.P.	-	-	2.65	0.26	Coarse Sand	SW
P4704	Crushed Trap Rock	27.0	63.0	-10.0-		-	N.P.	-	-	2.97	0.20	Coarse Sand	SM
P4705	Crushed Feldspar	25.5	70.3	- 4.2-		-	N.P.	-	-	2.56	0.75	Coarse Sand	SW
P4706	Crushed Granite	16.2	77.0	- 6.8-		-	N.P.	-	-	2.67	0.56	Coarse Sand	SW
P4702	20-30 Ottawa Sand	0.0	100.0	0.0	0.0	-	N.P.	-	-	2.65	0.17	Coarse Sand	SP
P4701	Graded Ottawa Sand	0.0	99.9	- 0.1-		-	N.P.	-	-	2.65	0.19	Medium Sand	SP
P4714	Fine Crushed Quartz	0.0	100.0	0.0	0.0	-	N.P.	-	-	2.65	-	Medium Sand	SP
P4709	Fairbanks Sand	27.5	70.0	- 2.5-		-	N.P.	12.0	122.5	2.72	-	Medium Sand	SW
P4604	Lowell Sand	0.0	100.0	0.0	0.0	-	N.P.	12.2	119.0	2.67	-	Medium Sand	SW
P4503	Northway Sand	3.0	97.0	0.0	0.0	-	N.P.	14.0	112.8	2.74	-	Medium Sand	SW
P4502	Northway Fine Sand	0.0	97.0	3.0	0.0	-	N.P.	11.4	116.0	2.76	-	Fine Sand	SP
P4711	Dakota Sandy Loam	10.9	57.9	21.2	10.0	17.1	4.9	6.5	138.5	2.71	-	Sandy Loam	SM
P4713	Ramsey Sandy Loam	0.4	53.6	27.5	18.5	24.6	9.3	9.0	127.5	2.68	-	Sandy Loam	CL
P4505	Northway Silt Loam	1.0	21.0	64.4	13.6	27.3	N.P.	15.7	112.0	2.70	-	Silt Loam	ML
P4602	Fairbanks Silt Loam	0.0	7.6	80.9	11.5	34.0	N.P.	15.5	110.0	2.70	-	Silt Loam	ML
P4710	Fairbanks Silty Clay Loam	0.0	9.2	63.8	27.0	39.2	12.4	18.0	102.0	2.71	-	Silty Clay Loam	ML
P4708	Healy Clay	0.0	1.9	20.1	78.0	39.4	15.0	17.0	108.0	2.59	-	Clay	CL
P4707	Fairbanks Peat	-	-	-	-	-	N.P.	-	-	-	-	Peat	Pt

1. Size in millimeters
2. Minus No. 40 mesh Fraction
3. See Appendix III
4. N.P. = non-plastic

U. S. Bureau of Chemistry and Soils textural class names have been used in most cases to identify the soils under discussion. The Corps of Engineers soil symbols have also been included on figures. The moisture-density curves from which the modified optimum moisture contents and maximum densities have been taken are plotted in Figures 34 to 43 in Appendix II. Mineralogical compositions of the soils are listed in Table II. The following paragraphs give a brief description of the soils.

Soil P4601, Chena River Gravel, is a material composed largely of quartz and basic igneous rock and is from the Chena River at Fairbanks, Alaska. It was used in base course construction in the Fairbanks Research Area. The gravel sample obtained from the field has many stones up to about 2 inches in size. Because of the size of the thermal conductivity test apparatus, all stones larger than 3/4 inch were eliminated and replaced with a like weight of 1/4 to 3/4 inch stone. The grading given in Table 1 is that of the altered material. The original sample had 56 per cent gravel and 22 per cent coarse sand, but otherwise was similar to the grading given.

The next seven materials in Tables I and II were included in the test program as a part of the study of the effect of mineral composition. They are not natural soils.

Soil P4703 is a quartz obtained from the Consolidated Feldspar Corporation at Keystone, South Dakota. The material as received was in angular pieces up to a pound size, plus or minus. It was passed through a jaw crusher (and some of it through a ball mill) in order to reduce it to the grading at which tests were made.

Soil P4704 is crushed trap rock or basalt screenings from the Trap Rock Company at Dresser Junction, Wisconsin. This sharp, angular material was tested as received with no further crushing.

Soil P4705 is crushed potash feldspar obtained from the Consolidated Feldspar Company at Keystone, South Dakota, the same source as for the crushed quartz. The test samples were prepared by screening the material through a No. 4 screen and rejecting the part retained.

Soil P4706 is crushed gray granite. The sample was obtained from the Howard Monument Company in St. Paul, Minnesota, from material which originally came from the quarries at St. Cloud, Minnesota. The test sample was prepared by passing it through a jaw crusher. A portion of it was further pulverized by putting it in a ball mill.

Soil P4702 is Standard 20 to 30 Mesh Ottawa Sand from the Ottawa Sand Company at Ottawa, Illinois. It is a pure, washed silica sand, and it meets the requirements of the A.S.T.M. Specification, C77-39.

Soil P4701 is Standard Graded Ottawa Sand from the same source as P4702. It conforms to the A.S.T.M. Specification, C109-37T.

Soil P4714 is crushed quartz from the same source as P4703 but prepared to a grading approximately the same as that of P4701.

Soil P4709, Fairbanks Sand, is a siliceous sand which was used as a fill material in the test runway sections at Fairbanks, Alaska. The moisture-density curve for this soil is shown in Figure 34, Appendix II. Similar curves for all the soils described below, except for the peat, are also given (Figures 35 to 43). These compaction tests were run by the so-called modified method employed by the Corps of Engineers, as described in Part XII, Chapter 2, of the Engineering Manual, 1947.

Soil P4604, Lowell Sand, is a material furnished by the Corps of Engineers, New England Division. It is a cohesionless, siliceous sand from a glacial outwash deposit at South Lowell, Massachusetts. Thermal conductivity tests were also made by the Frost

TABLE II - MINERAL AND ROCK COMPOSITION OF SOILS
(percentage by weight)

Soil No.	Soil Designation	Corps of Engineers Class	QUARTZ By Petrogr. Exam.	QUARTZ By X-Ray Analysis	Ortho-clase Feldspar	Felsite	Plagio-clase Feldspar	Pyroxene, Amphibole, and Olivine	Basic Igneous Rock	Kaolinite Clay Min. and Clay Coat.Mins.	Hematite and Magnetite	Mica	Coal	Others
P4601	Chena River Gravel	GP	43.1		11.6		12.9	27.0				2.1		3.3
P4703	Crushed Quartz	SW	95+[1]											
P4704	Crushed Trap Rock	SM	3.0		10.0		50.0[2]	34.0			2.0			1.0
P4705	Crushed Feldspar	SW	15.0		55.0		30.0							
P4706	Crushed Granite	SW	20.0		30.0		40.0							10.0
P4702	20-30 Ottawa Sand	SP	99+[3]											
P4701	Graded Ottawa Sand	SP	99+[3]											
P4714	Fine Crushed Quartz	SP	95+[1]											
P4709	Fairbanks Sand	SW	59.4		3.6	5.0	6.3	8.0	10.0		2.5	0.1		5.1
P4604	Lowell Sand	SW	72.2		20.5			3.0				1.3		3.0
P4503	Northway Sand	SW	7.5			11.5	9.0	7.5	51.0					13.5
P4502	Northway Fine Sand	SP	12.0			7.0	18.0	12.0	40.0					11.0
P4711	Dakota Sandy Loam	SM	59.1		12.9		1.0	12.1		12.4				2.5
P4713	Ramsey Sandy Loam	CL	51.3		11.8		5.6	12.6		15.9				2.8
P4505	Northway Silt Loam	ML	1.5				31.5	19.5	4.5	27.5	10.0			5.5
P4602	Fairbanks Silt Loam	ML	13.3	40.3						28.3		18.1		
P4710	Fairbanks Silty Clay Loam	ML	4.6	59.5				2.2		28.9	1.6	3.2		
P4708	Healy Clay	CL	22.5							55.0			22.0	0.5

1. By visual inspection; impurities less than 5 per cent
2. Andesine feldspar
3. By visual inspection; impurities less than 1 per cent

Effects Laboratory at Boston, so that the tests on this material afford a means of checking the results at Minnesota.

Soils, P4503, Northway Sand, and P4502, Northway Fine Sand, are from Northway Airfield, Alaska. The sands are similar in appearance except for their difference in grading. They are black and are composed largely of basalt or fine-grained gabbro.

Soil P4711, Dakota Sandy Loam, is a local soil from Dakota County, Minnesota. It was included in the test program since no soil of similar texture was obtained from Alaska.

Soil P4613, Ramsey Sandy Loam, is a local soil from Ramsey County, Minnesota. It was included in the program for the same reason as P4711. It is the heavier of the two sandy loams, with both the plasticity index and the clay content about twice those of P4711.

Soil P4505, Northway Silt Loam, is from Northway Airfield and is a non-plastic, silty soil with a brownish-gray color.

Soil P4602, Fairbanks Silt Loam, is from the research area at Fairbanks, Alaska. It is similar in appearance to the other silt loam, P4505, and it has a gray color. It has a somewhat higher silt content than the Northway Silt Loam.

Soil P4710, Fairbanks Silty Clay Loam, is an Alaska soil from the housing area at Fairbanks. It is similar to P4602 in appearance, but it has a greater clay content.

Soil P4708, Healy Clay, was obtained from the Healy coal mine at Healy, Alaska.

Soil P4707, Fairbanks Peat, is a fibrous, brown peat from the vicinity of Fairbanks, Alaska.

Thermal conductivity tests were run on all materials in Table I. Specific heat tests were made on 12 of them.

Insulating Materials

The insulating materials on which tests were made were light-weight concrete slabs cast in Alaska and shipped to the laboratory at the University of Minnesota. Unfortunately, a number of slabs were badly broken when received, so tests were not possible on all of the different types.

The concrete slabs were of two different types, "Zonolite" concrete and "Cell" concrete. The aggregate used in the Zonolite slabs is vermiculite, an expanded mica. Slabs were made with mixes by volume of one part of Portland cement to 4, 6, 8, 10, and 12 parts respectively of vermiculite. All of the slabs containing 12 parts of vermiculite were broken in transit, however.

The Cell concrete is composed of Portland cement, sand, water, and a foam compound which serves to introduce and entrain air. The slabs were designed for dry densities of 0.4, 0.6, 0.8, 1.0, and 1.2 grams per cubic centimeter. For test purposes, only two of the 0.8 and one each of the 1.0 and 1.2 mixes were available. The slabs actually had higher densities than the design values, but, for purposes of identification, the 0.8, 1.0 and 1.2 values will be used.

The slabs were approximately 24 inches square and 3 inches thick. The surfaces were rather rough, so they were made smooth by rubbing with a brick before tests were made. Absorption tests were made on pieces of the slabs by immersing them in water for a period of about two weeks. Table III lists the slabs with their measured densities and percentages of absorption.

TABLE III - PHYSICAL PROPERTIES OF INSULATING CONCRETE MATERIALS

Type of Concrete Slab	Design Mix. Proportion by Vol. Cement:Aggregate	Design Dry Density Grams per Cubic Centimeter	Actual Dry Density Pounds per Cubic Ft.	Absorption Per cent of Dry Weight	Per cent of Saturation[1]
Zonolite	1 : 4	--	33.6	79.0	53.
Zonolite	1 : 6	--	29.6	86.4	50.
Zonolite	1 : 8	--	28.6	137.4	76.
Zonolite	1 :10	--	20.4	198.1	74.
Cell	--	0.8	71.5	17.6	35.
Cell	--	1.0	80.5	15.4	38.
Cell	--	1.2	86.0	13.2	37.

1. Approximate. Based on specific gravity of 2.70

To gain some ideas as to the relative durability of the various types of light-weight concrete insulating materials, a series of freezing and thawing tests were run on four-inch cubes of the various mixes. After preliminary soaking, the cycle consisted of approximately 12 hours in a freezing chamber at about 10 degrees F, followed by a 12-hour immersion in water at room temperature. Upon removal from the water, the specimens were drained for 15 minutes, blown off with air from a hose under a pressure of 20 pounds per square inch, and then weighed. After each 20 cycles the specimens were dried in an oven. Tests were made on three cubes of a given type and were continued until approximately two-thirds of the original weight had been lost. If a specimen split, the smaller pieces were discarded. The results of these tests are presented in Table IV. The specimens of Zonolite and Cell concrete used in these tests were made independently from the thermal conductivity slabs previously mentioned. Hence the densities are different from those listed in Table III.

Tests were also run on cubes made of a Portland cement concrete for comparative purposes. These cubes had no visible deterioıation in 160 cycles. Results of tests on Foamglas are also included in Table IV, although no conductivity tests were made on this material.

Bituminous Paving Mixture.

Slabs were molded from an asphalt-gravel paving mixture which was received from Fairbanks Field Research Area, Area No. 2. The aggregate consisted of a gravel similar to Chena River gravel. The bituminous material appeared to be a cut-back asphalt and as shown by an extraction test, was 5.98 per cent by weight of the total mixture. Test specimens for thermal conductivity tests were prepared by heating the mixture and compressing it under static load in a 12 by 12 by 1-1/2 inch form. The resultant average density was 138 pounds per cubic foot.

UNITS OF MEASUREMENT

The unit of thermal conduction used in the presentation of the test results in this report can perhaps be most easily understood if the equation of elementary heat flow is introduced. The flow of heat can be pictured as being similar to the flow of water through porous media and is given by Darcy's law.

TABLE IV - FREEZING AND THAWING TESTS OF MATERIALS

Type of Material	Mix Proportion by Volume	Approximate Density Lb./cu. ft.	Absorption Start of test - %	No. of Cycles Run	Loss in Weight %	Absorption End of Test - %	No. of Cycles at 50% Loss in Weight	No. of Cycles at 67% Loss in Weight
Zonolite Concrete	1 : 4	44.9	59.5	160	3	74.5	-	-
	1 : 6	36.4	84.5	140	67	118.5	100	140
	1 : 8	27.9	110.0	80	88	146.7	61	69
	1 :10	24.4	126.0	59	72	155.0	48	56
	1 :12	20.2	146.0	19	76	181.0	11	15
ell Concrete, Danish Foam		20.6	79.0	25	69	96.2	19	25
Cell Concrete, Vicksburg Foam		27.1	96.0	31	81	76.0	24	28
Foamglas		9.5	14.3	51	67	65.0	37	51
Concrete		149.5	3.9	160	0	4.3	-	-

All values are average for six specimens of Zonolite 1 : 10 and 1 : 12 mixes and for three specimens of all other materials.

The basic equation is

$$q = kiAt$$

in which:

q = quantity of heat, British thermal units

i = thermal gradient, degrees Fahrenheit per inch

A = cross-sectional area, square feet

t = time, hours

The units given are not consistent with one another but are the ones commonly used in heat transfer problems.

Thus, for k, the coefficient of thermal conductivity, the following equation may be written:

$$k = \frac{q}{iAt} = \frac{\text{Btu}}{{}^{\circ}\text{F per inch x ft}^2 \text{ x Hr}}$$

Stated in words, the coefficient k represents the amount of heat expressed in British thermal units transmitted per hour through one square foot of soil one inch thick per degree Fahrenheit difference between the two surfaces. Values of conductivity thus expressed may be converted into British thermal units per hour per square foot <u>one foot thick</u> per degree Fahrenheit difference by multiplying by 0.08333, or into C.G.S. units, calories per second per square centimeter per centimeter thickness per degree Centigrade difference between the two surfaces, by multiplying by 0.0003446.

All temperatures are expressed in degrees Fahrenheit unless otherwise noted.

Specific heat, S, is the quantity of heat required to raise a unit weight of material one degree, or

$$S = \frac{\text{Btu}}{{}^{\circ}\text{F x Lb.}} = \frac{\text{Calories}}{{}^{\circ}\text{F x grams}}$$

The numerical value is the same in either system of units.

Heat of wetting, a value used in the specific heat tests, is the number of calories of heat evolved when a gram of soil at a given temperature is wetted in water at the same temperature.

Density, γ, is the weight of a material per unit volume. In this report, it is the weight of dry soil in pounds per cubic foot.

$$\gamma = \frac{\text{Lb}}{\text{Ft}^3}$$

Diffusivity, h^2, is the index of the facility with which a material will undergo temperature change. For dry soils, it may be calculated by the equation

$$h^2 = \frac{k}{S\gamma} = \frac{\text{Btu}}{{}^{\circ}\text{F x Ft x Hr}} \times \frac{{}^{\circ}\text{F x Lb}}{\text{Btu}} \times \frac{\text{Ft}^3}{\text{Lb}} = \frac{\text{Ft}}{\text{Hr}}$$

With the units of k as used in this report (i.e., per inch of thickness) the equation becomes

$$h^2 = \frac{0.08333k}{S \times \gamma}$$

Further considerations are necessary for moist soils.

Moisture content is expressed as a percentage of the dry weight of the soil and is designated by the symbol "w".

TEST EQUIPMENT AND METHODS

Thermal Conductivity of Soil.

Equipment - The design of the apparatus used to measure the thermal conductivity of soils was patterned in part on apparatus which was in use at the Engineering Experiment Station, University of Minnesota, for testing building materials and insulation. The testing of soils, however, posed many problems not encountered in the testing of building materials such as the need for placing soils at a variety of moisture content and density conditions; consequently, it was necessary to design and construct an entirely new apparatus.

The apparatus may be divided into the following parts for purposes of description:

1. A tubular soil container consisting of a central pipe containing heaters, and an outside cold jacket enclosed by an insulated box to keep heat losses at a minimum;
2. A motor-generator unit with an exciter and voltage regulator for supplying steady D. C. power to the heaters;
3. A condensing unit, cooling and mixing tanks, and a circulation system for supplying alcohol to the cold side of the soil container, with provision for controlling the alcohol temperature to obtain the desired soil temperature on the cold face;
4. A system of power and temperature measurement and control.

A general view of the test apparatus is shown in Plate 1. In the photograph, the cooling and mixing tanks are at the left front. These tanks were originally constructed to operate four soil containers, but only two containers have been built. The alcohol cooling tank is in the center, with two mixing tanks on each side. The condensing unit for the main tank is at the right front. The soil containers are at the left behind the tanks; one, with the insulated cover down, is behind the column. The control table is to the rear beyond the soil containers. At the right and beyond the condensing unit of the alcohol cooling tank is a smaller condensing unit for cold plates adjacent to the soil containers. Beyond this is the motor-generator unit and, against the wall, are two photo-electric relay units.

A close-up view of a soil container is shown in Plate II. Figure 1 shows the general assembly of this unit which is made up chiefly of concentric sections of three sizes of copper pipe with an over-all length of 20 inches. The smaller pipe, 2-3/4 inches in outside diameter, is divided into three sections, the upper and lower sections each being approximately 4 inches in length and the central one 12 inches in length. The three sections are separated from one another by Micarta and rubber discs which prevent, or hold to a negligible amount, the flow of heat from one section to another. Within these sections of pipe are located three cartridge-type electrical heaters, one within each of the sections.

The upper and lower 4-inch sections are termed guard sections. Their purpose is to regulate conditions at the two ends of the soil container so that there is no tendency for the heat from the central or main heating section to flow upward or downward, thus insuring only a true radial flow of heat through the soil being tested.

Two thermocouple connections are set in the outside wall of the central section of the central column. These thermocouples measure the temperature on the hot side of the soil sample.

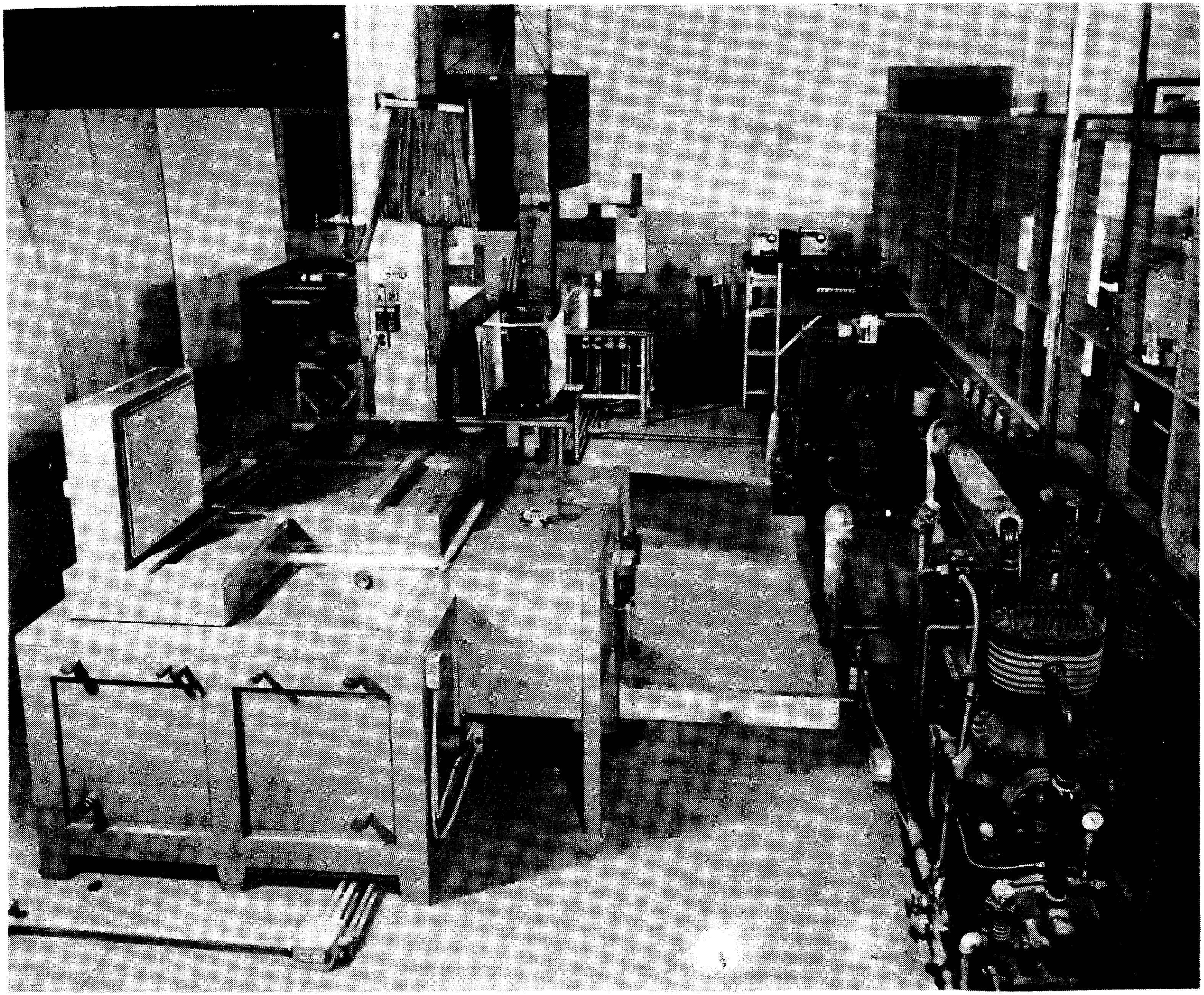


PLATE I. General View of Soil Thermal Conductivity Apparatus.

Balancing couples connect the central section and the upper and lower guard sections. These couples are used to check the temperature in the guard sections against that in the central section and thus aid in preventing any axial flow of heat from the main section.

The annular space between the heaters and the inside wall of the pipe is filled with a special refractory material which permits a ready flow of heat. The power and thermocouple leads also pass through this space.

The cooling jacket consists of two concentric copper cylinders, approximately 1/4-inch in wall thickness and 6-5/8 inches and 8-5/8 inches in outside diameter, respectively. The inside face of the smaller cylinder serves as the cold side of the soil container and is in direct contact with the soil. The two cylinders are assembled with rings at each end, the space between the cylinders serving as a chamber through which the alcohol is circulated.

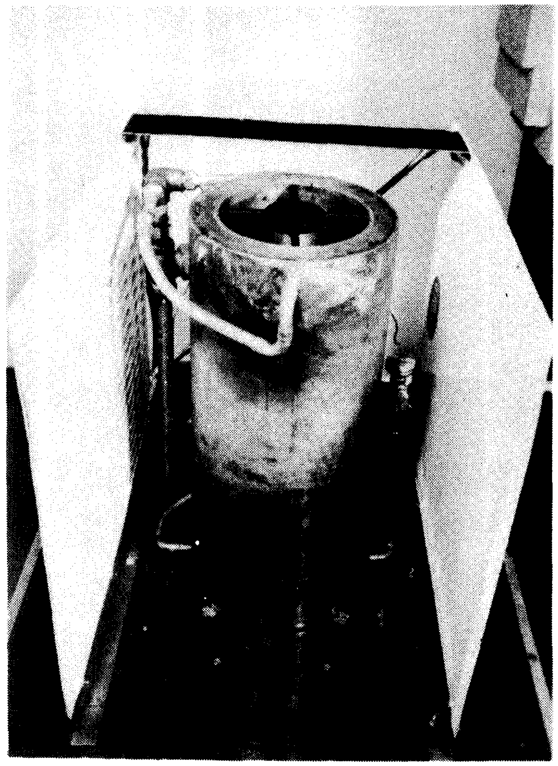


PLATE II. Tubular Soil Container and Refrigeration Plates

The soil to be tested is placed in the annular space between the 2-3/8 inch and 6-5/8 inch pipes. The central column itself is supported by an additional section of pipe placed below the bottom guard section, but separated from it by a Micarta spacer. The pipe extends to the floor. At the bottom of the soil container, the plug which seals that end has a Micarta face in contact with the soil. At the top of the container, the central column is held in a central position during filling by a metal "spider" which has three arms extending across to the cold jacket. This is replaced after filling by a Micarta cap without arms.

Two thermocouple connections are made on the inside face of the 6-5/8 inch pipe which corresponds to the outside or cold face of the soil. These thermocouples are located directly opposite the two thermocouples on the center column.

A cover made of bakelite and granulated cork fits over the top of the tubular container. The table on which the container is located and the plug at the bottom of the container have a one-inch layer of cork for insulation. The containers are located on a table approximately 2 feet high. From the bottom up, the table top is constructed of 1/4-inch steel plate to provide rigidity for the compaction of soil, one inch of cork to provide insulation during low temperature runs, and a 1/4-inch Masonite surface. The plug mentioned above, which is used for the bottom of the container, fits into a hole in this table.

To prevent excessive warming of the cooling liquid during runs at low temperatures, each soil container is enclosed by an insulated cover. These covers, in the form of large bottomless boxes, are constructed of plywood and 2 inches of cork insulation. They are lowered over the soil container from above, are mounted on pulleys, and are counterbalanced to provide ease in handling.

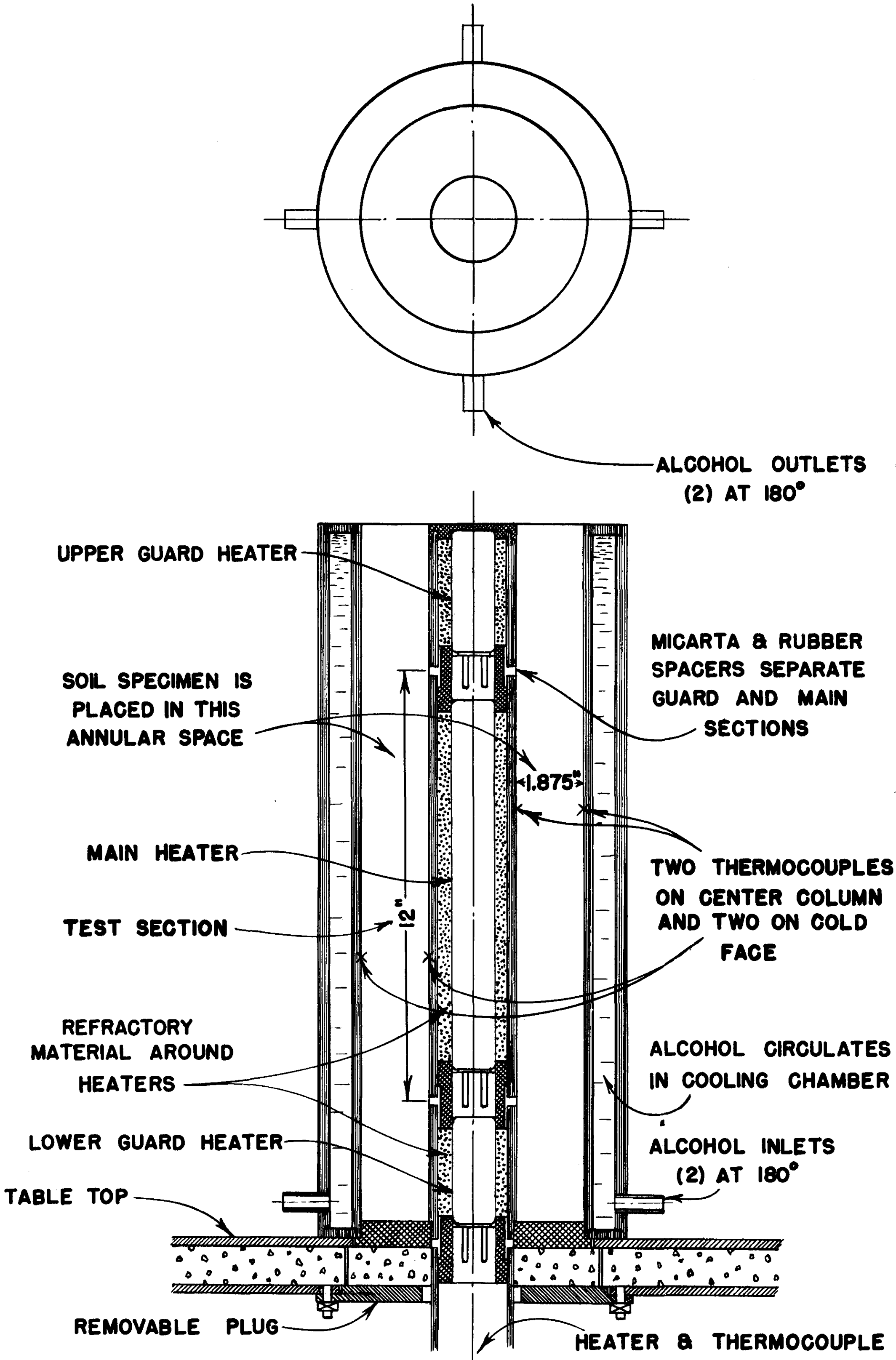


FIG. I

SOIL CONTAINER
FOR THERMAL CONDUCTIVITY TESTS

To maintain a low temperature within the insulated covers, two refrigeration plates are mounted on the table for each soil container. These plates are connected to a 1-1/2 horsepower condensing unit. The refrigeration system is complete with expansion valve, thermostat, liquid indicator, strainer, etc. One condensing unit serves both soil containers. Separate thermostats in each box and solenoid valves in the liquid lines provide separate control.

The cooling and mixing tank unit consists of separate mixing tanks for each soil container and a common central cooling tank. The tanks are of galvanized sheet steel and are insulated with 4 inches of granulated cork.

The cooling tank, which holds about 100 gallons of liquid, is equipped with a cooling coil. A circulator mounted at one end of the tank continually circulates the liquid to provide more efficient cooling and more even temperature control. The cooling coil is connected to a condensing unit which is controlled by thermostats whose bulbs are mounted in the tank.

Each mixing tank has a capacity of about 30 gallons. From each of these tanks, a 1-1/4 inch circulator feeds liquid to the cold side of a soil container. The mixing action is brought about by by-passing a part of the discharge of the circulator directly back to the mixing tank and also by the return liquid from the cold side of the soil container.

There are two inlets to the mixing tank from the circulation system of the cooling tank; one is controlled by a hand valve, the other by a solenoid valve. These valves provide a means for cooling the liquid in the mixing tank. An overflow connection is provided between the mixing and cooling tanks for the purpose of maintaining desired levels of liquid. An immersion heater is mounted in the mixing tank to provide necessary warming of the liquid for temperature control.

Separate circulation systems are provided between each mixing tank and soil container. The liquid is drawn from the bottom of the tank through the 1-1/4 inch circulator. Part is immediately returned to the top of the tank to provide mixing action, the amount returned being controlled by a hand valve. The balance of the liquid is conveyed in a single pipe to the table on which the soil container is mounted. A resistance thermometer is mounted in this line to detect temperature changes. At the table the line is divided and entrance is made into the bottom of the cold jacket, 180 degrees apart. The exit is through two points at the top of the jacket, 180 degrees apart. The inlet and outlet connections are 90 degrees apart. This arrangement is meant to provide circulation throughout the entire volume of the cold chamber. The connections to the container are fitted with hand valves, and the pipes are insulated to keep undesirable heat transfer at a minimum.

The power for the heaters in the central section of the soil container is furnished by a motor-generator set with a possible output of 110 volts, D.C. Because of the accuracy required in the maintenance of specified temperatures and the rate of heat supplied to the soil, the voltage is controlled by a voltage regulator.

Plate III is a view of the control table from which the entire apparatus is operated.

Temperature measurements are made at two points on the hot side and at two points on the cold side of the soil sample. On the hot side, thermocouples are mounted on the outside of the central heating section. The leads are carried through the wall and down through the refractory material into a conduit at the base. On the cold face, the thermocouples are mounted on the inside pipe of the cooling chamber at the face confining the soil; these are embedded in porcelain in a groove in the pipe wall and led out under the cooling chamber into a conduit.

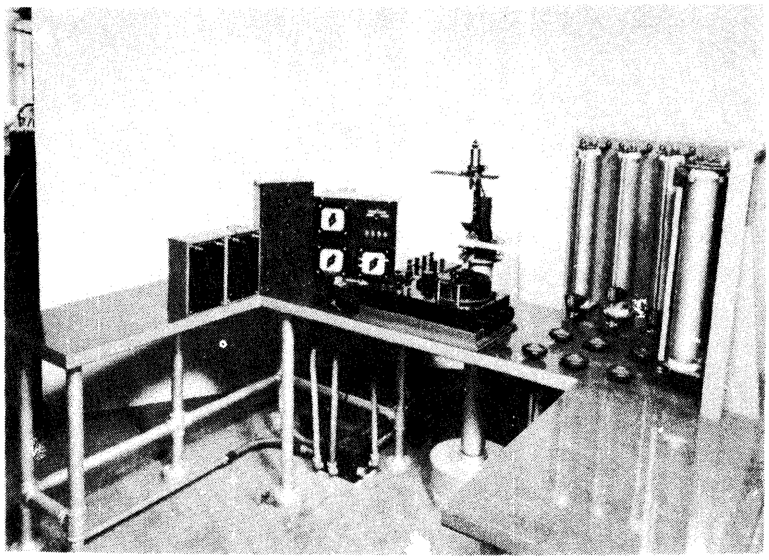


PLATE III. Control Table

The copper and constantan leads are led through conduits to the control panel. Their circuit includes a cold junction (ice bath), a switch panel for the selection of the thermocouple to be read, a Leeds-Northrup type K-2 potentiometer, and a reflecting light-beam galvanometer.

The temperature control is accomplished in the following manner. For the cold side, a resistance thermometer is located in the pipe carrying the alcohol to the cold chamber of the soil container. The resistance thermometer forms one leg of a Wheatstone bridge circuit which affects a galvanometer in a photo-electric thermostat box. Any change in temperature from that selected initiates a relay which either energizes the heater in the mixing tank or causes a solenoid valve to open permitting colder liquid to enter the mixing tank from the cooling tank. The temperature is selected by adjustment of a variable resistance in another leg of the same Wheatstone bridge.

The temperature control on the hot side of the soil sample is achieved by the control of voltage applied to the heaters.

With this apparatus, the power is measured for the main heater only and not for the guards. The voltage and amperage are determined by means of the potentiometer. The power in each of the main and guard sections is regulated separately by rheostats in series with the heater in each circuit. The amount of heat furnished by the central heater is regualted so as to obtain the desired temperature on the hot side of the soil. A balanced temperature between each guard section and the central section is accomplished by control of the guard heaters. This balance is indicated by thermocouples located at the end of the main heating section and the adjacent edge of the guard section.

Test Procedures. - The method of making the thermal conductivity tests on soils was changed somewhat as experience was gained. The procedures as finally developed will be explained in the following pages.

The moisture contents and densities at which conductivity tests were to be made were selected by a study of the moisture - density compaction curves. On most soils, tests were made at a range of densities from loose-poured to the maximum and at moisture contents from air-dry to more than the optimum.

The test conditions were so selected that there would be several points with the same density but with different moisture contents and also some with the same moisture content but with different densities.

After the desired density and moisture content for a test had been selected, a quantity of dry soil was weighed out and the necessary amount of water, including some provision for evaporation, mixed in. The plug was set in place at the bottom of the container and coated with hot paraffin to prevent the loss of any water. The soil was then compacted in layers, ramming being done with special hammers which fit the curvature of the pipe forming the container. The density was checked by noting the level of the soil approximately every four inches, and the intensity of the blows altered, if necessary, to obtain the required compaction. To aid in getting the required density in the top four inches, an extension of the container was used. The soil was leveled off flush with the top of the container; and the exact weight of wet soil used was recorded. Several samples for moisture content determination were taken during the placing of the soil. The dry density of the soil in place could thus be calculated.

To prevent loss of moisture by evaporation at the top, a rubber diaphragm was placed over the top of the soil and sealed at its edges with adhesive tape.

Some of the equipment used in placing and removing the soil is shown in Plate IV. Items included from left to right, are the extension for the top of the container used in placing the top layer, the metal spider used to hold the central column in place during compaction, compaction hammers, the tube used for taking moisture samples, and the pan into which the soil was dropped from the apparatus.

Upon completion of the thermal conductivity tests, the procedure for which will be described subsequently, the soil was removed from the container, and moisture content determinations were made. Before removal, the level of the top of the soil was noted, inasmuch as some dry soils with low densities settled somewhat. In each case, a final density was calculated.

Dry soils were removed by dropping them into a special soil pan placed below the table holding the soil container. The pan was slotted to permit it to fit around the central column support pipe, and the plug was removed at the bottom. Moisture content samples were taken from the soil in the pan.

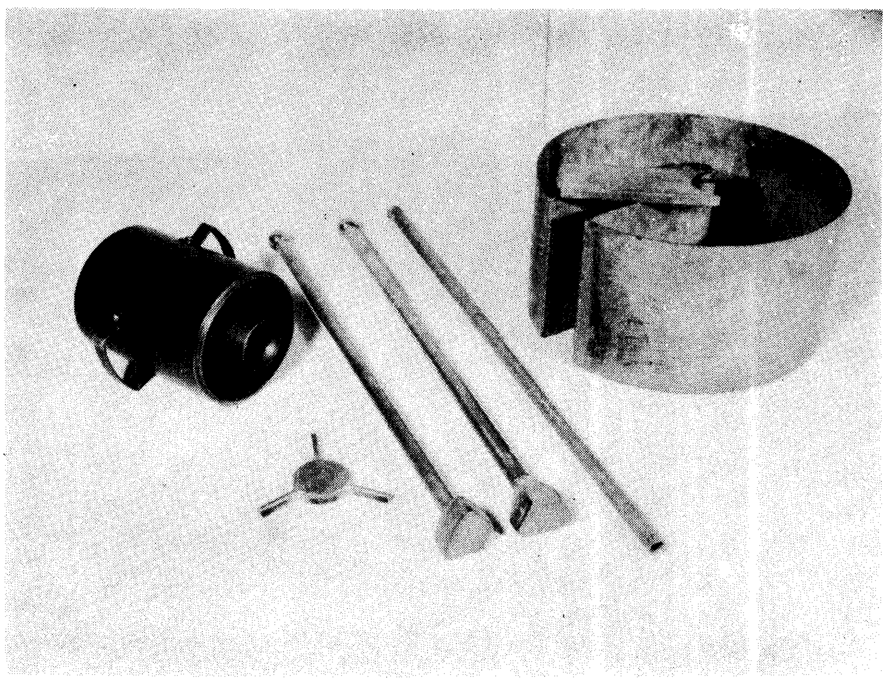


PLATE IV. Tools Used in Placing and Removing Soil

For runs with more moisture, the procedure of removal included the taking of a series of moisture content samples from the soil in place in the apparatus, since it was desirable to know the distribution pattern of the moisture at the completion of the test. Samples were taken at three different levels, the top, center, and bottom two inches of the test section (4 to 6, 9 to 11, and 14 to 16 inches from the top of the container) and at four points transversely from the cold jacket to the hot column on each level.

The thermal conductivity tests were run at several mean temperatures, in most cases at four: 70, 40, 25 and -20 degrees Fahrenheit. Some soils were tested at these four temperatures, and, in addition, at 0 degrees and a re-run at 70 degrees. At the start of the test program, the lowest temperature that could be reached was around 0 to 10 degrees. A temperature differential of 10 degrees was used; thus, the 70-degree mean temperature run had a cold face temperature of 65 and a hot face temperature of 75, the 40-degree run had 35 and 45, etc.

Runs were started by adjusting the cold face temperature to approximately 65 degrees and by regulating the rheostats until the hot face temperature was approximately 75 degrees. Adjustments were made until the temperatures were within about a quarter of a degree of the desired temperatures. Readings of the four thermocouples were taken every 15 minutes, and the balancing couples were also checked at these intervals. Voltage and amperage readings were made every hour. When the readings leveled out and showed only small changes, thermal conductivity coefficients were calculated for each hour's run. When these values showed less than one per cent variation for a five-hour period, the test was considered satisfactory.

Upon completion of a test at one temperature, the temperatures were lowered, and balancing was started for a run at another mean value.

Formulas and Calculations. - The flow of heat through the soil in the soil container is similar to that through a pipe covering or any other hollow cylindrical specimen. The equation for the flow of heat for such a condition may be written as follows:[1]

$$q = \frac{\dfrac{k(A_2 - A_1)}{2.3 \log_{10}(A_2/A_1)}(T_1 - T_2)}{t}$$

in which:

- q = rate of flow of heat in Btu per hour;
- k = coefficient of thermal conductivity in Btu per square foot per inch per hour per degree F;
- A_2 = area of outside face of soil test cylinder in square feet;
- A_1 = area of inside face of soil test cylinder in square feet;
- T_1 = temperature at inside face in degrees F;
- T_2 = temperature at outside face in degrees F;
- t = distance between inside and outside faces of cylinder, in inches.

1. For example, see William H. McAdams, Heat Transmission (Second Edition) pp. 11-12.

For the apparatus used, the dimensions are:

Diameter of central heating column, 2.375 inches;

Diameter of cooling chamber (face confining the soil) 6.125 inches;

Length of main heating section, 12.0 inches. (Assumed as length of main heating copper pipe, 11.75 inches, plus one-half of spacers at each end between main and guard sections, 0.25 inch).

Thus, $A_1 = \dfrac{2.375 \times \pi \times 12}{144} = 0.6218$ square foot

and $A_2 = \dfrac{6.125 \times \pi \times 12}{144} = 1.6035$ square feet

Also, $t = \dfrac{6.125 - 2.375}{2} = 1.875$ inches

In the test runs, q was determined from readings of the voltage and amperage on the main heater. The product of these, the watt input to the main heater, is multiplied by 3.415 to obtain Btu's per hour, or

$$q = E \times I \times 3.415$$

in which

E = volts

I = amperes.

Substituting all of these values in the original equation, reducing, and solving for k, the following formula is obtained:

$$k = \frac{6.172\ EI}{(T_1 - T_2)}$$

This is the formula which has been used for the thermal conductivity coefficients given in this report.

The manner of obtaining the value of $(T_1 - T_2)$, the temperature difference, merits some explanation. A calibration curve was available for thermocouple wire similar to that used in the apparatus; this calibration curve has been used for determining temperatures from the potentiometer readings. The actual temperatures obtained in this manner are estimated to be accurate within 0.1 degree, and the differences used in the solution for k within 0.01 degree.

Since the magnitude of the value, $T_1 - T_2$, is only about 10 degrees, an accuracy of 0.01 degree or more is desirable, since an error of this amount would cause a percentage error of 0.1 in the k value. A table was therefore made up from the calibration curve, listing the temperatures for millivolt readings in 0.001 millivolt steps for the entire range covered by the tests. The temperatures were calculated to thousandths of a degree. It is realized that the individual temperature values given in this table were not exact to this degree, but the temperature differences, i.e., $T_1 - T_2$, obtained by the use of the table, should be sufficiently accurate.

As previously mentioned, calculations of k were made for each hour's run in order that the degree of change could be noted. Since there are two thermocouples on the hot face and two on the cold face and readings were taken at 15-minute intervals, there were 10 readings to average for the hot temperature and 10 for the cold, if the readings at both the beginning and end of the hour were included. This was the method used, and the temperature corresponding to the average of the 10 millivolt readings was taken from the table by interpolation, being recorded to the thousandths place. The same was done for the other temperature; voltage and amperage values were noted for that hour; and the k value was calculated by the aforegiven formula.

After a period of usually four or five hours with a range of differences of hourly k values of less than one per cent, an over-all average of high and low temperatures and the conductivity coefficient were determined. The mean temperature was taken as the arithmetic mean of the high and the low.

Specific Heat of Soil.

Equipment - It was desired to make the specific heat tests by as simple a method as possible and to use readily available equipment rather than to construct complicated apparatus. Consequently, it was decided to make the tests with a calorimeter. The essential apparatus consisted of the following:

A copper calorimeter equipped with an electrically-driven stirrer;

Thermometers, one calibrated to 0.02 degrees C;

Small metal dippers, about 1-3/4 inches in diameter by 6-inches in depth, with tight rubber stoppers;

A steam bath;

Two temperature-controlled water and alcohol baths, one at approximately 130 degrees F. and one at approximately -40 degrees F.;

Miscellaneous scales, ovens, etc.

Plate V illustrates some of the apparatus. The calorimeter had a capacity of about 2,500 mls. The jacket consisted essentially of a compartment filled with water and was insulated on the outside; the cover was made of 3/4-inch plywood.

The 130-degree F. bath used was the mixing tank of the hot plate conductivity apparatus at the Engineering Experiment Station. This bath had a photo-electric relay temperature control and maintained a constant temperature within a fraction of a degree. The -40 degree F. bath was the main cooling tank of the cooling apparatus for the soil thermal conductivity apparatus. Although the temperature of this bath varied from day to day according to the demands made upon it by the thermal conductivity apparatus, it had a sufficient volume (about 100 gallons) to maintain a fairly constant temperature during the specific heat test runs. There was some apparent temperature stratification within the tank, the top 1/2 inch of alcohol being a few degrees warmer than the deeper strata. A metal table with holes through its top, to hold the dippers containing the soil, was placed within the temperature baths.

Test Procedures. - The test procedures varied somewhat for different phases of the tests. Consequently, the methods have been designated by letters A to F, and the particular method used has been given for each test. The letters were assigned more or less chronologically and have no significance as to preference.

Essentially, all methods are based on the same scheme which, basically, is as follows

A known weight of water was placed in the calorimeter, and its temperature was measured. A known weight of soil in a dipper was heated (or cooled) to a temperature different from that of the water in the calorimeter and was then suddenly taken from its bath and poured into the water in the calorimeter. The temperature change of the water was noted, and, by calculations, the specific heat of the soil determined.

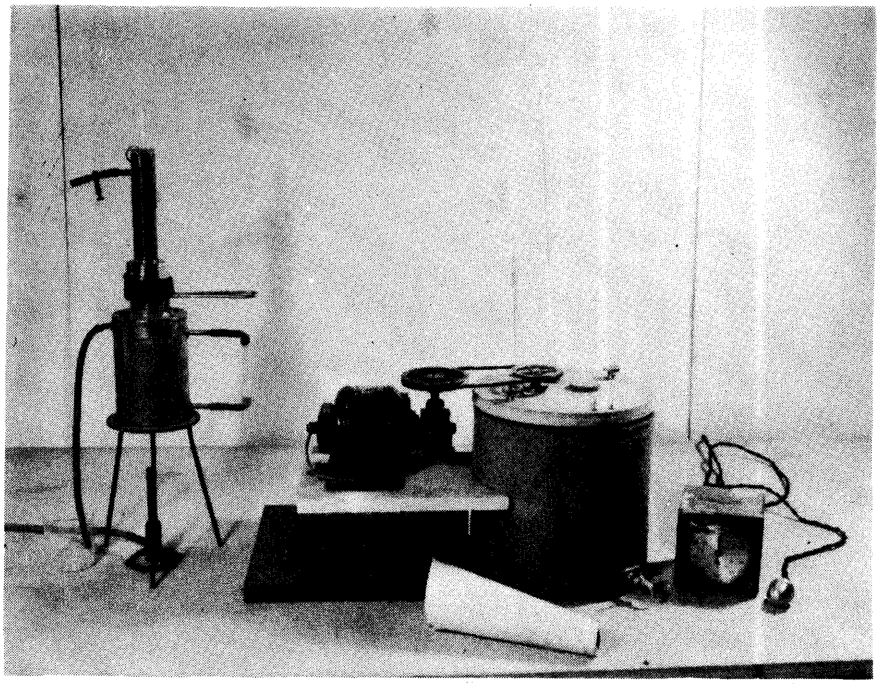


PLATE V. Steam Bath and Calorimeter
for Specific Heat Tests

In all methods, the soil to be tested was first over-dried and cooled to room temperature in a dessicator.

The various test methods varied chiefly in the means of getting the soil sample to its initial temperature. The main parts of each method are given below.

Method A: In this method, a quantity of soil sufficient to fill the dipper was taken, the dipper tightly stoppered, and a thermometer was inserted through a hole in the stopper so that its bulb was centered in the soil. The weight of the soil thus tested varied from about 200 grams for the silt loams to 300 grams for the sands. The dipper was then inserted into a steam bath and heated for a period of about two hours. The temperature shown by the thermometer checked the boiling point of water calculated from the corrected barometric pressure.

In the meantime, about 1,000 to 1,100 grams of water were placed in the calorimeter. An attempt was made to have this water at a temperature somewhat below room temperature, the plan being that the addition of the soil would raise the temperature approximately to that of the room. The water in the calorimeter jacket was kept there continually; consequently, it was always close to room temperature.

When the soil in the dipper had been constant at the boiling point for several minutes, the calorimeter cover was placed, and the electrical stirrer started. The calorimetric thermometer was inserted into the water. This instrument had a range from 14.5 to 24.5 degrees C., with 0.02-degree divisions, and readings could be estimated to the third place.

Readings were taken every odd minute for an 11-minute period to establish the temperature curve for the water and calorimeter. The soil dipper was then removed from the steam bath, its stopper removed, and its contents poured through a paper funnel into the calorimeter at exactly 12 minutes. Temperature readings were taken every minute until the 25-minute point (from the original starting time, not the pouring time) was reached and then were taken every five minutes up to 45 or 60 minutes. The calorimeter was then removed and its total weight determined to check the total of the fractional parts. The volume of the thermometer immersed in the water was also determined for use in a correction applied later.

The detailed calculations necessary to calculate the specific heat will be explained in another section.

Method B: Method B was used in tests in which the samples were heated in the 130-degree F. bath. The dippers, filled with soil, were stoppered and placed on a rack immersed in the 130-degree bath. There were no thermometers within the individual samples. The samples were left in the bath overnight, and their temperatures were assumed to be equal to that recorded by a thermometer within the bath.

In making the actual calorimeter test by this method, there was a slight undesirable delay in transferring the soil from the bath to the calorimeter. It was necessary to wipe off the stopper and dipper with a rag before it could be opened and poured. The method of recording temperatures was the same as that specified in Method A.

Method C: This method was similar to Method B in all respects, except that the thermometer was placed through the stopper in each individual sample instead of in the bath. With this arrangement, it was not possible to close the cover of the constant temperature bath.

Method D: Method D was used in some of the tests on wet soil. It was used in an attempt to solve one of the problems which was encountered in the testing of soil - moisture mixtures. The difficulty encountered in such tests utilizing Method B or C was that the wet soil would adhere to the dipper or to the funnel when it was poured into the calorimeter. To circumvent this, some tests were run by placing the wet soil within the calorimeter initially, adding additional water to it, and noting the resultant change in temperature. The test was used only for mixtures of high moisture content which were fluid enough to be mixed by the stirrer. The water to be added was weighed into a thermos bottle, and the bottle corked. Its temperature was measured periodically; a temperature of approximately 100 degrees F. was normally used. The temperature readings during the test were taken as previously described.

Method E: Method E was used in an attempt to get specific heats at a temperature of 65 degrees F., plus or minus. In this method, the soil was left to stand in the dippers in the laboratory air with thermometers inserted. The water within the calorimeter was started out at approximately 60 degrees F.

Method F: The lowest mean temperature runs were made by using the main alcohol cooling tank of the thermal conductivity apparatus. The table for holding the dippers was placed in this tank. The samples were placed in the bath the day before the tests were to be run. The temperature of the bath was ordinarily around -40 degrees F. Tests were run just as in Method B. After pouring the soil, 10 temperature readings were taken in the bath at various depths. These readings were generally quite uniform except for those in the upper 1/2-inch depth. The average of the 10 values was considered the soil temperature.

Heat of Wetting. - It was recognized at the beginning of the specific heat tests that the results would be affected by the heat of wetting of the soils. If a soil at a given temperature is placed into the water at the same temperature, heat is evolved and causes a rise in temperature. This value must be known in order to calculate the true specific heat. The method of determining this value was about the same as that outlined in Method E for specific heat, except that an attempt was made to have the water in the calorimeter at approximately the same temperature as the soil, both being at room temperature. The regular series of temperature readings were taken, just as in the specific heat tests. In the calculations, any rise in temperature not accounted for by a cooling of the soil (the soil was occasionally a degree or so warmer than the water) was the result of the heat of wetting.

Calculations. - The method of calculation of specific heat was essentially the same for all methods of test. Therefore, a typical calculation will be given for only one method. The calculations for heat of wetting will also be described.

The following computations are accompanied by an explanation of each step.

Observed Data, Specific Heat Test

Run No.: 100

Soil : P4604, Lowell Sand

Method : A (Sample heated in steam bath)

Weight of calorimeter, stirrer, water, soil:	1911.0 grams	(1)
Weight of calorimeter, stirrer, water:	1602.5 grams	(2)
Weight of calorimeter, stirrer:	505.6 grams	(3)
Volume of thermometer in water:	7.3 cubic centimeters	(4)
Barometric reading:	736.6 millimeters	(5)
Air temperature:	23.8 Degrees C.	

Temperature data:

Time	Elapsed Time, Minutes	Temperature of Calorimeter (°C.)	Temperature of Jacket (°F.)
11:38	0	--	--
	1	17.300	--
	3	17.354	--
	5	17.404	--
	7	17.456	--
	9	17.504	--
	11	17.556	--
	12 (Soil added)	--	--
	13	19.856	--
	14	20.350	--
	15	20.714	74.76
	16	20.950	--
	17	21.146	--
	18	21.272	--
	19	21.376	--
	20	21.444	--
	25	21.626	--
	30	21.686	--
	36	21.742	--
	40	21.770	--
	50	21.842	--

The weight of dry soil in the test is Items (1) minus (2), or:

Weight of soil = W_s = 1911.0 - 1602.5 = 308.5 grams

When the heated soil is added to the calorimeter, the temperature of not only the water but also of the calorimeter, the lower portion of the stirrer, and a part of the thermometer is raised. The weight of each of these is multiplied by its specific heat, and the values are then added together to obtain the "water equivalent" of the apparatus.

Weight of calorimeter and stirrer = 505.6 grams

Water equivalent of calorimeter and stirrer = 505.6 x 0.09305 = 47.046.

Water equivalent of thermometer = volume immersed x 0.45 = 7.3 x 0.45 = 3.285

The value, 0.45, is the value commonly used for this purpose in calorimetry.

Water in calorimeter = W_w = Items (2) - (3) = 1602.5 - 505.6 = 1096.9 grams

Water + water equivalent of apparatus = $W_w + E$ = 1096.9 + 47.046 + 3.285
= 1147.231

The other data required for the calculations are the three temperatures:

T_S = the temperature of the soil

T_I = the temperature of the calorimeter before the soil addition, or the initial temperature.

T_F = The temperature after the mixture of soil and water, or the final temperature.

The temperature of the soil is taken as the boiling point of water calculated from the corrected barometric pressure. In this instance, the uncorrected barometer reading was 736.6 millimeters, and the air temperature was 23.8 degrees C.

Boiling point = 99.017 degrees C.*

The initial and mixture temperatures in the calorimeter were found in one of two different ways. Both proved about equally successful, and so both will be explained.

The first method is one sometimes employed in the use of a bomb calorimeter used in determining the heating value of coal, oils, etc. A plot is made of the observed temperatures versus time, both before and after the soil is added. This is shown in Figure 2. It will be noted in the figure that, after the soil is added, the temperature rises rapidly, but that it requires several minutes for the thermometer to register the rise and to give again a straight-line temperature-time relationship. To arrive at some definite initial and final temperatures, some given time must be selected; the temperature curve before the soil addition projected to that time; and the curve for the uniform rate of temperature rise after the addition projected to the same time.

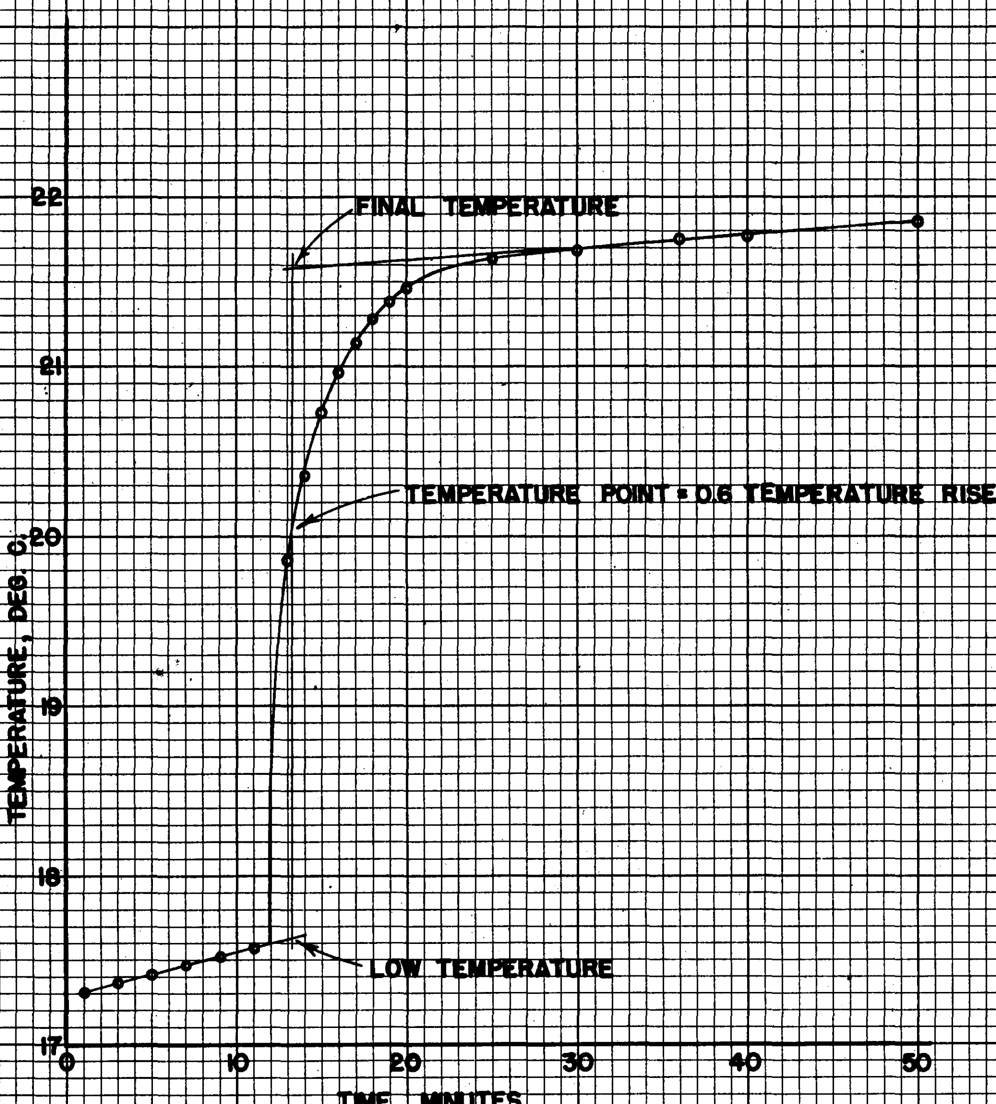
A suitable time was found to be that at which about 60 per cent of the temperature rise has occurred. This point, as indicated in Figure 2, was at approximately the 13-minute point, and the final temperature is obtained by extending the straight line defined by the 30- to 50-minute readings, back to the 13-minute point. These plots are actually made to more exaggerated scales than is shown to facilitate more accurate reading of the temperatures. By such a procedure, the following values were obtained:

T_I = 17.613 degrees C;

T_F = 21.583 degrees C.

*Taken from Physics and Chemistry Handbook.

FIG. 2
METHOD OF DETERMINATION OF
INITIAL AND FINAL TEMPERATURES
IN SPECIFIC HEAT TEST



The other method of calculation is accomplished by assuming that the rate of temperature change of the calorimeter is dependent upon the difference in temperature between the calorimeter and the calorimeter jacket. A rate of change curve is constructed by determining the rate at a time well after the soil has been added, taking a zero rate at the jacket temperature and connecting the two by a straight line.

For Run No. 100 the rate of temperature rise was calculated for the 36 to 50-minute time period and was found to be 0.00714 degrees per minute at an average temperature of 21.792 degrees. A rate-of-temperature-rise curve was drawn using this value and a zero rate at 23.756 degrees which was the temperature of the jacket. By means of such a curve and the test run temperature readings, the following calculations were made:

Temperature - Degrees, Centigrade

Time	Observed	Average	Rate of Rise per minute	Correction	Accumulated Correction	Corrected
12	17.581					
		18.718	0.0181			
13	19.856			0.0181		
		20.103	0.0131			
14	20.350			0.0131		
		20.532	0.0116			
15	20.714			0.0116		
		20.832	0.0106			
16	20.950			0.0106		
		21.048	0.0097			
17	21.146			0.0097		
		21.209	0.0092			
18	21.272			0.0092		
		21.324	0.0087			
19	21.376			0.0087		
		21.410	0.0084			
20	21.444			0.0084		
		21.535	0.0079			
25	21.626			0.0395		
		21.656	0.0076			
30	21.686			0.0380		
		21.714	0.0073			
36	21.742			0.0438	0.2107	21.5313
		21.756	0.0072			
40	21.770			0.0288	0.2395	21.5305
		21.806	0.0070			
50	21.842			0.0700	0.3095	21.5325
					Average =	21.531

The "time" and first column of temperature readings are from the original test data, except the 12-minute value which was obtained by projecting the curve of 1 to 11-minute readings. The next column consists merely of the average temperatures for the intervals between readings. These values were used to enter a rate-of-temperature-rise curve so as to obtain the rate for that time interval. This change is due to the difference in temperature existing between the calorimeter and its jacket, and not to the gain of heat from the added soil. The correction was obtained by multiplying the rate by the time interval to which it applied. The accumulated corrections are merely the sum of the corrections to that point. These values were then applied to the original temperature readings to obtain the final temperature which would have existed if there had been no gain of heat from the jacket. The final corrected temperatures were calculated only for the last few readings, or those which define the straight line as shown by the 30 to 50-minute readings in Figure 2. The 36, 40 and 50-minute readings were averaged in the above tabulation to obtain the final temperature, or that of the soil-water mixture. The 12-minute reading was taken as the temperature before the soil addition. Or, by this method:

$$T_I = 17.581 \text{ degrees C;}$$

$$T_F = 21.531 \text{ degrees C.}$$

The specific heat, uncorrected for heat of wetting, is calculated in the following manner:

$$\text{Heat gained} = \text{heat lost}$$

$$(W_w + E)(T_F - T_I) = W_S (S)(T_S - T_F)$$

in which

W_w = weight of water in calorimeter;

E = water equivalent of apparatus;

W_s = weight of soil;

S = specific heat of soil;

T_F = final temperature of soil - water mixture;

T_I = initial temperature, or that of calorimeter before soil addition;

T_S = soil temperature, or that of soil before addition to calorimeter.

All weights are in grams, and all temperatures in degrees Centigrade.

Solving the above for S:

$$S = \frac{(W_w + E)(T_F - T_I)}{W_S(T_S - T_F)}$$

In test No. 100, as shown on page 24.

$W_w + E = 1147.2$ and $W_s = 308.5$

If the temperatures determined by the first method are used,

$$S = \frac{1147.2\,(21.583 - 17.613)}{308.5\,(99.017 - 21.583)} = 0.191$$

If the temperatures determined by the second method are used,

$$S = \frac{1147.2\,(21.531 - 17.581)}{308.5\,(99.017 - 21.531)} = 0.190.$$

The difference in the two results is insignificant and would be so in any tests where the change in temperature resulting from the addition of the soil was a matter of two or three degrees or more. However, in tests where the resultant temperature change was of a magnitude of less than one degree, the accuracy of the calculated temperatures has a much greater bearing on the correctness of the final result. This condition occurred in heat of wetting tests and in the specific heat tests made with mean temperatures of from 65 to 100 degrees F. In these tests the second method, or that which utilizes the rate of temperature change corrections, was found to give more consistent results and was therefore used.

Following are the data and calculations of a run for the heat of wetting of a soil:

Observed Data, Heat of Wetting Test

Run No.: 103

Soil: P4604, Lowell Sand

Weight of Calorimeter, stirrer, water, soil:	1903.9 grams
Weight of calorimeter, stirrer, water:	1611.3 grams
Weight of calorimeter, stirrer:	505.6 grams
Volume of thermometer in water:	7.0 cubic centimeters

Temperature data:

Time	Elapsed Time Minutes	Temperature of Calorimeter Degrees, C.	Temperature of Jacket Degrees, F.	Temperature of Soil Degrees, F.
3:40	0	--	--	--
	1	23.538	74.9	75.4
	3	23.538	--	--
	5	23.540	--	--
	7	23.542	--	--
	9	23.544	--	--
	11	23.546	--	75.4
	12 (Soil added)	--	--	--
	13	23.584	--	--
	14	23.590	--	--
	15	23.596	--	--
	16	23.602	--	--
	18	23.606	--	--
	19	23.610	--	--
	20	23.614	--	--
	28	23.626	--	--
	30	23.634	--	--
	35	23.642	--	--
	40	23.652	--	--

Calculations:

Weight of soil = W_s = 1903.9 - 1611.3 = 292.6 grams

Water equivalent of calorimeter and stirrer = 505.6 x 0.09305 = 47.046

Water equivalent of thermometer = 7.0 x 0.45 = 3.150

Weight of water in calorimeter = W = 1611.3 - 505.6 = 1105.7 grams

Water plus equivalent of apparatus = $W_w + E$ = 1105.7 + 47.046 + 3.150 = 1155.896

The calculation of the temperature of the calorimeter just before the addition of the soil and that resulting after the addition of the soil was calculated by the second method explained in the previously presented specific heat calculations and will not be repeated here. The values obtained in this procedure were:

$$T_I = 23.547 \text{ degrees C;}$$

$$T_F = 23.593 \text{ degrees C.}$$

The temperature of the soil before addition, or T_S, was 75.4 degrees F, or 24.111 degrees C.

In order to determine the heat of wetting, it is necessary to know the approximate specific heat of the soil at the temperature at which the test was run. The value may be selected from a curve, such as that shown in Figure 135, Appendix II. A value of 0.173 may be taken for Soil P4604.

The equation for determination of heat of wetting is derived as follows:

$$\text{Total heat gained} = (W_w + E)(T_F - T_I)$$

$$\text{Total heat lost} = W_s\,(S)\,(T_S - T_F) + W_s\,(H)$$

in which H is the heat of wetting and the other symbols are as before.

Equating the heat gained and lost and solving for H:

$$H = \frac{(W_w + E)(T_F - T_I)}{W_s} - S(T_S - T_F)$$

Substituting the values for Run No. 103,

$$H = \frac{1155.896\,(23.593 - 23.547)}{292.6} - 0.173\,(24.111 - 23.593)$$

$$= 0.092 \text{ calories per gram.}$$

The effect of heat of wetting on specific heat is illustrated by the following calculation. The specific heat determined for Soil P4604, Lowell Sand, in Run No. 100 was 0.190 as shown on Page 27. In that calculation, however, all of the temperature rise was attributed to heat given off in cooling the soil, and none was attributed to heat of wetting. The calculation should be corrected in the following manner:

$$\text{Total heat gained} = (W_s + E)(T_F - T_I);$$

$$\text{Total heat lost} = W_s\,(S)\,(T_S - T_F) + W_s\,(H)$$

Equating and solving for the specific heat,

$$S = \frac{(W_w + E)(T_F - T_I)}{W_s(T_S - T_F)} - \frac{H}{(T_S - T_F)}$$

This is exactly the same formula as that used before in determining specific heat (page 27) except for the subtracted term on the right hand side. If the specific heat test is one in which the soil added is at a lower temperature than the calorimeter, the term will be added rather than subtracted, since the denominator will also be negative.

The average heat of wetting for Soil P4604 derived from three tests was 0.075 calories per gram. Thus, correcting the value of Run No. 100 shown on Page 27:

$$\text{Specific heat, corrected} = 0.190 - \frac{0.075}{99.017 - 21.531}$$

$$= 0.190 - 0.001 = 0.189$$

It will be noted that calculations for heat of wetting are dependent upon the corrected specific heat value, and the specific heat, in turn, is dependent upon the heat of wetting value. A small change in specific heat, however, makes such a very small change in heat of wetting that two calculations are sufficient for a final value.

In the corrections for specific heat, the heat of wetting has been assumed to be the same at all temperatures. This may not be correct, but in nearly all instances the amount of correction is so small that the error thus introduced would be very small.

Thermal Conductivity of Insulating Materials.

Equipment. - The thermal conductivity tests on the slabs were made on the hot plate apparatus at the Engineering Experiment Station, University of Minnesota. This apparatus is the kind used in tests on various types of insulation used for building construction. Essentially, the scheme is the same as that used in the thermal conductivity tests on soils; the test specimens are placed between plates rather than in a tubular container. The apparatus is so constructed that the test is made on two similar slabs. A central plate contains the heating element and is divided into two parts: an inner section, 16 inches square, and a band or guard ring, 4 inches wide, surrounding this section. The test specimens, each 24 inches square, are placed on each side of the heating plate, and each is covered by a cooling plate. The assembled apparatus is surrounded by an insulated cover which serves as a precaution against heat losses from the edge of the specimen.

Copper-constantan thermocouples are mounted at both the hot and cold faces of both test specimens; four are provided for each face. A differential couple is provided across the air gap between the inner and outer portions of the hot plate so that a balanced temperature may be maintained. Heat supplied is measured by means of voltage and amperage readings of the mean heating section.

Test Procedures and Calculations. - Slabs as received were 24 inches square and approximately 3 inches thick. The surfaces were rather rough, so they were first made smooth by being rubbed with a brick. They were then oven-dried, and weighings and measurements were then made for density determinations.

The procedure of running thermal conductivity tests when two slabs of the same design mix were available was as follows:

The two slabs were placed in the hot plate apparatus; the cold plate temperature adjusted to the desired temperature; and power supplied to the hot plate heating unit until a temperature differential of about 30 degrees Fahrenheit was obtained. The test continued until uniform temperatures were maintained for five or six hours. Two other tests would then be run at two progressively lower mean temperatures.

The calculations for such a test consist of the following:

Test data:

Slab A: Hot plate temperature
Cold plate temperature
Thickness

Slab B: Hot plate temperature
Cold plate temperature
Thickness

Hot plate heater: Voltage
Amperage

Area of test section: 16 x 16 = 256 sq. in. = 1.7778 sq. ft.

One may write:

$$\text{Heat transmitted} = \frac{k_A\ (\text{Area})\ (\text{Temperature Difference})}{\text{Thickness}_A}$$

$$+ \frac{k_B\ (\text{Area})\ (\text{Temperature Difference})}{\text{Thickness}_B}$$

in which k_A and k_B are the coefficients of thermal conductivities of the two slabs. The term, k/thickness, is called the coefficient of thermal conductance. This term is designated by C. The solution is simplified by using average values of thickness and temperature difference for the two slabs.

One may then write:

$$\text{Heat transmitted} = 2C(\text{Area})\ (\text{Temperature Difference}).$$

The heat transmitted is 3.415 x voltage x amperage (3.415 EI) in Btu's per hour. If one expresses the area in square feet and the temperature difference in degrees Fahrenheit, C will be in Btu's per square foot per hour per degree F. Solving:

$$C = \frac{3.415\ EI}{2\ \text{Area}\ (\text{Temperature Difference})}$$

$$= \frac{3.415\ EI}{2\ (1.7778)(\text{Temperature Difference})} = \frac{0.9605\ EI}{\text{Temperature Difference}}$$

The value of k, the coefficient of thermal conductivity, in Btu's per square foot per inch per hour per degree F. is obtained by multiplying C by the average thickness, in inches, or

$$k = C\ (\text{Average thickness}).$$

The procedure for tests of slabs where only one slab was available (the other having been broken in transit) was somewhat different and was as follows:

A series of tests was made with three slabs, two of a given design and the single slab. Designating the two like slabs as A and B and the single one as C, tests were conducted at a given mean temperature with slabs A and B, A and C, and B and C.

From these three tests, the following equations may be written:

$$\text{Test 1:}\ 3.415\ EI = C_A\ (\text{Area})\ (\text{Temp. Diff.}_A) + C_B(\text{Area})\ (\text{Temp. Diff.}_B)$$

$$\text{Test 2:}\ 3.415\ EI = C_A\ (\text{Area})\ (\text{Temp. Diff.}_A) + C_C(\text{Area})\ (\text{Temp. Diff.}_C)$$

$$\text{Test 3:}\ 3.415\ EI = C_B\ (\text{Area})\ (\text{Temp. Diff.}_B) + C_C(\text{Area})\ (\text{Temp. Diff.}_C)$$

Solving simultaneously, the coefficients of conductance, C_A, C_B, and C_C of three slabs may be obtained.

Previous tests on slabs A and B had established the effect of mean temperature on conductivity. By such a relationship, the k of slab A could be estimated at any temperature. Additional tests were therefore run at different mean temperatures with slabs A and C. Knowing the conductivity (and therefore the conductance) of slab A, the coefficient for slab C could be calculated by means of the formula,

$$3.415\ EI = C_A\ (\text{Area})\ (\text{Temp. Diff.}_A) + C_C\ (\text{Area})\ (\text{Temp. Diff.}_C)$$

or,

$$C_C = \frac{3.415\ EI - C_A\ (\text{Area})\ (\text{Temperature Difference}_A)}{\text{Area}\ (\text{Temperature Difference}_C)}$$

The value of k is then obtained by multiplying C_C by the thickness of the slab.

Thermal Conductivity of Bituminous Paving Mixture.

The method of making the thermal conductivity tests on the bituminous paving mixture was similar to that for the insulating materials. The test specimens were 12 by 12 inches square and a hot plate apparatus for this size of slab was used. Calculations were similar to those for tests on insulating materials when a pair of test specimens were available.

RESULTS

General

The results of thermal conductivity tests on soils are given in Appendix I of this report. As previously noted, this table lists the soils in approximate order of textures with the coarser materials listed first. Results on 19 soils are included.

The moisture contents reported for the test runs in Appendix I were obtained in the following manner. The moisture content shown at the completion of a test run is the average of the 12 samples taken. (See Page 18). If this value differed from the average moisture content at the start of the test, it was assumed that the change had occurred gradually, and the change was then proportioned accordingly through the several tests.

In some soils, particularly the sandy ones, moisture migration occurred during the test runs. Upon removal, the moisture contents were found to be higher toward the outside (cold) face and toward the bottom. Because of this condition, the moisture contents for which thermal conductivity values are reported are average moisture contents. The conductivity with respect to a uniform moisture distribution of the same amount, might differ from the value reported herein. It is felt, however that the given conductivity constants are approximately correct and are sufficiently so as to permit comparison between the various soils, densities and moisture contents.

The average results of the specific heat tests are presented in Table V. Each value in this table is the average of from two to six values. The heat of wetting values used in the correction of the test results are given in Table VI. The specific heat results of the individual tests on one soil, P4701, Graded Ottawa Sand, at moisture contents varying from 2 to 100 per cent, are shown later, along with certain calculations, in Table XV.

The results of the thermal conductivity tests on the pre-cast insulating slabs and the asphalt paving mixture are given in Table VII. All of the slabs were in an oven-dry condition when tested. Temperature differentials of from about 25 to 45 degrees were used.

Thermal Conductivity of Soil

Effect of Temperature. - Tests were made on all soils at two mean temperatures above the freezing point, 70 and 40 degrees, and on at least two below freezing, 25 and -20 degrees. Because many of the soils at the test areas in Alaska exist at temperatures close to the freezing point, the conductivity values at 40 and 25 degrees are perhaps the most important, and much of the discussion to follow will be on the results at these two mean temperatures.

Comparing first the conductivity values for the two temperatures above the freezing point, Table VIII gives, for each soil tested, the maximum, minimum, and average ratios of the conductivities at 70 degrees to those at 40 degrees for the test runs made. Only in a few cases was the 40 degree value greater than that at 70 degrees. On the average, the conductivity at 70 degrees is about 4 per cent greater than that at 40 degrees.

TABLE V - AVERAGE SPECIFIC HEAT VALUES - DRY SOILS

Soil No.	Soil Designation	Corps of Engineers Class	Mean Temperature Degrees F.	Specific Heat
P4601	Chena River Gravel	GP		
	(Passing No. 4)		141.8	0.194
	(Passing 3/4" Retained No. 4)		140.7	0.196
P4703	Crushed Quartz	SW	141.6	0.190
P4704	Crushed Trap Rock	SM	139.8	0.193
P4705	Crushed Feldspar	SW	138.7	0.190
P4706	Crushed Granite	SW	8.1	0.161
			66.9	0.174
			141.6	0.189
P4702	20-30 Ottawa Sand	SP	99.9	0.183
			139.8	0.189
P4701	Graded Ottawa Sand	SP	14.9	0.157
			65.3	0.164
			99.7	0.176
			140.5	0.189
P4604	Lowell Sand	SW	14.9	0.159
			67.5	0.188
			141.6	0.188
P4503	Northway Sand	SW	14.9	0.171
			65.7	0.185
			140.2	0.191
P4502	Northway Fine Sand	SP	141.8	0.197
P4505	Northway Silt Loam	ML	13.3	0.168
			68.7	0.176
			140.7	0.193
P4602	Fairbanks Silt Loam	ML	16.9	0.164
			65.8	0.183
			142.3	0.194

TABLE VI - AVERAGE HEAT OF WETTING VALUES

Soil No.	Soil Designation	Corps of Engineers Class	Heat of Wetting Calories Per Gram
P4703	Crushed Quartz	SW	0.00*
P4704	Crushed Trap Rock	SM	0.18
P4705	Crushed Feldspar	SW	0.001
P4706	Crushed Granite	SW	0.07
P4701	Graded Ottawa Sand	SP	0.06
P4604	Lowell Sand	SW	0.08
P4503	Northway Sand	SW	0.58
P4502	Northway Fine Sand	SP	0.49
P4505	Northway Silt Loam	ML	2.17
P4602	Fairbanks Silt Loam	ML	2.60

*Actual average: minus 0.010

TABLE VII - SUMMARY OF THERMAL CONDUCTIVITY TESTS OF INSULATING MATERIALS AND ASPHALT PAVING MIXTURE

Type of Material	Design Mix Proportion By Volume	Design Density Grams/Cu. Cm.	Actual Density Lbs./Cu. Ft.	Mean Temp. Deg. F.	k Btu./Sq. Ft./ In./Hr./Deg. F.
Zonolite Concrete	1:4	--	33.6	72.3	1.091
				29.9	1.075
				- 0.1	1.051
Zonolite Concrete	1:6	--	29.6	75.3	1.058
				70.1	1.044
				35.0	1.027
				0.2	0.998
Zonolite Concrete	1:8	--	28.6	100.3	1.010
				75.3	1.001
				55.2	0.995
				15.1	0.941
Zonolite Concrete	1:10	--	20.4	70.0	0.684
				35.0	0.665
				0.1	0.635
Cell Concrete	--	0.8	71.5	176.1	3.072
				125.3	3.100
				88.0	3.093
				74.9	3.094
				70.0	3.057
				34.9	3.082
				7.0	3.041
Cell Concrete	--	1.0	80.5	88.2	3.793
				75.4	3.869
				50.6	3.863
				28.4	3.829
Cell Concrete	--	1.2	86.0	75.8	4.153
				49.8	4.108
				25.0	4.105
Asphalt Paving Mixture	--	--	138.0	40.1	10.30
				25.0	10.15
				-19.6	9.90

The relationship of the conductivity values at the temperatures below the freezing point, 25 and -20 degrees, appears to be dependent upon the moisture content. For tests made on all soils, excluding the peat, the ratio of the conductivity at -20 degrees to that at 25 degrees for moisture contents of 0 to 5 per cent (121 tests) average 0.99; 5 to 10 per cent (22 tests), 1.01; 10 to 15 per cent (21 tests), 1.05; 15 to 20 per cent (13 tests), 1.06; and 20 per cent or more (15 tests), 1.04. Thus it may be stated that on the basis of averages of a large number of tests, the conductivity of frozen soils does not vary markedly in a temperature range from 25 to -20 degrees. The conductivity at -20 degrees becomes somewhat greater than that at 25 degrees as the moisture content increases. Further inspection of the data indicates that the increase in conductivity of frozen soils for a drop in mean temperature is greater for a soil with a high density than for the same with a low density. The foregoing facts may be explained by the decrease in conductivity of soil solids and the increase in conductivity of ice with a decrease in mean temperature. The resultant effect is a function of the amount of moisture present.

TABLE VIII - COMPARISON OF THERMAL CONDUCTIVITIES AT 70 AND 40 DEGREES F.

Soil No.	Soil Designation	Corps of Engineers Class	Ratio $k_{70°}/k_{40°}$ Maximum Ratio	Minimum Ratio	Average Ratio
P4601	Chena River Gravel	GP	1.114	1.013	1.055
P4703	Crushed Quartz	SW	1.085	0.987	1.033
P4704	Crushed Trap Rock	SM	1.160	1.018	1.095
P4705	Crushed Feldspar	SW	1.122	0.997	1.061
P4706	Crushed Granite	SW	1.160	1.000	1.076
P4702	20-30 Ottawa Sand	SP	1.050	0.986	1.024
P4701	Graded Ottawa Sand	SP	1.086	1.003	1.038
P4714	Fine Crushed Quartz	SP	1.052	0.966	1.008
P4709	Fairbanks Sand	SW	1.119	1.002	1.045
P4604	Lowell Sand	SW	1.068	0.994	1.024
P4503	Northway Sand	SW	1.189	1.006	1.054
P4502	Northway Fine Sand	SP	1.101	0.999	1.042
P4711	Dakota Sandy Loam	SM	1.059	0.979	1.022
P4713	Ramsey Sandy Loam	CL	1.084	1.008	1.031
P4505	Northway Silt Loam	ML	1.074	1.008	1.039
P4602	Fairbanks Silt Loam	ML	1.083	1.005	1.036
P4710	Fairbanks Silty Clay Loam	ML	1.114	0.984	1.039
P4708	Healy Clay	CL	1.093	1.006	1.059
P4707	Fairbanks Peat	Pt	1.351	0.994	1.156
	Average (P4707 omitted)		1.101	0.998	1.042

In the test program, in making the change from tests above freezing to tests below freezing, the change in temperature was accomplished as rapidly as possible. In most instances, it took about an hour or two to freeze the soil. With this short freezing period, it is doubtful if ice lenses formed in the soil to any great extent. The presence or absence of such lenses would undoubtedly affect the thermal conductivity of the soil.

The most important relationship in a consideration of the effect of mean temperature upon thermal conductivity is the change in conductivity which occurs in passing through the freezing point. Tests on all soils were made just above freezing; i.e., hot side, 45 degrees, cold side, 35 degrees, mean 40 degrees, and just below freezing; i.e., 30 and 20 degrees, respectively, and mean, 25 degrees. It was found that the difference in k values at these two points was chiefly dependent upon the moisture content. On relatively dry soils, for example those in the air-dry condition, very little difference was found. As the moisture content was increased, the k value at 25 degrees became less than that above freezing. With a further increase in moisture content, the below-freezing value became progressively greater than that above freezing. The ratio of the frozen to unfrozen value also depended somewhat upon the density of the soil, the ratio in general being greater for a high density test than for a low density test at the same moisture content. Figure 3 illustrates the relationship between the ratio of the conductivity of the frozen soil to the conductivity of the unfrozen soil and the moisture content for one soil, P4602, Fairbanks Silt Loam. Curves for nine other soils are shown in Figures 44 to 52, which are in Appendix II.

The curves of Figure 3 and 44 to 52 inclusive are reproduced, without the individual test points, in Figures 4 and 5; Figure 4 is for five sandy soils, and Figure 5 for the six heavier textured soils. Soil P4711, Dakota Sandy Loam, which contains 69 per cent sand is included with the sandy soils. Although the curves do not coincide, there are marked similarities. All of them show a decreasing ratio (k_{25}/k_{40}) for small moisture increases followed by a marked rise in the ratio for further increases in moisture content. The point

FIG. 3

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4602, FAIRBANKS SILT LOAM (ML)

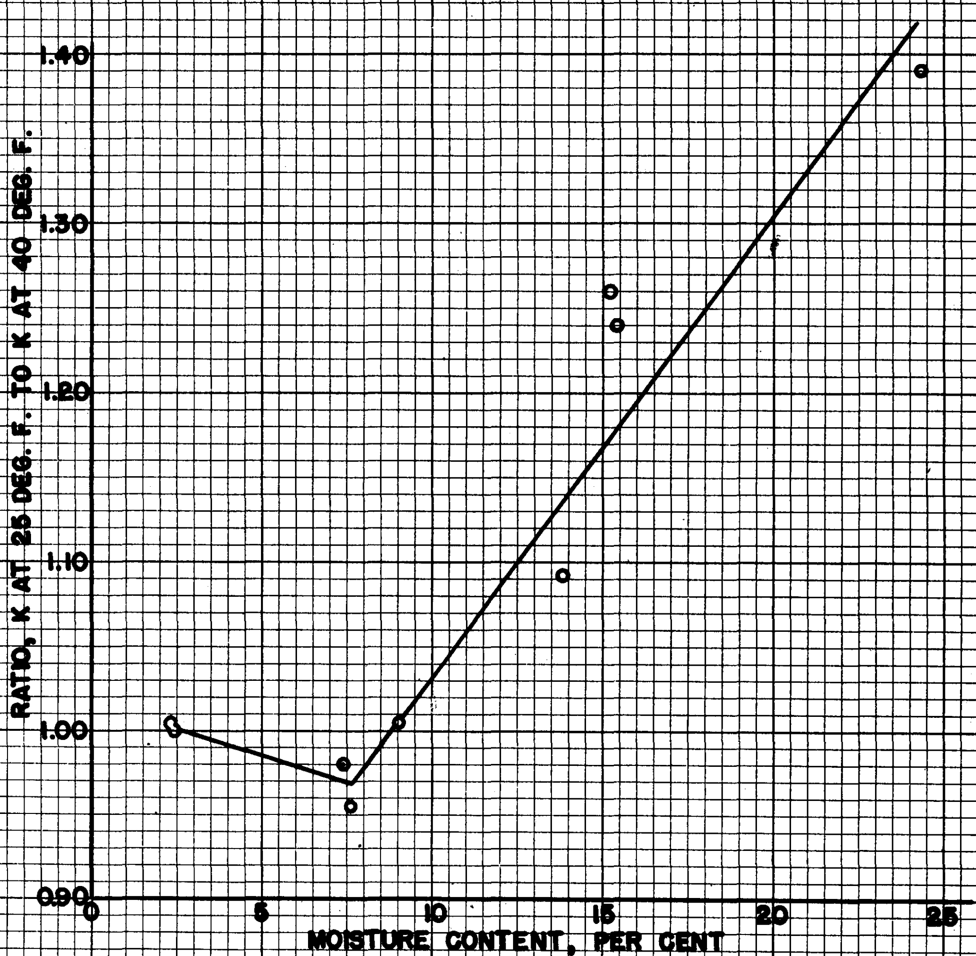
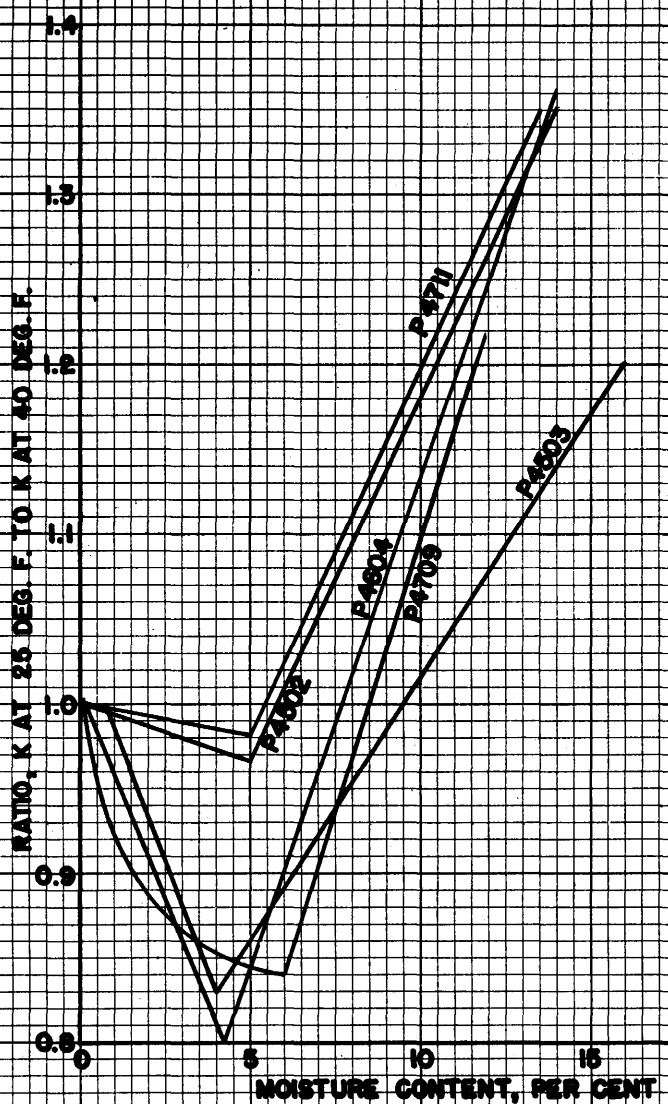


FIG. 4

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SANDY SOILS



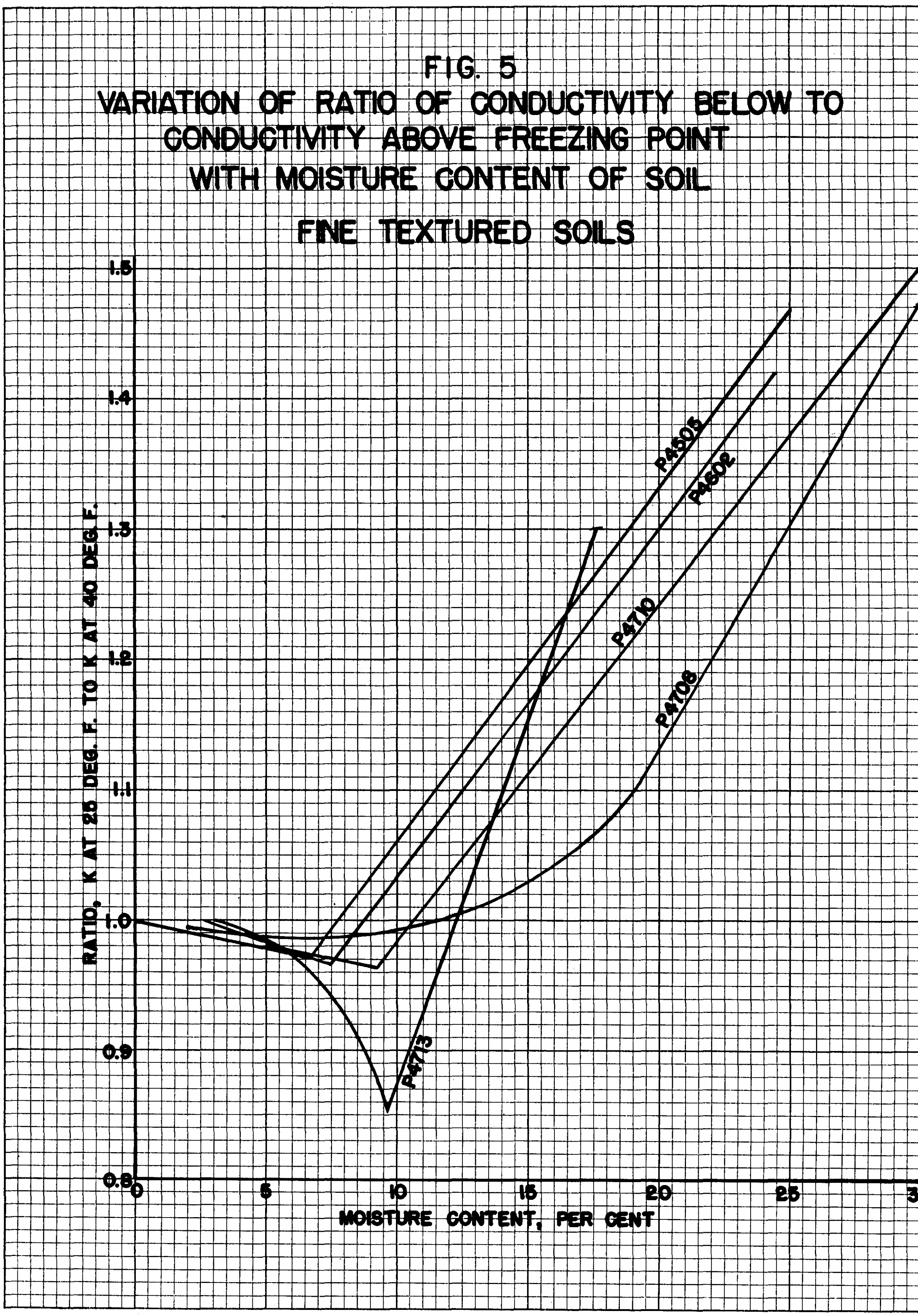


FIG. 5
VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL
FINE TEXTURED SOILS
RATIO, K AT 25 DEG. F. TO K AT 40 DEG. F.
MOISTURE CONTENT, PER CENT
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0
5
10
15
20
25
30
P4505
P4602
P4710
P4708
P4713

of minimum ratio varies from 4 to 9 per cent moisture content. With the exception of one of the sandy loams (Soil P4713), the ratio of k_{25} to k_{40} at the modified optimum moisture content is greater than 1.00, varying from about 1.03 to 1.25 and averaging about 1.17. At 5 per cent more than the modified optimum moisture content the ratios average about 1.35.

Effect of Density. - It was found in tests on all soils that an increase in density resulted in an increase in thermal conductivity. This was the case for any given moisture content and for any given temperature. Curves are presented herein to show the relationships at mean temperatures of 40 and 25 degrees.

The thermal conductivity was found to vary with density according to the following equation:

$$k = A(10)^{B \cdot \text{Density}}$$

A and B being constants. Such an equation plots as a straight line on semi-logarithmic paper, the density being on the arithmetic scale and the conductivity on the log scale.

The rate of increase of conductivity with an increase in density is approximately the same at any moisture content for a given soil. Figure 6 is an example of the results on one soil at a mean temperature of 40 degrees. Similar curves for other soils are given in Appendix II, Figures 53 to 70. It will be noted in Figure 6 that all five curves have about the same slope, indicating the same percentage increase in conductivity per pound per cubic foot increase in density for moisture contents as high as 25 per cent.

Table IX presents the conductivity-density equations for all curves shown in Figure 6 and 53 to 70 inclusive, which are for a mean temperature of 40 degrees. In tests on some soils, tests were made at only two densities at a given moisture content; this is the case, for example, for tests on the crushed quartz, trap rock and granite samples (P4703, P4704, and P4706). However, because of the established relationship for other soils, it seemed reasonable to assume that the same relationship would be correct for these soils.

The curves for a mean temperature of 25 degrees are shown in Figure 7 and Figures 71 to 88 in Appendix II. The equations for the curves are given in Table X. It will be noted that results are similar to those at 40 degrees.

In the case of the peat soil, P4707, tests with moisture contents of 175 and 280 per cent at extremely low densities, such as 7.5 pounds per cubic foot, gave conductivity values lower than those indicated by the given equations. It may be that the relationship is not correct for such extreme cases.

With the exception of the curves for the peat, P4707, and two or three isolated curves for other soils, all of the curves have approximately the same slope; or, in other words, the rate of increase in k with an increase in density at a constant moisture content is approximately the same for the several soils and all moisture contents at which tests were made. As shown in Table IX for tests at 40 degrees, the percentage increase in k for a one-pound per cubic foot increase in density varies from 1.2 to 4.4 with four exceptions, and averages 2.8 per cent. For the frozen soils, Table X, the values vary from 1.6 to 4.6 with seven exceptions, and average 3.0 per cent. About 70 per cent of the values in both tables are within the range from 2.0 to 3.5 per cent increase in k for a one pound increase in density.

The equations of Tables IX and X are substantially correct for the density range in which tests were conducted, but may not necessarily be correct if values are extrapolated far beyond this range.

TABLE IX - CONDUCTIVITY-DENSITY RELATIONSHIPS

Mean Temperature 40°F.

Soil No.	Approximate Moisture Content	Equation of Curve for Conductivity*	Percentage Increase in k per Pound Increase in Density
P4601	0.2	$k = 0.096(10)^{0.0134\gamma}$	3.1
	0.7	$k = 0.038(10)^{0.0172\gamma}$	4.0
	1.9	$k = 0.11\ (10)^{0.0164\gamma}$	3.9
	3.1	$k = 0.071(10)^{0.0185\gamma}$	4.3
P4703	0.03	$k = 0.11\ (10)^{0.0137\gamma}$	3.2
	0.7	$k = 0.21\ (10)^{0.0139\gamma}$	3.3
	2.0	$k = 0.40\ (10)^{0.0135\gamma}$	3.2
	4.0	$k = 0.40\ (10)^{0.0145\gamma}$	3.4
P4704	0.2	$k = 0.12\ (10)^{0.0119\gamma}$	2.8
	1.0	$k = 0.11\ (10)^{0.0134\gamma}$	3.1
	1.8	$k = 1.10\ (10)^{0.00532\gamma}$	1.2
	3.8	$k = 0.80\ (10)^{0.00782\gamma}$	1.8
P4705	0.07	$k = 0.25\ (10)^{0.00997\gamma}$	2.4
	1.0	$k = 0.40\ (10)^{0.00995\gamma}$	2.3
	2.0	$k = 1.20\ (10)^{0.00628\gamma}$	1.5
	4.0	$k = 0.76\ (10)^{0.00910\gamma}$	2.1
P4706	0.08	$k = 0.16\ (10)^{0.0108\gamma}$	3.0
	0.7	$k = 0.082(10)^{0.0148\gamma}$	3.5
	1.6	$k = 0.46\ (10)^{0.00961\gamma}$	2.2
	4.0	$k = 0.29\ (10)^{0.0127\gamma}$	3.0
P4702	0.014	$k = 0.064(10)^{0.0146\gamma}$	3.4
	1.6	$k = 0.00345(10)^{0.0329\gamma}$	7.6
P4701	0.02	$k = 0.03\ (10)^{0.0180\gamma}$	4.2
	0.7	$k = 0.19\ (10)^{0.0127\gamma}$	3.0
	1.7	$k = 0.15\ (10)^{0.0158\gamma}$	3.6
	5.4	$k = 0.65\ (10)^{0.0125\gamma}$	2.9
P4714	0.02	$k = 0.25\ (10)^{0.0104\gamma}$	2.4
	2.0	$k = 1.47\ (10)^{0.00833\gamma}$	1.9
	4.5	$k = 1.28\ (10)^{0.0100\gamma}$	2.3
P4709	0.2	$k = 0.066(10)^{0.0143\gamma}$	3.3
	1.3	$k = 0.10\ (10)^{0.0153\gamma}$	3.6
	2.6	$k = 0.52\ (10)^{0.0114\gamma}$	2.7
	6.0	$k = 0.58\ (10)^{0.0120\gamma}$	2.8
	11.0	$k = 0.33\ (10)^{0.00605\gamma}$	1.4
P4604	0.2	$k = 0.14\ (10)^{0.0113\gamma}$	2.6
	4.0	$k = 0.76\ (10)^{0.0105\gamma}$	2.4
	11.8	$k = 0.41\ (10)^{0.0140\gamma}$	3.3
	14.0	$k = 1.45\ (10)^{0.00911\gamma}$	2.1
P4503	0.7	$k = 0.12\ (10)^{0.0115\gamma}$	2.7
	4.0	$k = 0.20\ (10)^{0.0136\gamma}$	3.2
	14.0	$k = 0.86\ (10)^{0.00872\gamma}$	2.0
P4502	0.5	$k = 0.11\ (10)^{0.0114\gamma}$	2.7
	2.0	$k = 0.11\ (10)^{0.0134\gamma}$	3.1
	5.2	$k = 0.90\ (10)^{0.00808\gamma}$	1.9
	11.2	$k = 1.20\ (10)^{0.00776\gamma}$	1.8
P4711	2.0	$k = 0.11\ (10)^{0.0143\gamma}$	3.4
	3.5	$k = 0.15\ (10)^{0.0145\gamma}$	3.4
	4.9	$k = 0.18\ (10)^{0.0146\gamma}$	3.4
	9.0	$k = 1.4\ \ (10)^{0.00863\gamma}$	2.0
P4713	2.7	$k = 0.048(10)^{0.0185\gamma}$	4.4
	6.6	$k = 0.34\ (10)^{0.0125\gamma}$	2.9
	9.5	$k = 0.49\ (10)^{0.0120\gamma}$	2.8

TABLE IX - CONDUCTIVITY-DENSITY RELATIONSHIPS, Continued

Mean Temperature 40°F.

Soil No.	Approximate Moisture Content	Equation of Curve For Conductivity*	Percentage Increase in k per Pound Increase in Density
P4713	13.0	$k = 0.58\ (10)^{0.0117\,\gamma}$	2.7
	18.0	$k = 1.7\ (10)^{0.00782\,\gamma}$	1.8
P4505	1.7	$k = 0.20\ (10)^{0.00937\,\gamma}$	2.2
	16.0	$k = 0.66\ (10)^{0.0100\,\gamma}$	2.3
	23.0	$k = 2.30\ (10)^{0.00513\,\gamma}$	1.2
P4602	2.3	$k = 0.18\ (10)^{0.0112\,\gamma}$	2.6
	7.5	$k = 0.19\ (10)^{0.0145\,\gamma}$	3.4
	15.3	$k = 0.31\ (10)^{0.0144\,\gamma}$	3.4
	21.0	$k = 0.72\ (10)^{0.0116\,\gamma}$	2.7
	24.0	$k = 0.64\ (10)^{0.0124\,\gamma}$	2.9
P4710	2.5	$k = 0.23\ (10)^{0.0109\,\gamma}$	2.6
	6.8	$k = 0.42\ (10)^{0.0107\,\gamma}$	2.5
P4710	12.4	$k = 0.58\ (10)^{0.0112\,\gamma}$	2.6
	18.0	$k = 0.80\ (10)^{0.0106\,\gamma}$	2.5
	25.0	$k = 0.73\ (10)^{0.0118\,\gamma}$	2.8
P4708	3.1	$k = 0.14\ (10)^{0.0137\,\gamma}$	3.2
	6.5	$k = 0.083(10)^{0.0183\,\gamma}$	4.3
	17.0	$k = 0.91\ (10)^{0.0102\,\gamma}$	2.4
	22.0	$k = 0.96\ (10)^{0.0103\,\gamma}$	2.4
	35.0	$k = 0.187(10)^{0.0206\,\gamma}$	4.9
P4707	10.0	$k = 0.238(10)^{0.0134\,\gamma}$	3.1
	110.0	$k = 0.358(10)^{0.0326\,\gamma}$	7.8
	175.0	$k = 0.724(10)^{0.0265\,\gamma}$	6.3
	280.0	$k = 1.70\ (10)^{0.0149\,\gamma}$	3.5

*k in Btu's per square foot per inch per hour per degree F.

γ is dry density in pounds per cubic foot.

TABLE X - CONDUCTIVITY-DENSITY RELATIONSHIPS

Mean Temperature 25°F.

Soil No.	Approximate Moisture Content	Equation of Curve For Conductivity*	Percentage Increase in k per Pound Increase in Density	Soil No.	Approximate Moisture Content	Equation of Curve For Conductivity*	Percentage Increase in k per Pound Increase in Density
P4601	0.2	$k = 0.098(10)^{0.0133\gamma}$	3.1	P4714	0.02	$k = 0.17\ (10)^{0.0121\gamma}$	2.8
	0.7	$k = 0.054(10)^{0.0158\gamma}$	3.7		1.9	$k = 1.0\ (10)^{0.00957\gamma}$	2.2
	1.9	$k = 0.14\ (10)^{0.0142\gamma}$	3.3	P4709	0.2	$k = 0.056(10)^{0.0149\gamma}$	3.5
	3.1	$k = 0.037(10)^{0.0195\gamma}$	4.6		1.2	$k = 0.065(10)^{0.0165\gamma}$	3.9
	3.9	$k = 0.082(10)^{0.0168\gamma}$	3.9		2.5	$k = 0.086(10)^{0.0171\gamma}$	4.0
P4703	0.03	$k = 0.12\ (10)^{0.0134\gamma}$	3.1		6.0	$k = 0.30\ (10)^{0.0139\gamma}$	3.2
	0.7	$k = 0.13\ (10)^{0.0154\gamma}$	3.6		11.0	$k = 0.86\ (10)^{0.0118\gamma}$	2.7
	2.0	$k = 0.17\ (10)^{0.0160\gamma}$	3.8	P4604	0.2	$k = 0.17\ (10)^{0.0105\gamma}$	2.4
	4.0	$k = 0.09\ (10)^{0.0195\gamma}$	4.6		4.0	$k = 0.23\ (10)^{0.00686\gamma}$	3.4
P4704	0.2	$k = 0.134(10)^{0.0114\gamma}$	2.7		11.0	$k = 3.30\ (10)^{0.00686\gamma}$	1.6
	1.0	$k = 0.14\ (10)^{0.0123\gamma}$	2.9		13.0	$k = 0.40\ (10)^{0.0153\gamma}$	3.6
	1.8	$k = 0.62\ (10)^{0.00703\gamma}$	1.6	P4503	0.7	$k = 0.10\ (10)^{0.0124\gamma}$	2.9
	3.8	$k = 0.42\ (10)^{0.00998\gamma}$	2.3		4.0	$k = 0.066(10)^{0.0212\gamma}$	5.0
P4705	0.07	$k = 0.27\ (10)^{0.00967\gamma}$	2.3		13.5	$k = 0.53\ (10)^{0.0112\gamma}$	2.6
	1.0	$k = 0.29\ (10)^{0.0108\gamma}$	2.5	P4502	0.5	$k = 0.094(10)^{0.0122\gamma}$	2.9
	2.0	$k = 0.32\ (10)^{0.0114\gamma}$	2.7		2.0	$k = 0.144(10)^{0.0122\gamma}$	2.9
	4.0	$k = 0.29\ (10)^{0.0124\gamma}$	2.9		5.2	$k = 0.76\ (10)^{0.00869\gamma}$	2.0
P4706	0.08	$k = 0.10\ (10)^{0.0126\gamma}$	2.9		11.2	$k = 0.61\ (10)^{0.0115\gamma}$	2.7
	0.7	$k = 0.078(10)^{0.0147\gamma}$	3.4	P4711	2.0	$k = 0.12\ (10)^{0.0168\gamma}$	3.9
	1.6	$k = 0.19\ (10)^{0.0123\gamma}$	2.9		3.5	$k = 0.10\ (10)^{0.0259\gamma}$	5.3
	4.0	$k = 0.083(10)^{0.0171\gamma}$	4.0		4.9	$k = 0.028(10)^{0.0210\gamma}$	5.0
P4702	0.014	$k = 0.053(10)^{0.0154\gamma}$	3.7		9.0	$k = 1.25\ (10)^{0.00945\gamma}$	2.2
	1.5	$k = 0.012(10)^{0.0236\gamma}$	5.6	P4713	2.7	$k = 0.04\ (10)^{0.0193\gamma}$	4.5
P4701	0.02	$k = 0.04\ (10)^{0.0166\gamma}$	3.9		6.5	$k = 0.19\ (10)^{0.0147\gamma}$	3.4
	0.7	$k = 0.226(10)^{0.0117\gamma}$	2.7		9.5	$k = 0.25\ (10)^{0.0143\gamma}$	3.3
	1.7	$k = 0.140(10)^{0.0146\gamma}$	3.4		3.0	$k = 0.44\ (10)^{0.0132\gamma}$	3.1
	5.0	$k = 0.064(10)^{0.0196\gamma}$	4.6		18.0	$k = 1.3\ (10)^{0.0101\gamma}$	2.3

TABLE X - CONDUCTIVITY-DENSITY RELATIONSHIPS, Continued

Mean Temperature 25°F.

Soil No.	Approximate Moisture Content	Equation of Curve For Conductivity*	Percentage Increase in k per Pound Increase in Density
P4505	1.7	$k = 0.17\ (10)^{0.0102\gamma}$	2.4
	6.0	$k = 1.02\ (10)^{0.00904\gamma}$	2.1
	23.0	$k = 1.00\ (10)^{0.0105\gamma}$	2.4
P4602	2.3	$k = 0.17\ (10)^{0.0116\gamma}$	2.7
	7.5	$k = 0.16\ (10)^{0.0153\gamma}$	3.6
	15.3	$k = 0.46\ (10)^{0.0137\gamma}$	3.2
	21.0	$k = 0.79\ (10)^{0.0125\gamma}$	2.9
	24.0	$k = 0.79\ (10)^{0.0130\gamma}$	3.0
P4710	2.4	$k = 0.25\ (10)^{0.0103\gamma}$	2.4
	6.8	$k = 0.57\ (10)^{0.00897\gamma}$	2.1
	12.3	$k = 0.37\ (10)^{0.0134\gamma}$	3.1

Soil No.	Approximate Moisture Content	Equation of Curve For Conductivity*	Percentage Increase in k per Pound Increase in Density
P4710	17.7	$k = 0.76\ (10)^{0.0118\gamma}$	2.7
	25.0	$k = 0.86\ (10)^{0.0124\gamma}$	2.9
P4708	3.1	$k = 0.130(10)^{0.0141\gamma}$	3.3
	6.5	$k = 0.075(10)^{0.0187\gamma}$	4.2
	17.0	$k = 0.53\ (10)^{0.0130\gamma}$	3.0
	22.0	$k = 0.42\ (10)^{0.0149\gamma}$	3.5
	34.0	$k = 0.68\ (10)^{0.0161\gamma}$	3.8
P4707	10.0	$k = 0.22\ (10)^{0.0149\gamma}$	3.5
	110.0	$k = 0.32\ (10)^{0.0420\gamma}$	10.2
	175.0	$k = 0.76\ (10)^{0.0413\gamma}$	10.0
	280.0	$k = 2.60\ (10)^{0.0269\gamma}$	6.4

*k in Btu's per square foot per inch per hour per degree F.

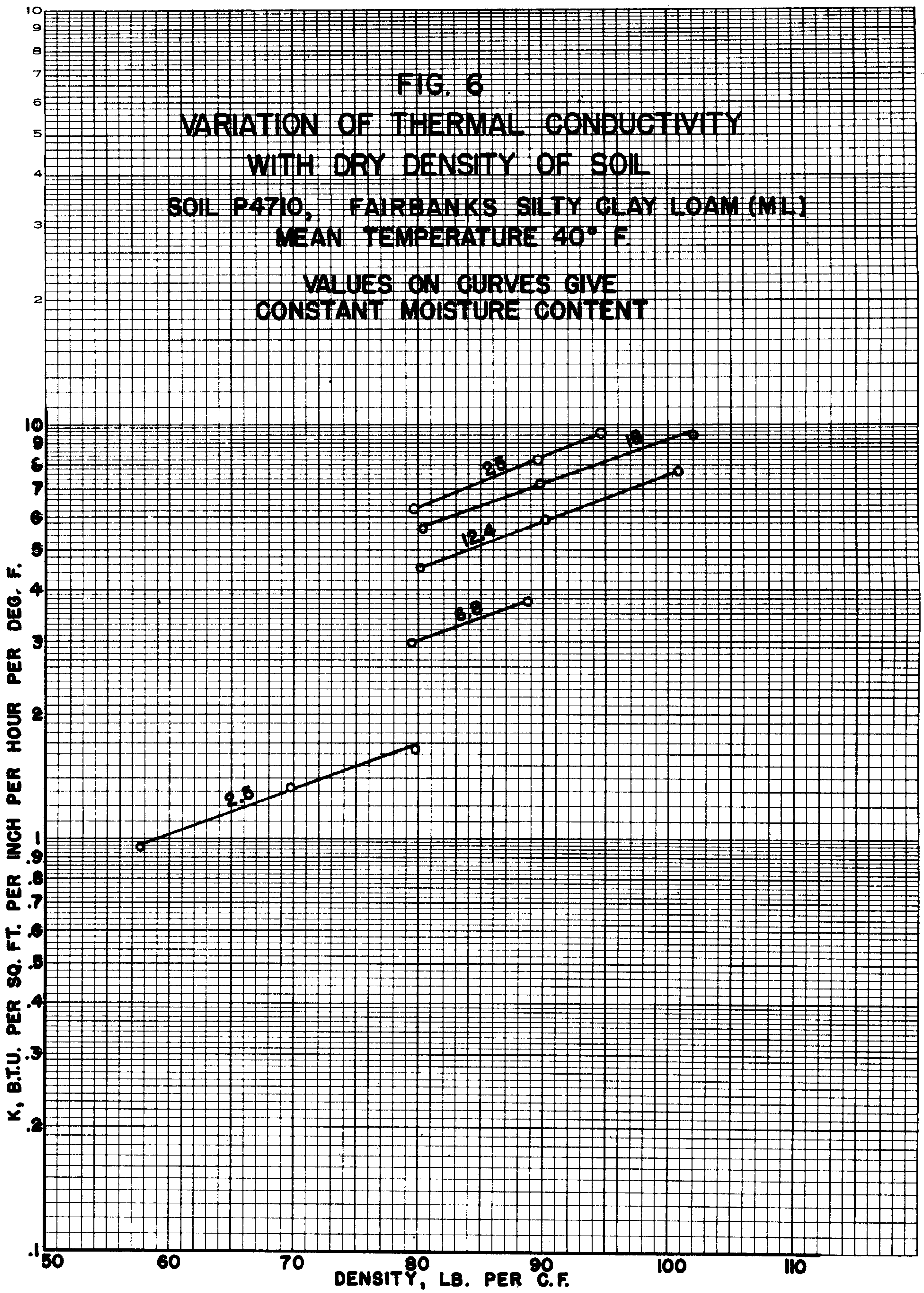
γ is dry density in pounds per cubic foot.

FIG. 6

VARIATION OF THERMAL CONDUCTIVITY WITH DRY DENSITY OF SOIL

SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 40° F.

VALUES ON CURVES GIVE CONSTANT MOISTURE CONTENT



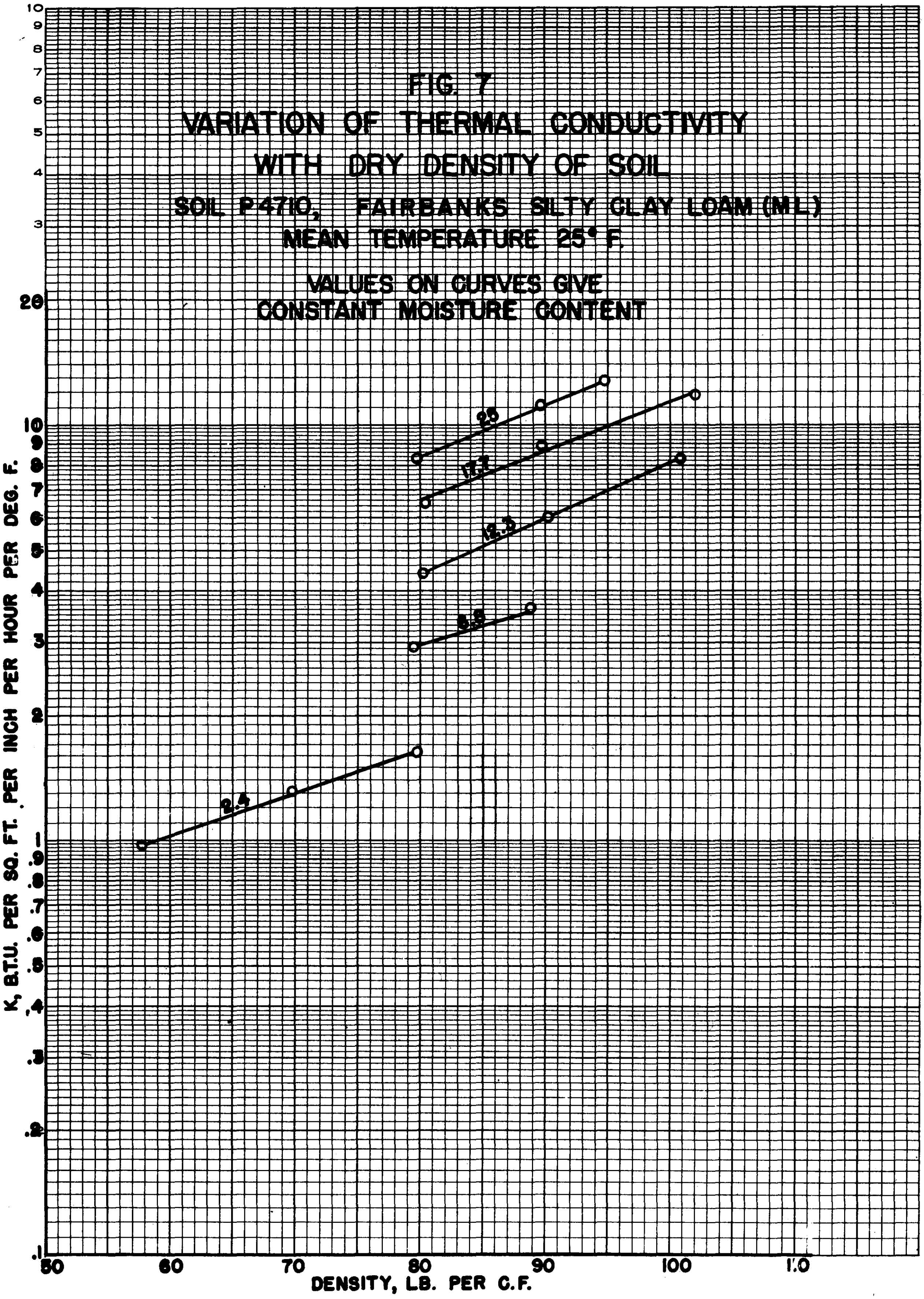


FIG. 7
VARIATION OF THERMAL CONDUCTIVITY WITH DRY DENSITY OF SOIL
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE CONSTANT MOISTURE CONTENT

No measurements were made of variations in density of the soil within the test cylinder. With the method of placement used (See Page 17) it is thought that the variations would be small.

Effect of Moisture Content. - The effect of moisture content upon the thermal conductivity of a soil is an important one, and this factor has been studied with many of the soils. Tests were normally made at several moisture contents varying from the air-dried condition, which was usually less than one per cent in the sands and 2 or 3 per cent in the fine grained soils, to several per cent more than the modified optimum moisture content. On the clay soil, P4708, for example, which has a modified optimum moisture content of 17.0 per cent, tests were made at 35 per cent moisture content. On the sand soils, tests were possible at moisture contents up to a maximum of 17 per cent. Tests on the crushed rock materials, the Ottawa sands, and the Chena River Gravel were made at moisture contents of about 4 per cent or less; consequently, the results on these soils are of somewhat limited value in the study of the effect of moisture content. Four sand soils and six heavier soils had tests at moisture content ranges of more than 10 per cent, and the study is based largely on these ten soils.

Conductivity values at a mean temperature just above freezing, 40 degrees, will first be considered. Figures 8 and 9 present the test results of one soil, P4709, Fairbanks Sand, in two different manners. The points for these curves have been obtained partially from the table of test data (Appendix I) but chiefly from the Density versus Conductivity curves given in Figure 61 for this soil. This soil has been selected as an example because tests were run upon it at three different densities at each of five different moisture contents.

Figure 8 is a plot of the conductivity values versus the moisture content on arithmetic graph paper. Each curve is for a constant dry density. For nearly all the soils, curved lines such as those shown were obtained for such plots.

Figure 9 is a plot of the same data, but the moisture content values are plotted to a logarithmic scale. Such plots ordinarily gave straight lines for that part of the data above a moisture content of approximately 1 or 2 per cent for the sands and above approximately 7 per cent in the silt or clay soils. The points at 2.6 per cent moisture are somewhat high for the lines drawn in Figure 9. In most instances, however, deviations of test data from such a straight line were small. Curves of this type for soils which were tested with a high moisture content range are shown in Figures 96 to 105, Appendix II. Similar curves for the crushed rocks and gravel are given in Figures 89 to 95, Appendix II.

Since this type of plot seems to fit the test points best, equations have been computed for the relationships shown in Figures 9 and 89 to 95, inclusive. The equations are of the form:

$$k = A \log (\text{moisture content}) + B$$

A and B being constants. B is equal to the k value at the intercept of the curve (or extended curve) at one per cent moisture, and A is equal to the difference between the k intercepts of the straight line at 10 and one per cent moisture content. The equations are given in Table XI, together with the moisture range to which they apply.

To gain an approximate idea of the effect of moisture content upon thermal conductivity, some average values may be cited. For four sands, P4709, P4604, P4503, and P4502, at a density of 110 pounds per cubic foot, the average k at 2.5 per cent moisture would be about 6.8; at 5 per cent, 8.9; and at 10 per cent, 11.2. For five of the soils of finer texture (P4713, P4505, P4602, P4710, and P4708) at a density of 100 pounds per cubic foot, k at 10 per cent moisture is approximately 6.7; and at 20 per cent, 9.5. Thus

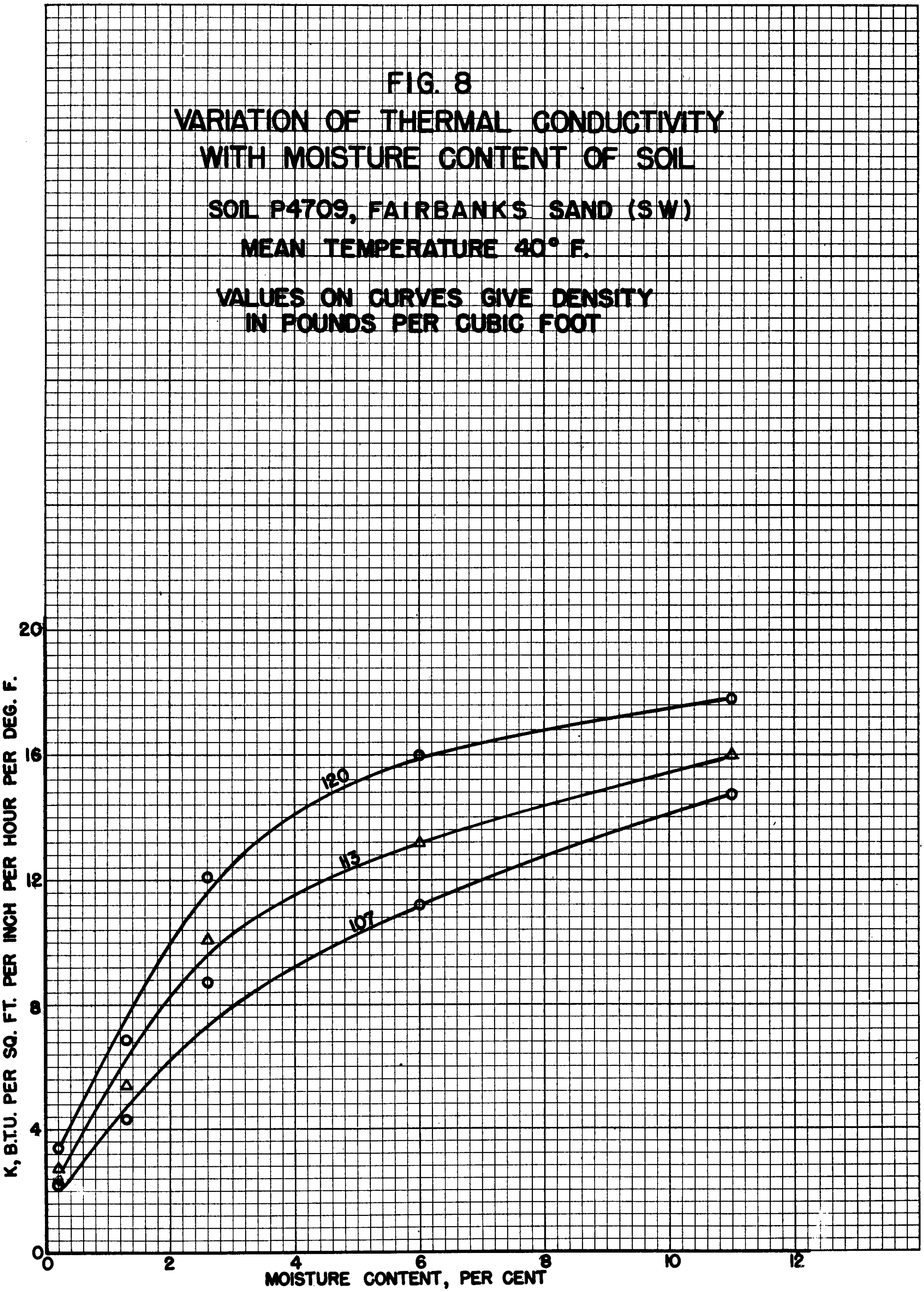


FIG. 8
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
113
107
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
0
2
4
6
8
10
12
MOISTURE CONTENT, PER CENT

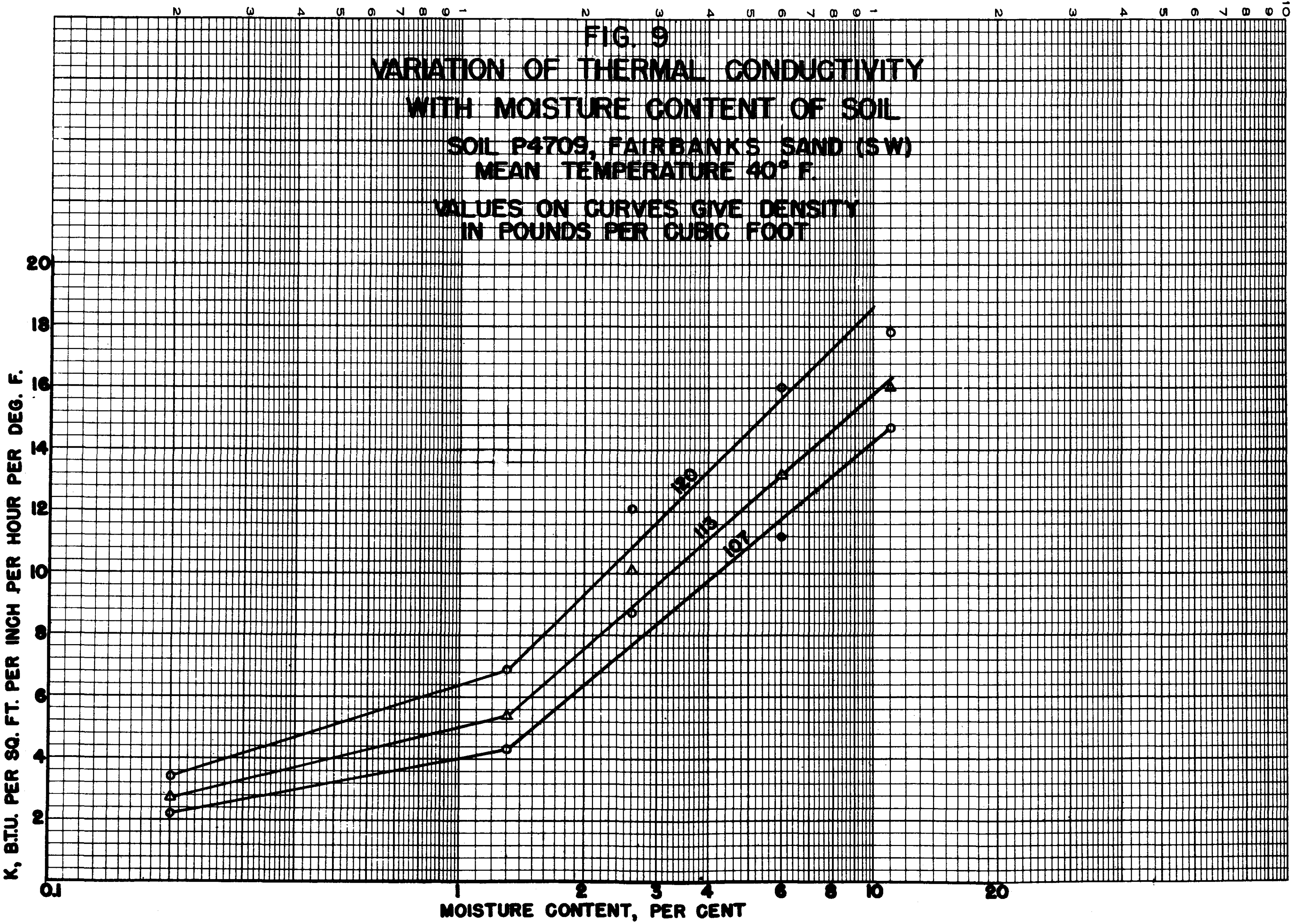


FIG. 9
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

TABLE XI - CONDUCTIVITY-MOISTURE CONTENT RELATIONSHIPS

Mean Temperature 40°F.

Soil No.	Approximate Density Lbs./Cu.Ft.	Equation for Conductivity*	Moisture Content Range in Which Applicable
P4601	115	k = 9.8 log.(w) + 5.2	0.7 to 3.0
	120	k = 12.1 log.(w) + 6.3	0.7 to 3.0
P4703	103	k = 9.0 log.(w) + 7.0	0.7 to 4.0
	120	k = 15.7 log.(w) + 12.3	0.7 to 4.0
P4704	103	k = 4.1 log.(w) + 2.7	1.0 to 4.0
	120	k = 6.7 log.(w) + 3.0	1.8 to 4.0
P4705	103	k = 3.8 log.(w) + 4.2	1.0 to 4.0
	120	k = 4.9 log.(w) + 6.3	1.0 to 4.0
P4706	103	k = 4.5 log.(w) + 3.4	0.7 to 4.0
	120	k = 8.4 log.(w) + 4.7	1.6 to 4.0
P4701	98	k = 11.4 log.(w) + 2.6	1.7 to 4.0
	108	k = 13.6 log.(w) + 4.4	1.7 to 5.4
P4714	98	k = 11.4 log.(w) + 5.5	1.0 to 4.4
	108	k = 12.4 log.(w) + 7.7	0.7 to 4.6
P4709	107	k = 11.3 log.(w) + 3.0	1.3 to 11.0
	113	k = 11.8 log.(w) + 4.0	1.3 to 11.0
	120	k = 13.3 log.(w) + 5.3	1.3 to 11.0
P4604	105	k = 5.7 log.(w) + 6.2	0.2 to 14.0
	112	k = 7.0 log.(w) + 7.5	0.2 to 14.0
P4503	100	k = 3.7 log.(w) + 2.2	0.7 to 14.0
	106	k = 4.4 log.(w) + 2.7	0.7 to 16.0
P4502	103	k = 7.0 log.(w) + 0.6	2.0 to 11.0
	110	k = 7.5 log.(w) + 1.0	2.0 to 14.0
P4711	120	k = 14.5 log.(w) + 0.9	2.0 to 14.0
	130	k = 18.5 log.(w) + 1.2	3.5 to 9.0
P4713	100	k = 10.0 log.(w) - 2.3	6.6 to 18.0
	110	k = 8.7 log.(w) + 1.4	2.7 to 18.0
P4505	97	k = 6.2 log.(w) - 1.3	6.6 to 25.0
P4602	84	k = 7.9 log.(w) - 3.7	7.5 to 24.0
	94	k = 10.0 log.(w) - 4.4	7.5 to 25.0
	102	k = 11.4 log.(w) - 4.3	9.0 to 21.0
P4710	80	k = 6.4 log.(w) - 2.3	6.8 to 37.0
	90	k = 7.7 log.(w) - 2.6	6.8 to 30.0
	100	k = 9.4 log.(w) - 2.8	12.0 to 18.0
P4708	93	k = 8.8 log.(w) - 4.3	6.4 to 35.0
	84	k = 9.3 log.(w) - 3.5	6.4 to 22.0

*k in Btu's per square foot per inch per hour per degree F.
w is moisture content in per cent of dry weight.

doubling the moisture content within the range cited increases the conductivity by approximately 30 or 40 per cent. At higher moisture contents, the percentage increase would be less.

The moisture contents in all graphs discussed thus far have all been in terms of percentage of dry weight of soil, the common method of such expression. Use of another means, the percentage of saturation, is helpful in making further deductions from the moisture content-thermal conductivity graphs. The percentage of saturation is defined as the percentage of the void space of a soil occupied by water. It is dependent upon the density of the soil, the specific gravity of the soil particles, and the moisture content.

The curves for Soil P4709 in Figure 9 for the moisture contents above 1.3 per cent have been redrawn in Figure 10 with the moisture expressed in terms of percentage of saturation. In Figure 10, the straight line curves have been extended (dash-lines) to reach 100 per cent saturation. Similar curves for other soils upon which tests were made at relatively high moisture contents are given in Figures 106 to 114 in Appendix II.

A study of Figures 10 and 106 to 114, inclusive, indicates an important item. At equal percentages of saturation, conductivity values decrease for a decrease in dry density. If the extrapolated portions of the curves are accepted, this is also the case at 100 per cent saturation. It should be noted that the moisture contents at 100 per cent saturation, if expressed in terms of a per cent of the dry weight, are greater for the lower densities. For example, in Figure 10, 15.2 per cent moisture by weight saturates the soil at a density of 120 pounds per cubic foot; 18.5 per cent at 113 pounds; and 21.6 per cent at 107 pounds. Thus, in spite of the increased moisture contents by weight, the thermal conductivity values become less. This fact is of importance in the estimate of thermal conductivities for soils with extremely low densities and in a saturated condition. Because of operating difficulties, thermal conductivity tests could not be made on soils in such conditions.

The relationship between moisture content and thermal conductivity is different for frozen soils than for unfrozen. In Figure 11, the conductivity values for Soil P4709, Fairbanks Sand, are plotted in a manner similar to Figure 9 but for a mean temperature of 25 degrees. The difference between the curves of this figure and those of Figure 9 can be immediately noticed. As explained on Page 35, the conductivity values at high moisture contents are greater for the frozen soil than for the unfrozen; whereas for low moisture contents there is only a small difference. Consequently, the curves in Figure 11 are not straight as they were for the results at 40 degrees. Curves for other soils gave similar results.

In Figure 12, the 25-degree conductivity values are plotted versus moisture content to arithmetic scales. The approximation of a straight line is apparent. This relationship seemed to hold true for nearly all soils, and such curves are presented in Figures 115 to 124, Appendix II. Curves for those soils on which tests were made at moisture contents up to approximately 4 per cent are not included. The equations for the curves are of the form

$$k = A + B \text{ (moisture content)}$$

A and B being constants. Table XII lists the equations of the various soils, the densities, and the moisture ranges to which the equations apply.

The following averages are indicative of the rate of increase in conductivity for an increase in moisture content, the density remaining constant. For a density of 100 pounds per cubic foot, the increase in conductivity for a 1 per cent increase in moisture averages approximately 1 for the sands and approximately 0.5 for the soils of heavier texture.

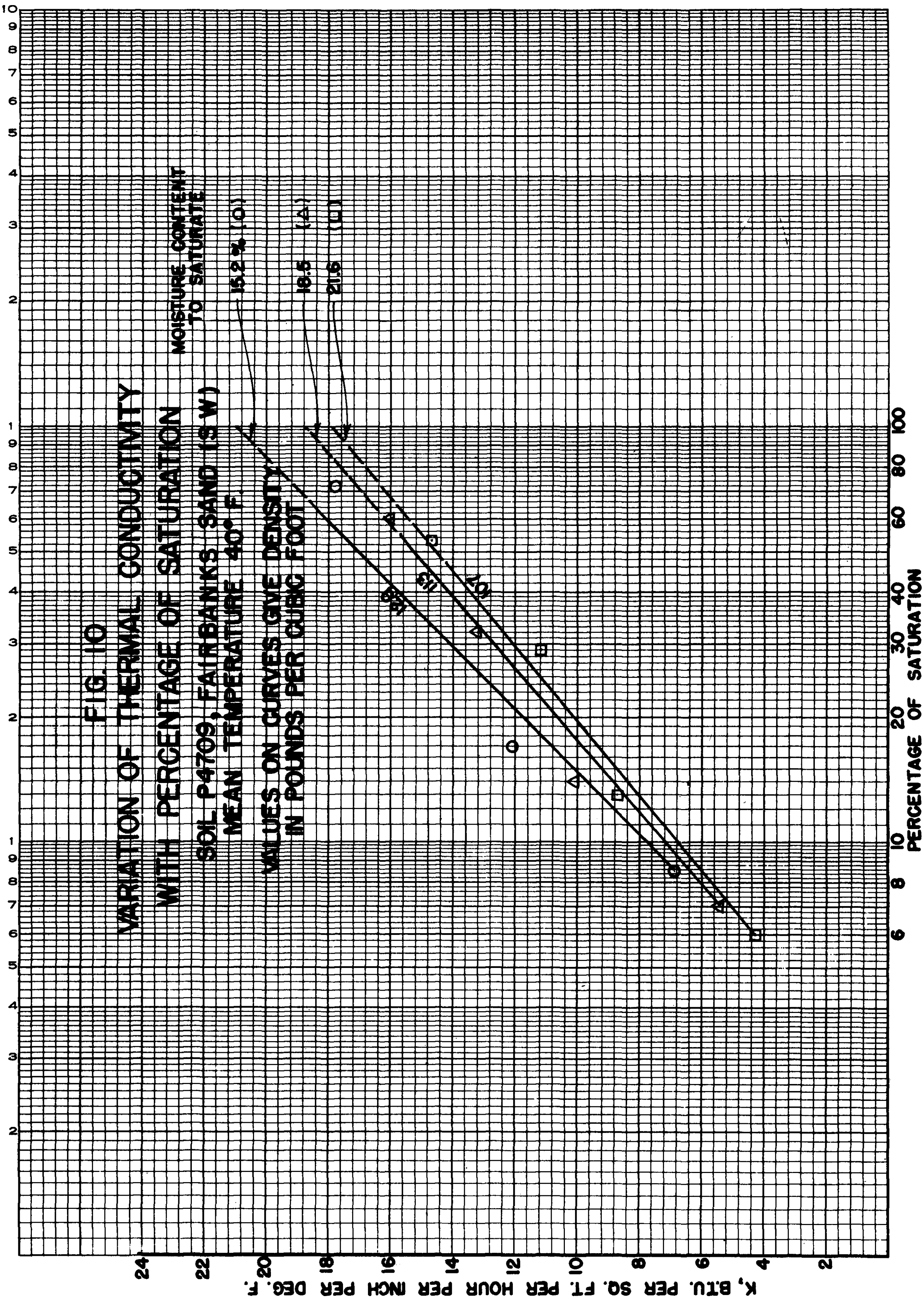


FIG. 10
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4709, FAIRBANKS SAND (S W)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
15.2% (○)
18.5 (△)
21.6 (□)
118
113
107
K, B.T.U. PER SQ. FT. PER HOUR PER INCH PER DEG. F.
PERCENTAGE OF SATURATION

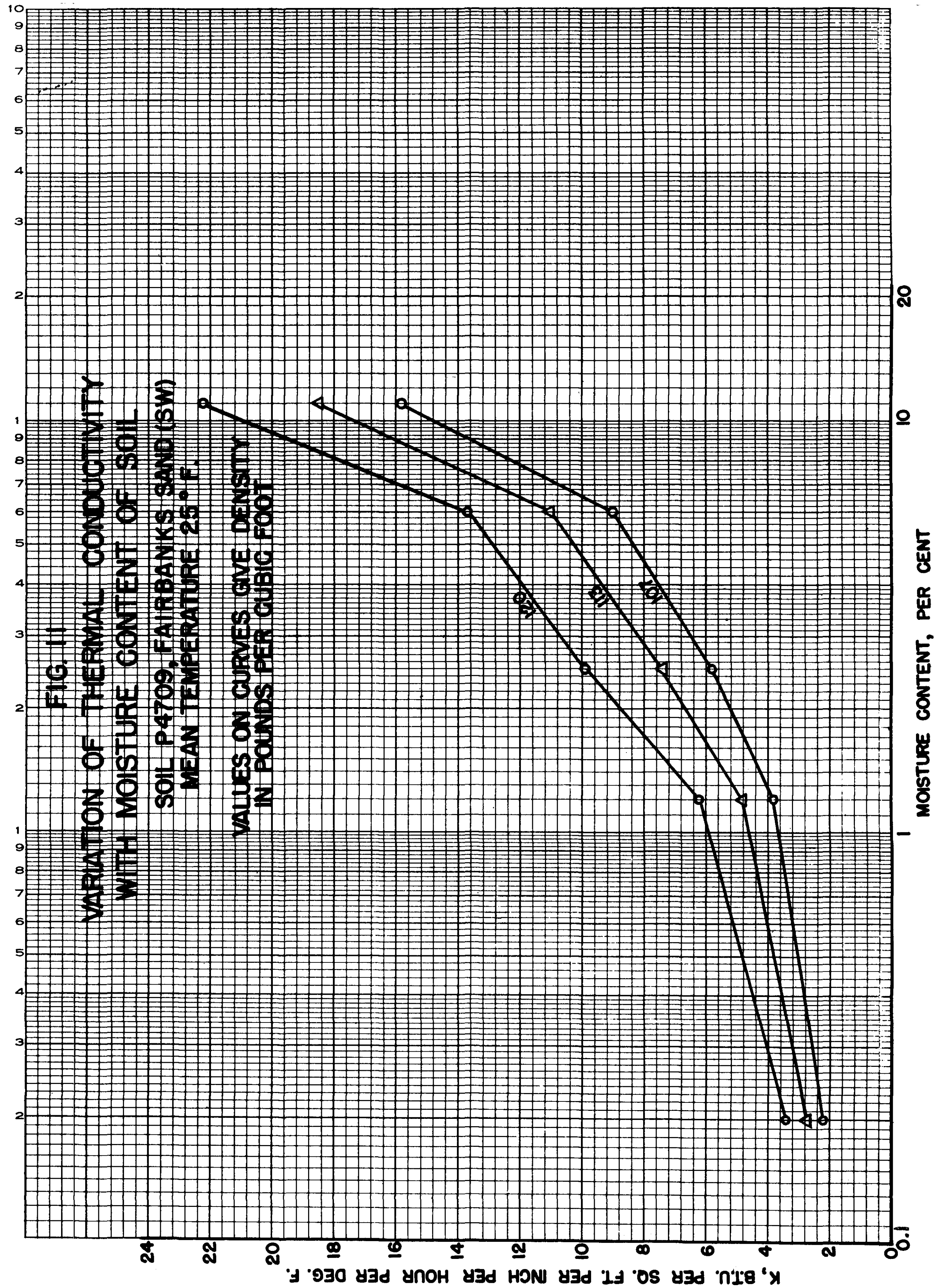


FIG. 11
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
113
101
MOISTURE CONTENT, PER CENT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.

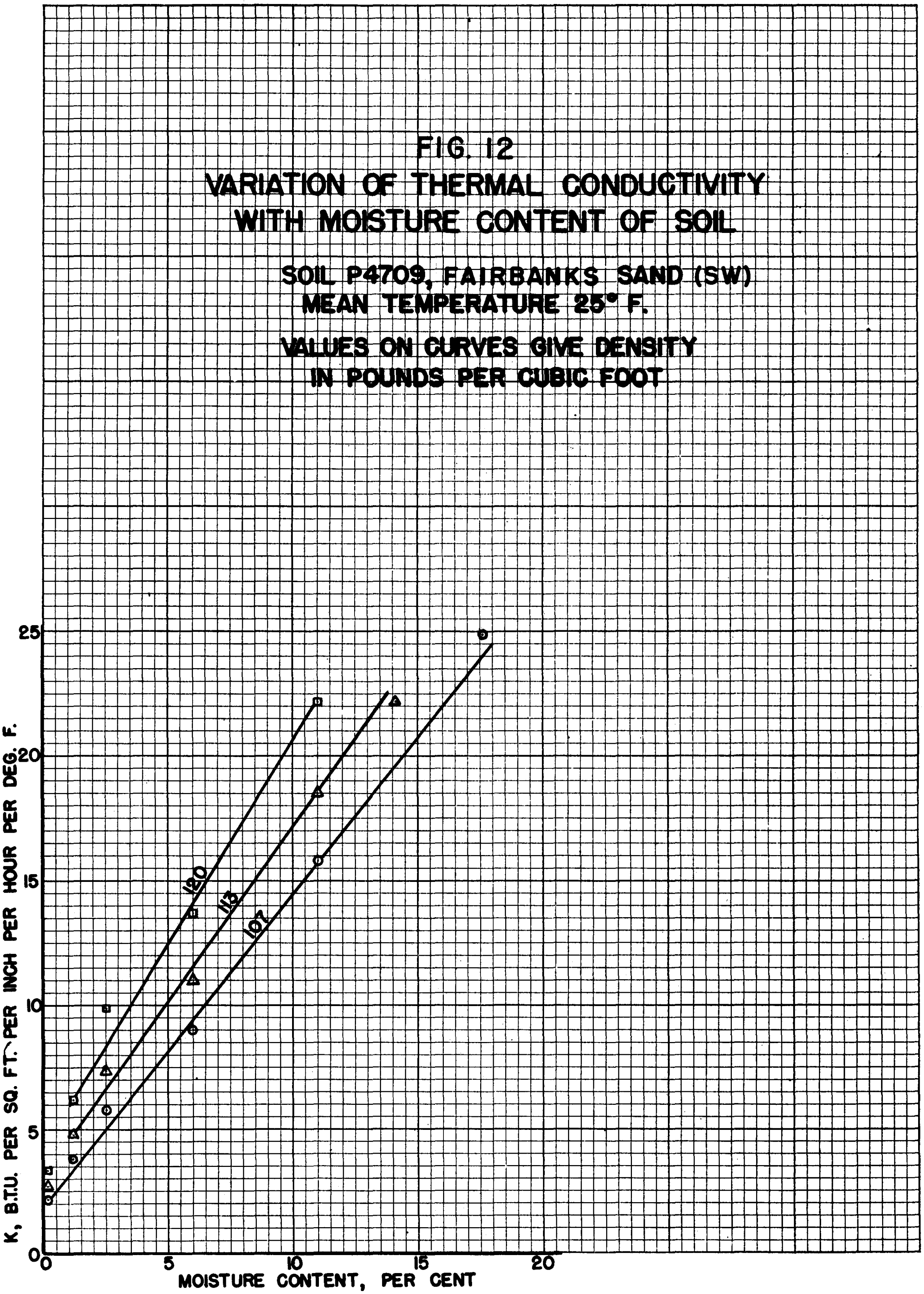


FIG. 12
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
113
107
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT
0
5
10
15
20
25

TABLE XII - CONDUCTIVITY-MOISTURE CONTENT RELATIONSHIPS

Mean Temperature 25°F.

Soil No.	Approximate Density Lb./Cu. Ft.	Equation for Conductivity*	Moisture Content Range in Which Applicable
P4709	107	$k = 1.8 + 1.27\ (w)$	0 to 18
	113	$k = 3.2 + 1.39\ (w)$	1 to 14
	120	$k = 4.2 + 1.64\ (w)$	1 to 11
P4604	105	$k = 1.8 + 1.15\ (w)$	0 to 18
	112	$k = 5.0 + 1.15\ (w)$	4 to 13
P4503	100	$k = 1.3 + 0.46\ (w)$	1 to 22
	106	$k = 1.5 + 0.61\ (w)$	1 to 16
P4502	103	$k = 1.2 + 0.72\ (w)$	0.5 to 13
	110	$k = 1.7 + 0.81\ (w)$	0.5 to 14
P4711	120	$k = 2.1 + 1.56\ (w)$	2 to 13
	130	$k = 5.7 + 1.76\ (w)$	3.5 to 9
P4713	100	$k = 1.65 + 0.63(w)$	3 to 18
	110	$k = 2.9 + 0.75\ (w)$	3 to 18
P4505	90	$k = 0.7 + 0.36\ (w)$	2 to 23
	97	$k = 0.9 + 0.42\ (w)$	2 to 23
P4602	83	$k = 0.6 + 0.39\ (w)$	2.5 to 34
	90	$k = 0.1 + 0.54\ (w)$	7.5 to 24
	102	$k = 1.1 + 0.65\ (w)$	9 to 21
P4710	80	$k = 0.6 + 0.34\ (w)$	2.5 to 37
	90	$k = 0.7 + 0.43\ (w)$	7 to 30
	100	$k = 0.9 + 0.56\ (w)$	12.5 to 18
P4708	84	$k = 0.4 + 0.39\ (w)$	3 to 34
	93	$k = 1.1 + 0.44\ (w)$	6.5 to 22
P4707	15	$k = 2.2 + 0.039(w)$	110 to 280
	21	$k = 2.7 + 0.046(w)$	110 to 280

*k in Btu's per square foot per inch per hour per degree F.
w is moisture content in per cent of dry weight.

If moisture contents are expressed as a percentage of saturation, curves such as those of Figure 13 are obtained. In this instance, since ice is approximately 9 per cent greater in volume than an equal weight of water, the moisture contents necessary for saturation are less than those shown in Figure 10. The curves are extrapolated to reach 100 per cent saturation (dash lines in Figure 13). Similar curves for other soils are plotted in Figures 125 to 133, Appendix II.

Effect of Saturation. - Tests in the field indicated that many soils existed at very high moisture contents, in a nearly saturated or saturated condition. It was desirable, therefore, to determine conductivities under such conditions. As has previously been mentioned, however, tests at high moisture contents caused certain operating difficulties and in some instances actually fouled the wiring system. A number of tests were made on

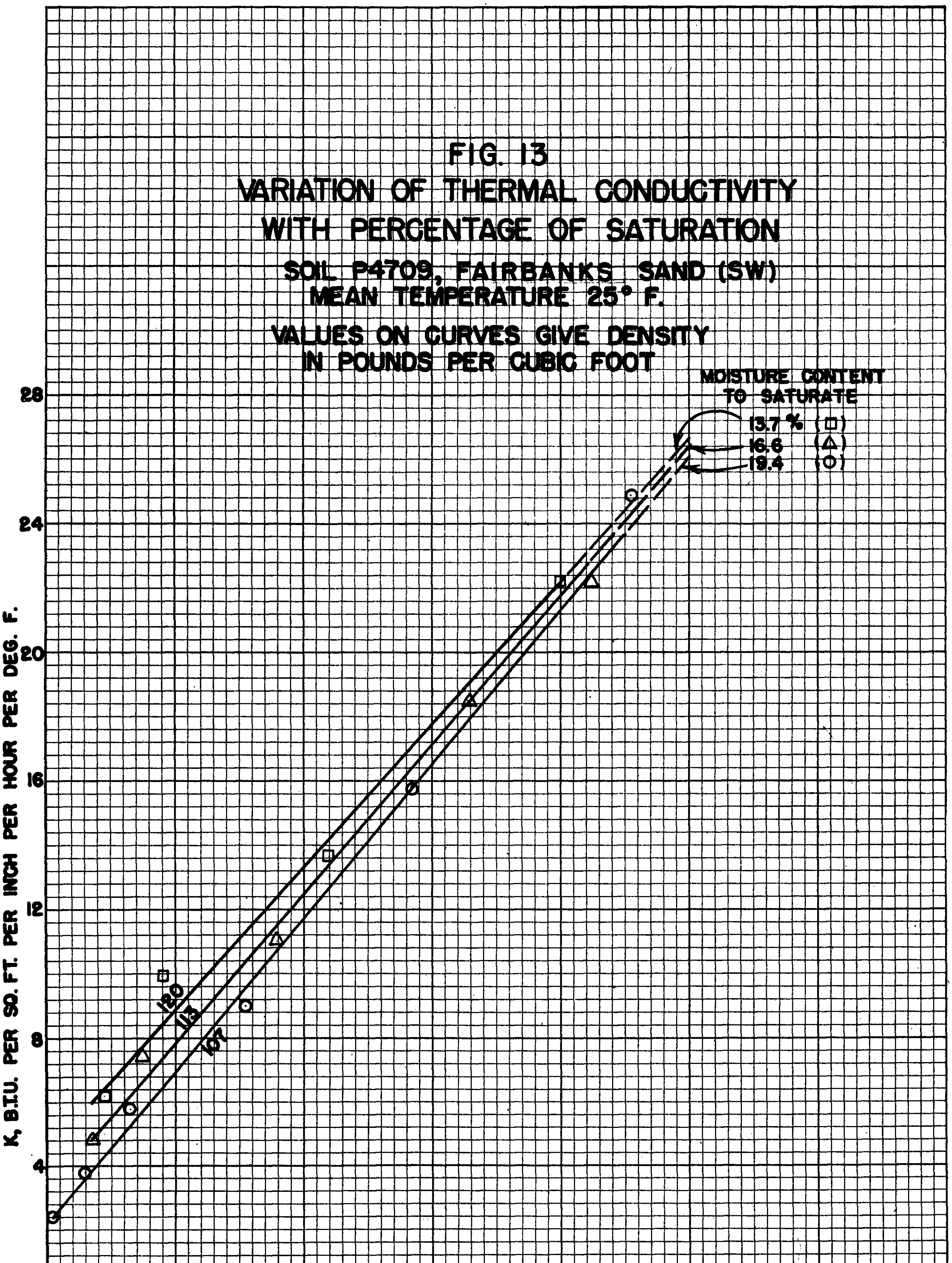


FIG. 13
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
13.7 % (□)
16.6 (△)
19.4 (○)
120
113
107
0
4
8
12
16
20
24
28
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
20
40
60
80
100
PERCENTAGE OF SATURATION

saturated or nearly saturated soils in a frozen condition. The completed tests appear to be adequate to make reliable predictions of conductivities of saturated soils.

The study for saturated soils at a temperature above freezing, i.e., 40 degrees, may be made by means of the thermal conductivity - per cent of saturation curves, Figures 10 and 106 to 114. The dash portions of these curves are extrapolations, but a study of such curves as Figures 110 and 112, in which tests were made at between 80 and 100 per cent saturation, indicate such extrapolations are sound. The graphs for nearly all soils are remarkably similar in that any decrease in density results in a decrease in conductivity for a condition of 100 per cent saturation. It should be recalled that a decrease in density corresponds to an increase in moisture content, expressed as a per cent of the dry weight of the soil, for saturation. The thermal conductivity of water is about 4*. Thus, the decrease in conductivity for decreasing densities appears to be entirely rational. One might expect the values to approach 4 as a minimum value for extremely low densities.

A general relationship of the decrease in conductivity of saturated soils with a decrease in density is shown in Figure 14. In this graph, the conductivity values for 100 per cent saturation have been plotted versus their corresponding densities for eight soils; the data are from Figures 10 and 106 to 114. Two soils have been omitted, the Northway Sands, P4502 and P4503. These soils gave unique results for sands. (This point will be considered later.) The data for the eight different soils very definitely show the decrease in conductivity for a density decrease. It would seem that soils at even lower densities than those in Figure 14 and in a saturated condition would have conductivity values of 8 or less.

Thermal conductivities of saturated, frozen soils may be studied by means of Figures 13 and 125 to 133. The data of these figures are for a mean temperature of 25 degrees F. Again, many of the saturated values must be extrapolated, but numerous tests made on nearly saturated soils indicate such curves are reasonable.

A plot of the conductivity values of frozen soils at 100 per cent saturation is shown in Figure 15. This figure indicates a rather distinct division of soils. For seven of them, including all those with high silt or clay contents, the conductivity values for all densities for which curves have been drawn (17 values) are within the range 11 to 17 with an average of about 14. The two Northway sands, P4502 and P4503, and the Ramsey Clay Loam, P4713 which contains 46 per cent silt and clay, are within this group. The other three soils all have conductivity values between 21 and 27. These soils are all sandy, and, excluding the two Northway sands, are the three sandiest soils in the group of ten being considered.

Ice has a conductivity value of about 15**. Thus, one might expect that the conductivity of saturated frozen soils would not deviate much from this value as the density decreases. The fact that 17 values for seven different soils gave an average conductivity of 14 would seem to be significant. It would seem that as densities became even less than those shown in Figure 15 the conductivity for frozen saturated soils would not change markedly. The results on Soil P4602, Fairbanks Silt Loam, indicate this tendency quite well. Tests at densities of 102, 94, 83, and 77 pounds per cubic foot all have conductivity values between 14.0 and 16.8 for saturation.

Sandy soils which are predominately quartz have high conductivities when saturated and frozen. Figures 13, 125 and 128 all show values of 21 or greater for 100 per cent saturation. Although it would seem reasonable to assume that with a decrease in density the conductivity values would decrease and approach 15 for saturated sands, the curves

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*Kent-Mechanical Engineers' Handbook, Power, 11th Edition, p. 3-28.

**Kent-Mechanical Engineers' Handbook, Power, 11th Edition, p. 3-29.

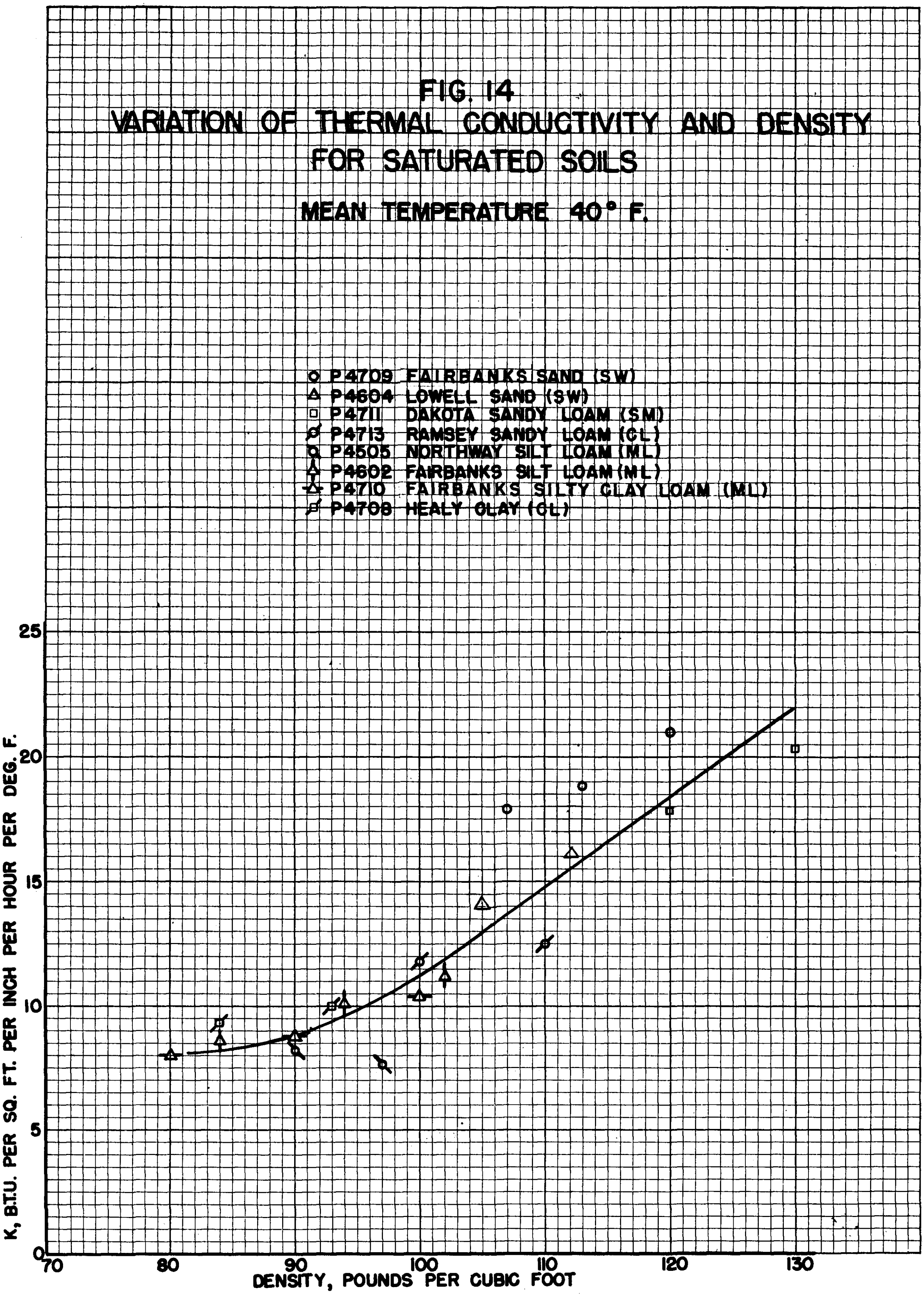


FIG. 14
VARIATION OF THERMAL CONDUCTIVITY AND DENSITY
FOR SATURATED SOILS
MEAN TEMPERATURE 40° F.
P4709 FAIRBANKS SAND (SW)
P4604 LOWELL SAND (SW)
P4711 DAKOTA SANDY LOAM (SM)
P4713 RAMSEY SANDY LOAM (CL)
P4505 NORTHWAY SILT LOAM (ML)
P4602 FAIRBANKS SILT LOAM (ML)
P4710 FAIRBANKS SILTY CLAY LOAM (ML)
P4708 HEALY CLAY (CL)
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, POUNDS PER CUBIC FOOT
0
5
10
15
20
25
70
80
90
100
110
120
130

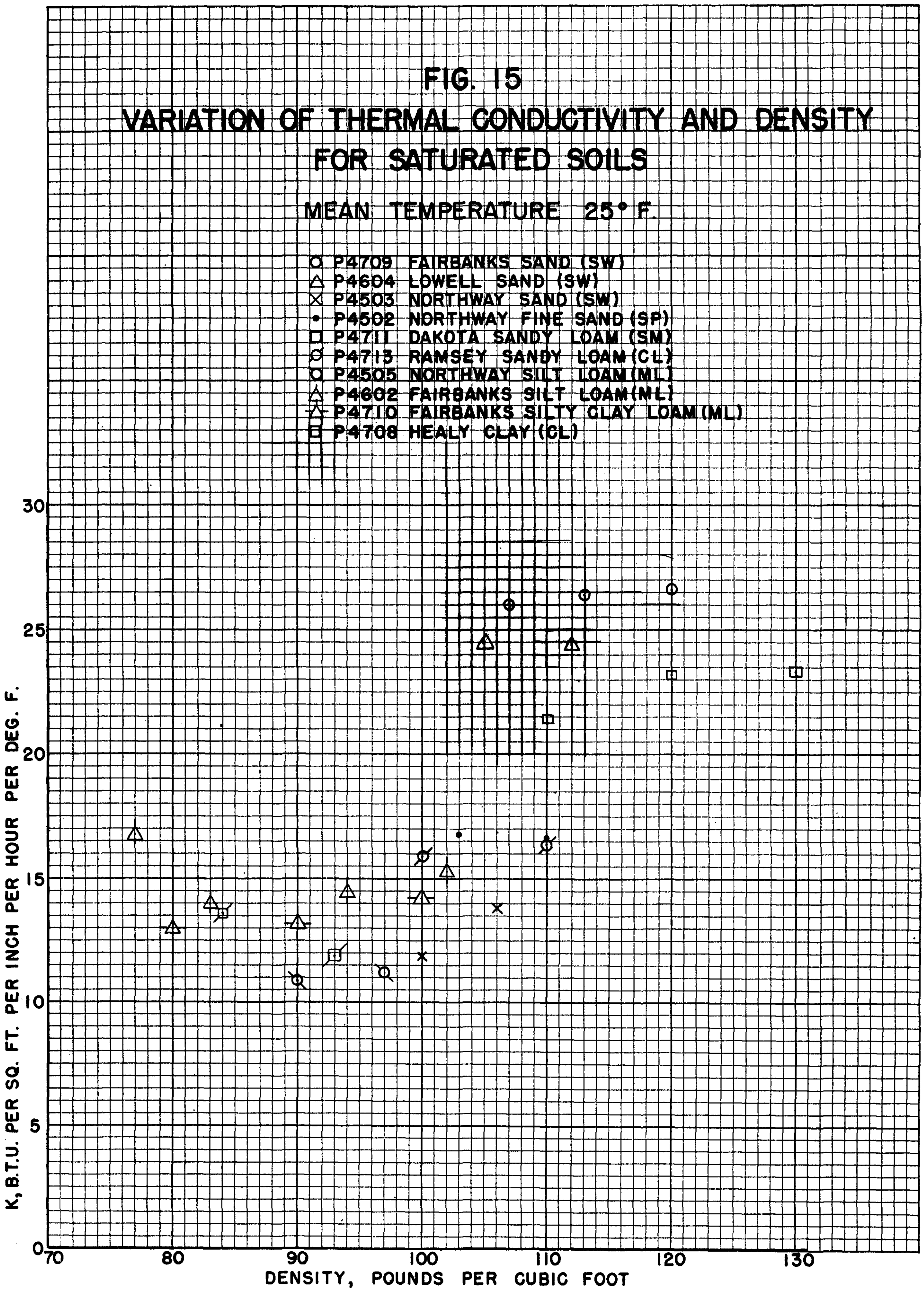


FIG. 15
VARIATION OF THERMAL CONDUCTIVITY AND DENSITY FOR SATURATED SOILS
MEAN TEMPERATURE 25° F.
P4709 FAIRBANKS SAND (SW)
P4604 LOWELL SAND (SW)
P4503 NORTHWAY SAND (SW)
P4502 NORTHWAY FINE SAND (SP)
P4711 DAKOTA SANDY LOAM (SM)
P4713 RAMSEY SANDY LOAM (CL)
P4505 NORTHWAY SILT LOAM (ML)
P4602 FAIRBANKS SILT LOAM (ML)
P4710 FAIRBANKS SILTY CLAY LOAM (ML)
P4708 HEALY CLAY (CL)
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
20
25
30
70
80
90
100
110
120
130
DENSITY, POUNDS PER CUBIC FOOT

indicate only slight reductions in the k value for a lowering of density. It would appear that in order to obtain conductivity values of 15 or slightly higher the densities of such sand soils would have to be quite low, and such soils do not ordinarily occur at low densities.

Effect of Texture. - The soils tested in this program were of a wide textural range, varying from a rather coarse gravel and several crushed rocks with about 50 per cent retained on a No. 20 sieve down through several sands and two sandy loams to such fine grained soils as two silt loams, a silty clay loam, and a clay. This wide range permits a study of the effect of soil texture upon conductivity. Such a comparison should preferably be made for tests conducted under similar conditions of moisture content and density. As might be expected, however, the densities at which the sandy soils could be placed for test purposes were relatively greater than those to which the silt and clay soils could be compacted; also, the range of moisture contents at which the sands could be tested was less than that for the fine grained soils. Consequently, it is impossible to select any density-moisture content combination at which tests were made on all soils.

In Table XIII, the soils have been listed in approximate order of magnitude of thermal conductivities from greatest to least with the thermal conductivity values at a mean temperature of 40 degrees, for eight different density-moisture content conditions. The moisture contents range from 4 to 20 per cent and the densities from 90 to 120 pounds per cubic foot. The conductivities are also given for the condition of maximum density and modified optimum moisture content. Some of the conductivity values in this table have been determined by extrapolation and are consequently approximate. In all instances, values have been approximated to the closest one-half unit, if possible. Blank spaces in the table indicate that the density or moisture content or both are such that no tests were possible for that condition or sufficiently close to it so that a reasonable extrapolation of the data could be made. For example, at 4 per cent moisture content, it was not possible to compact the silt loams to a density as great as 100 pounds per cubic foot; consequently, no conductivity value is given for the silt loams in this condition. The test results at 10 per cent moisture content and 110 pounds per cubic foot density facilitate the textural comparison greatly in that some of both the coarse and the fine grained soils are included.

The order of soils in Table XIII permits some generalizations. For one thing, three quartz materials head the table followed by three siliceous sands. This immediately suggests the probability of mineral composition being of importance. This factor is considered in the next section. The sand content of soils also appears to be important. Sand soils, such as Fairbanks Sand (P4709), and Lowell Sand (P4604), are high in the list of conductivities. Dakota Sandy Loam (P4711), which contains 69 per cent of the sand fraction and Ramsey Sandy Loam (P4713) with 54 per cent sand are midway in the table. The clay (P4708), the silty clay loam (P4710) and the two silt loams, (P4505 and P4602), all with less than 22 per cent of sand fraction, have the lowest conductivity values. The two Northway sands (P4502 and P4503) are seemingly out of order in this consideration of sand content; the low conductivity of these two materials may be due to their distinctive mineral composition, as will be pointed out subsequently. In general, however, it would appear that at equal moisture contents and densities, thermal conductivities vary with texture, being greater for coarse grained, or sandy materials, and lower for the finer grained soils such as silt loams or clays. It must be realized in considering the data of Table XIII that the moisture contents and densities at which soils normally exist in the field also vary with texture. Sandy soils assume relatively high densities and low moisture contents while silty soils and clays have low densities and high moisture contents. Thus, the thermal conductivities of the soils in a natural position are not necessarily in the same order as the listing of Table XIII.

TABLE XIII - TABULATION OF THERMAL CONDUCTIVITY (k) VALUES OF SOILS IN APPROXIMATE ORDER OF DECREASING VALUES

Mean Temperature - 40 Degrees Fahrenheit

Soil No.	Soil Designation	Corps of Engineers Class	Moisture Content %	4	4	4	10	10	20	20	Mod. Opt.[1]
			Density. Lb./Cu.Ft.	100	110	120	90	110	90	100	Maximum
P4714	Fine Crushed Quartz	SP		12.0	16.0						
P4703	Crushed Quartz	SW		11.5	16.0	22.03					
P4701	Graded Ottawa Sand	SP		10.0	14.0						
P4709	Fairbanks Sand	SW		8.5±	10.5	13.5		15.0			19.0
P4604	Lowell Sand	SW		8.5	11.0			13.5			17.5
P4601	Chena River Gravel	GP			9.±	13.0					
P4705	Crushed Feldspar	SW		6.0	7.5	9.5					
P4706	Crushed Granite	SW		5.5	7.5	10.0					
P4711	Dakota Sandy Loam	SM			6.5	9.5		13 ±			19.0
P4704	Crushed Trap Rock	SM		5.0	6.0	7.0					
P4713	Ramsey Sandy Loam	CL		4.5	6.5			10.0			16.5
P4502	Northway Fine Sand	SP		4.5	5.5			8.5			9.5
P4503	Northway Sand	SW		4.5	6.0			7.5±			8.5
P4708	Healy Clay	CL		4 ±			5.5	9.0±	8.0	10.0	11.5
P4602	Fairbanks Silt Loam	ML					5.0	9.0±	7.5	10.0	12.0
P4710	Fairbanks Silty Clay Loam	ML					5.0	9.0±	7.5	9.5	9.5
P4505	Northway Silt Loam	ML					4.0±	7.0±	6.0±	7.0±	9.0

1. See Table I for values of Modified Optimum Moisture Content and Maximum Density for each soil. Soil P4702, 20-30 Ottawa Sand is not included in the table since no tests were made at moisture contents of more than 2 per cent.

If the conductivity values at the modified optimum moisture content and maximum density are considered, the values are in a somewhat different order. This is due both to the difference in moisture content and the variation in density. One of the sandy loams, (P4711), for example, has a greater conductivity value than the Lowell Sand (P4604). This sandy loam had a maximum density of 137 pounds per cubic foot whereas the Lowell Sand had 119.

It might also be noted that although the Chena River Gravel (P4601) has conductivity values approximately equal to the Fairbanks Sand (P4709) and Lowell Sand (P4604), it can be compacted to higher densities than either of these soils, resulting in the attainment of high conductivity at relatively low moisture content. At a moisture content of 4 per cent and a density of 129 pounds per cubic foot, for example, a conductivity of over 16 is obtained on the Chena River Gravel. (See Appendix I, page 97).

In discussing the effect of texture on thermal conductivity, the results of tests on four different quartz soils are of interest and significance. The four materials are P4701, Graded Ottawa Sand, a rounded sand which grades between the No. 30 and No. 100 sieve sizes; P4702, 20-30 Ottawa Sand, also a rounded material with all particles of a size between the 20 and 30 mesh sieves; P4703, a crushed angular quartz grading from 1/4 inch to dust; and P4714, a crushed quartz approximately duplicating the grading of Soil P4701. Soils P4701 and P4702 are from the same source and differ only in grading; while Soils P4703 and P4714 are also from a common source and differ only in grading. All four soils are nearly pure quartz. The test results for these four soils at a density of 98 pounds per cubic foot are shown in Figure 16. The values for Soil P4703 were obtained by extrapolation. (See Figure 54). The curves show that the two crushed materials, Soils P4703 and P4714, have quite similar conductivities in spite of their differences in grading. The same is true for the other two materials, which have rounded particles but are of different gradings.

The results for tests at a density of 108 pounds per cubic foot are shown in Figure 17. The results on Soil P4702, 20-30 Ottawa Sand, at 1.6 per cent moisture content, appear to be out of order on this graph. The maintenance of uniform moisture conditions in a clean sand such as this was practically impossible, and this factor may have influenced the results. Otherwise, this figure also indicates some similarity between results for the two crushed materials.

Thus, the results on the four quartz soils show that differences of grading within the sand sizes of a given material (to the extent of difference in these samples) do not cause any appreciable differences in thermal conductivity.

The test data on the four quartz soils show a marked difference in the conductivities of the two crushed samples and the two with rounded particles. The former have conductivity values in general from 20 to 50 per cent greater than the latter. This difference would seem to be due either to the type of contact between the particles or to the character of the quartz.

Effect of Mineral Composition. - To determine the variations in thermal conductivity of some common soil constituents, tests were made on four materials which were:

Soil No.	Designation	Source
P4703	Crushed Quartz	Keystone, South Dakota
P4704	Crushed Trap Rock	Dresser Junction, Wisc.
P4705	Crushed Potash Feldspar	Keystone, South Dakota
P4706	Crushed Granite	St. Cloud, Minnesota

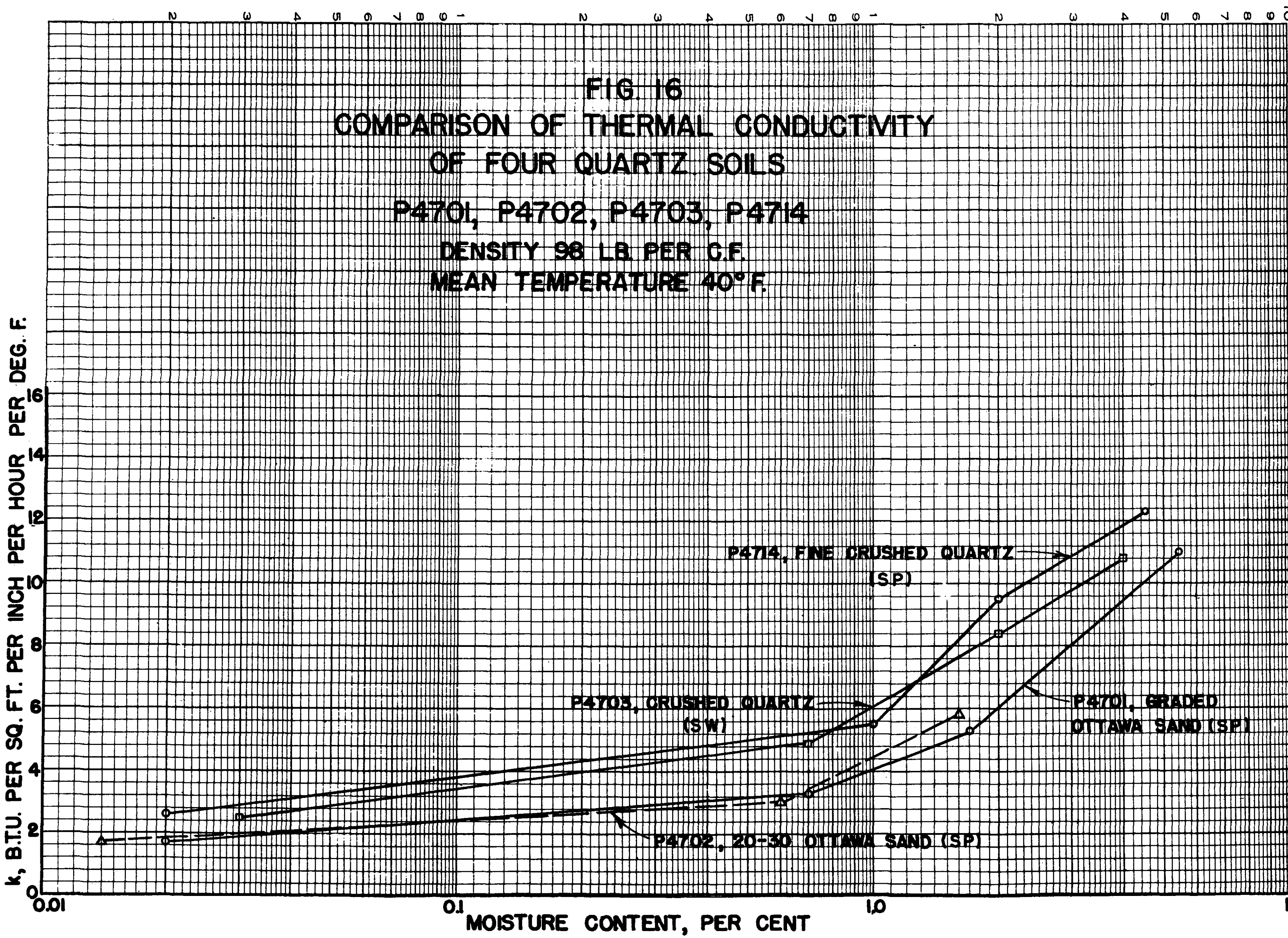


FIG. 16
COMPARISON OF THERMAL CONDUCTIVITY
OF FOUR QUARTZ SOILS
P4701, P4702, P4703, P4714
DENSITY 98 LB. PER C.F.
MEAN TEMPERATURE 40° F.

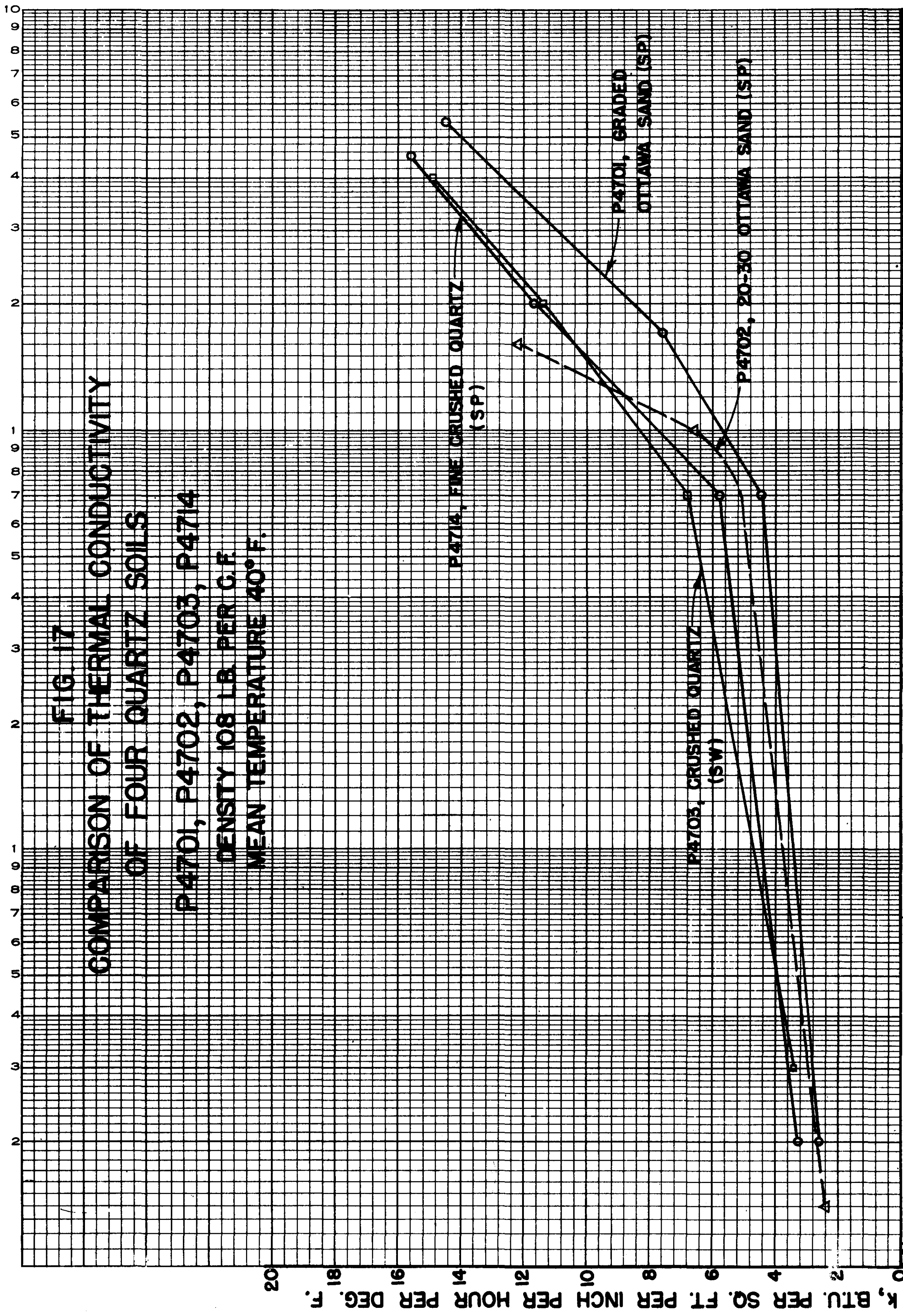


FIG. 17
COMPARISON OF THERMAL CONDUCTIVITY
OF FOUR QUARTZ SOILS
P4701, P4702, P4703, P4714
DENSITY 108 LB. PER C.F.
MEAN TEMPERATURE 40° F.
P4714, FINE CRUSHED QUARTZ
(SP)
P4701, GRADED
OTTAWA SAND (SP)
P4702, 20-30 OTTAWA SAND (SP)
P4703, CRUSHED QUARTZ
(SW)
0.01
0.1
1.0
10
MOISTURE CONTENT, PER CENT
2
4
6
8
10
12
14
16
18
20
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.

All four of these materials are crushed products. An attempt was made to prepare them so that approximately similar gradings would be obtained. The gradings are presented in Table I and for quicker comparison are plotted in Figure 18. The amounts of dust, or material passing the No. 270 sieve, vary from 4.2 to 10.0 per cent. The gradings were as close as could be obtained without extensive screening and combination of fractions.

Tests were made on all four materials at two densities, about 103 and 120 pounds per cubic foot. This represents about the minimum that could be obtained by just pouring the material into the container and the maximum that could be obtained by ramming. Four different moisture contents were used, varying from air-dry (about 0.03 to 0.2 per cent) to 4 per cent. The conductivity-moisture content curves are shown for the four materials at 103 pounds per cubic foot in Figure 19 and at 120 pounds per cubic foot in Figure 20. The results indicate a marked difference in the conductivities of the four materials, particularly between the quartz and the three other materials. The order of thermal conductivities from least to greatest is trap rock, granite, feldspar, and quartz. The granite is slightly greater than the feldspar for a moisture content of 4 per cent moisture, and a density of 120 pounds per cubic foot, but is otherwise lower. The approximate ratios of magnitude of thermal conductivities, taking the values at 1 per cent moisture content and taking trap rock at 1.0 are: trap rock 1.0; granite, 1.3; feldspar, 1.4; and quartz, 2.5.

The extreme difference in conductivity between trap rock and quartz is in accord with reports of tests on the solid materials. A number of conductivity values are given in "Handbook of Physical Constants" published by the Geological Society of America, January, 1942. The conductivity of quartz crystals is dependent upon the direction of the axis. Values at 32 degrees Fahrenheit vary from approximately 50 to 85. Tests on a variety of basalts, trap rock, and gabbro vary from 11 to 17 and average about 14. Thus, the difference which exists in the conductivities of the broken masses are reasonable.

On the basis of the mineral composition of the soils tested (Table II), the soils may be divided into fairly distinct groups. These are: (1) soils in which the quartz content is high; (2) soils which have a high basic igneous rock content with such minerals as plagioclase feldspar, pyroxene, amphibole, and olivine; (3) soils whose mineral composition is intermediate between acid and basic igneous rock; and (4) soils with an appreciable quantity of kaolinite and other clay minerals. The soils and their mineralogical data from Table II are rearranged into these four groups in Table XIV.

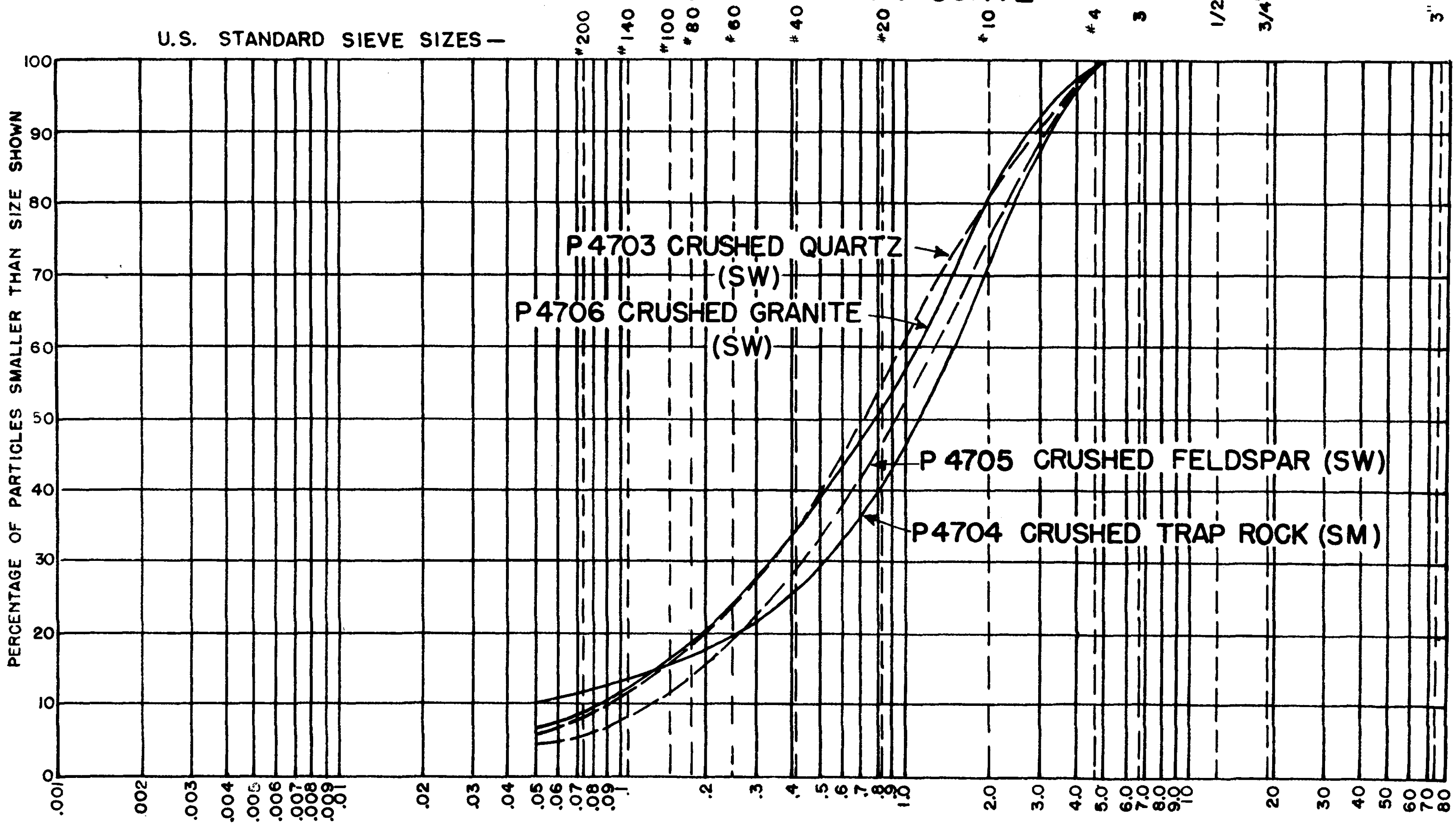
The first group includes nine soils which are all granular in nature. The two sandy loams, P4711 and P4713, are the soils having the finest texture in this group. These soils are characterized by high contents of quartz, felsite, and orthoclase feldspar. Quartz and orthoclase feldspar are indicative of acidic rocks. Felsite is not a mineral but a rock whose chief constituents are quartz and orthoclase feldspar. The soils have relatively small quantities of plagioclase feldspar, pyroxene, amphibole, olivine, and basic igneous rock fragments.

The second group of soils in Table XIV, which includes only two soils, consists of the two Northway sands. These soils are characterized by relatively high percentages of plagioclase feldspar, pyroxene, amphibole and olivine, which are minerals and of basic igneous rock grains which contain these minerals.

The third group consists of three crushed rock materials. They are characterized by low quartz content and high sodium content in the feldspars. The andesine feldspar of Soil P4704 is a component of rocks which are near the dividing line between acid and basic rocks.

The fourth group includes four soils of fine texture which have from 25 to 55 per cent of clay minerals. Two of the soils, P4602, Fairbanks Silt Loam, and P4710, Fairbanks

GRAIN SIZE ACCUMULATION CURVE



TOTAL CLAY-less than .005 COLLOIDS-less than .001	SILT .005 -.05	SAND .05 - 2.0	GRAVEL 2.00+

FIGURE 18

GRADING OF FOUR CRUSHED ROCK MATERIALS

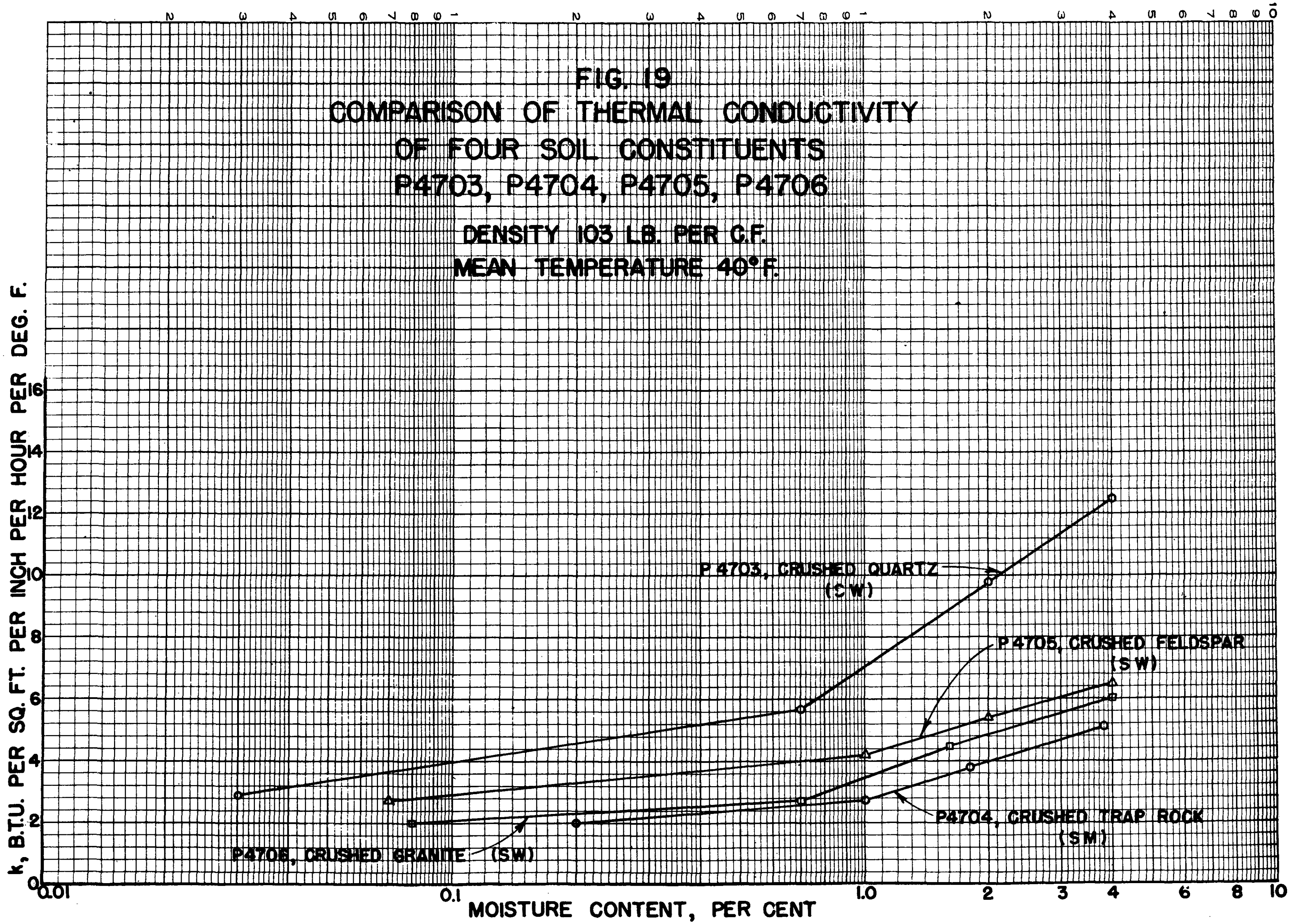


FIG. 19
COMPARISON OF THERMAL CONDUCTIVITY
OF FOUR SOIL CONSTITUENTS
P4703, P4704, P4705, P4706

DENSITY 103 LB. PER C.F.
MEAN TEMPERATURE 40°F.

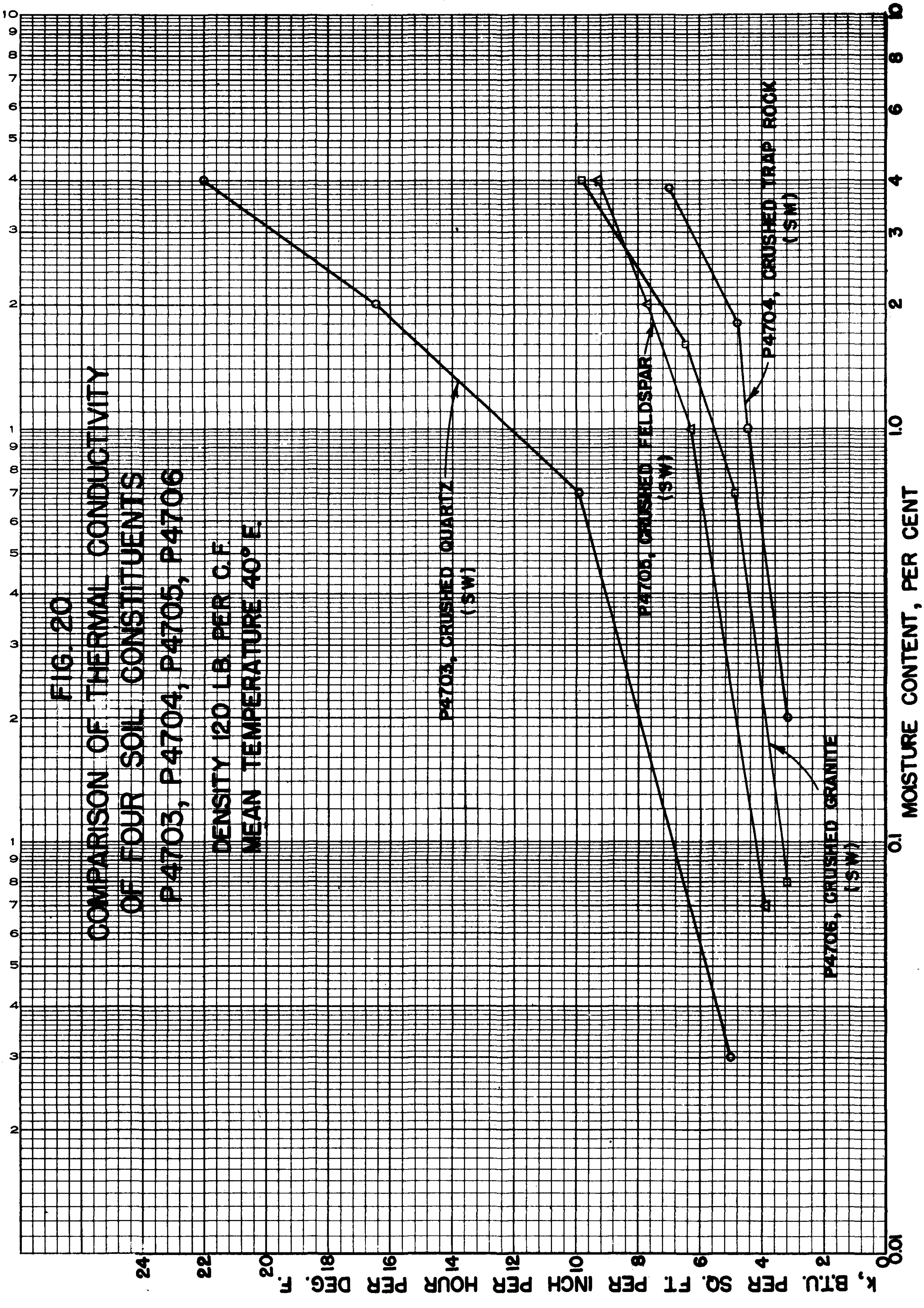


FIG. 20
COMPARISON OF THERMAL CONDUCTIVITY
OF FOUR SOIL CONSTITUENTS
P4703, P4704, P4705, P4706
DENSITY 120 LB. PER C.F.
MEAN TEMPERATURE 40° F.
P4703, CRUSHED QUARTZ (SW)
P4705, CRUSHED FELDSPAR (SW)
P4704, CRUSHED TRAP ROCK (SM)
P4706, CRUSHED GRANITE (SW)
MOISTURE CONTENT, PER CENT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0.01
0.1
1.0
10
0
2
4
6
8
10
12
14
16
18
20
22
24

TABLE XIV - GROUPING OF SOILS ON BASIS OF MINERAL AND ROCK COMPOSITION
(Percentage by Weight)

Soil No.	Soil Designation	Corps of Engineers Class	QUARTZ By Petrogr. Exam.	QUARTZ By X-Ray Analysis	Ortho-clase Feld-spar	Fel-site	Plagio-clase Feld-spar	Pyroxene, Amphibole, and Olivine	Basic Igne-ous Rock	Kaolinite, Clay Minerals, and Clay Coated Minerals	Hema-tite & Magne-tite	Mica	Coal	Others
GROUP I[1]														
P4702	20-30 Ottawa Sand	SP	99+[2]											
P4701	Graded Ottawa Sand	SP	99+[2]											
P4703	Crushed Quartz	SW	95+[3]											
P4714	Fine Crushed Quartz	SP	95+[3]											
P4604	Lowell Sand	SW	72.2		20.5			3.0				1.3		3.0
P4709	Fairbanks Sand	SW	59.4		3.6	5.0	6.3	8.0	10.0		2.5	0.1		5.1
P4711	Dakota Sandy Loam	SM	59.1		12.9		1.0	12.1		12.4				2.5
P4713	Ramsey Sandy Loam	CL	51.3		11.8		5.6	12.6		15.9				2.8
P4601	Chena River Gravel	GP	43.1		11.6		12.9	27.0				2.1		3.3
GROUP II														
P4503	Northway Sand	SW	7.5			11.5	9.0	7.5	51.0					13.5
P4502	Northway Fine Sand	SP	12.0			7.0	18.0	12.0	40.0					11.0
GROUP III														
P4704	Crushed Trap Rock	SM	3.0		10.0		50.0[4]	34.0			2.0			1.0
P4705	Crushed Feldspar	SW	15.0		55.0		30.0							
P4706	Crushed Granite	SW	20.0		30.0		40.0							10.0
GROUP IV														
P4708	Healy Clay	CL	22.5							55.0			22.0	0.5
P4710	Fairbanks Silty Clay Loam	ML	4.6	59.5				2.2		28.9	1.6	3.2		
P4602	Fairbanks Silt Loam	ML	13.3	40.3						28.3		18.1		
P4505	Northway Silt Loam	ML	1.5				31.5	19.5	4.5	27.5	10.0			5.5

1. For definition of groups, see Page 64.
2. By visual inspection; impurities less than 1 per cent.
3. By visual inspection; impurities less than 5 per cent.
4. Andesine feldspar.

Silty Clay Loam, also have a large percentage of quartz; whereas another, P4505, Northway Silt Loam, has a high percentage of the basic rock minerals.

The significance of this mineralogical grouping of soils may be obtained by a study of Table XIII in which the soils were listed in an approximate order of thermal conductivities. The first six soils in this tabulation, which are those with the highest conductivities, are all within the mineralogical group of high quartz content. The second and third groups have low quartz content and a relatively high percentage of plagioclase feldspar and basic igneous rock fragments. When considered together as a single group, they have markedly lower conductivities than the quartz group. The two natural sands, P4502, Northway Fine Sand, and P4503, Northway Sand, have conductivity values of approximately half those of the three natural granular materials in the quartz group: P4709, Fairbanks Sand, P4604, Lowell Sand, and P4601, Chena River Gravel. The two natural sandy loams in the quartz group, P4711 and P4713 also have greater conductivities than the Northway Sands.

The four fine grained soils, or those which contain 25 per cent or more of clay minerals, occupy the positions of lowest conductivity in Table XIII. It may be significant that, of these four, the one with the lowest conductivity is also the one with the lowest quartz content and the largest quantities of plagioclase feldspar, pyroxene, amphibole, and olivine, which are constituents of basic igneous rock.

It may be concluded from this study that the thermal conductivity of granular soils is affected by mineral composition. Sands with a high quartz content tend to have a high thermal conductivity as compared to sands which have a high basic rock content composed of such minerals as plagioclase feldspar and pyroxene. Fine textured soils with appreciable quantities of kaolinite or other clay minerals have low conductivities. These statements are for conditions of equal moisture contents and densities. It is again noted that fine textured soils, if tested at moisture contents comparable to those at which they exist in their natural position, would have relatively higher thermal conductivity values.

Specific Heat.

Effect of Temperature. - Specific heat tests were made at three mean temperatures on five soils and at four on another. All of these tests show an increase in specific heat with an increase in temperature. The relationship has been approximated as a straight line for all of the soils. The curve for one of the soils is shown in Figure 21. Curves for the other five soils are shown in Figures 134 to 138, Appendix II. In Figure 22, the curves for all six soils have been reproduced without the individual tests points. The curves are quite similar. The average variation in specific heat is from 0.19 at 140 degrees to 0.16 at 0 degrees, or approximately a decrease of 11 per cent for a 100 degree Fahrenheit drop in temperature.

Effect of Moisture Content. - The study of the effect of moisture content was made with just one soil, P4701, Graded Ottawa Sand. This study introduced some difficulties not encountered in tests on dry soils. For one thing, it was difficult to pour the damp soils out of the dippers into the calorimeter. Several weighings were required to check the moisture content of the samples.

Tests were run by several different methods, but the results of all will be considered collectively. The specific heat test results of the moist soils, together with certain additional calculations, are shown in Table XV. The first column of specific heat values presented are those of the soil-water mixture. No corrections have been applied for heat of wetting, since the soils had already been wetted before being poured into the calorimeter.

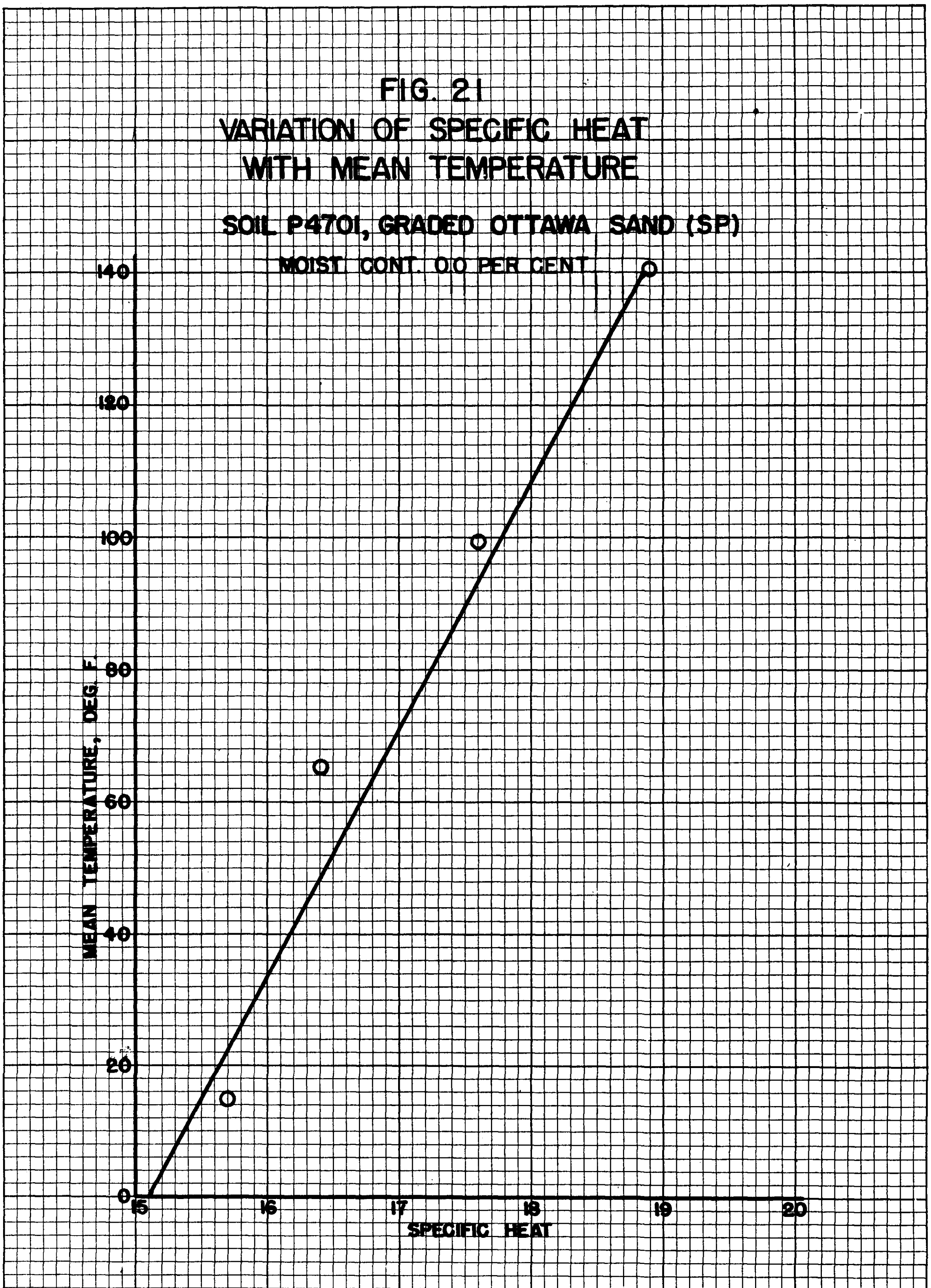


FIG. 21
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
SOIL P4701, GRADED OTTAWA SAND (SP)
MOIST. CONT. 0.0 PER CENT
MEAN TEMPERATURE, DEG. F.
140
120
100
80
60
40
20
0
15
16
17
18
19
20
SPECIFIC HEAT

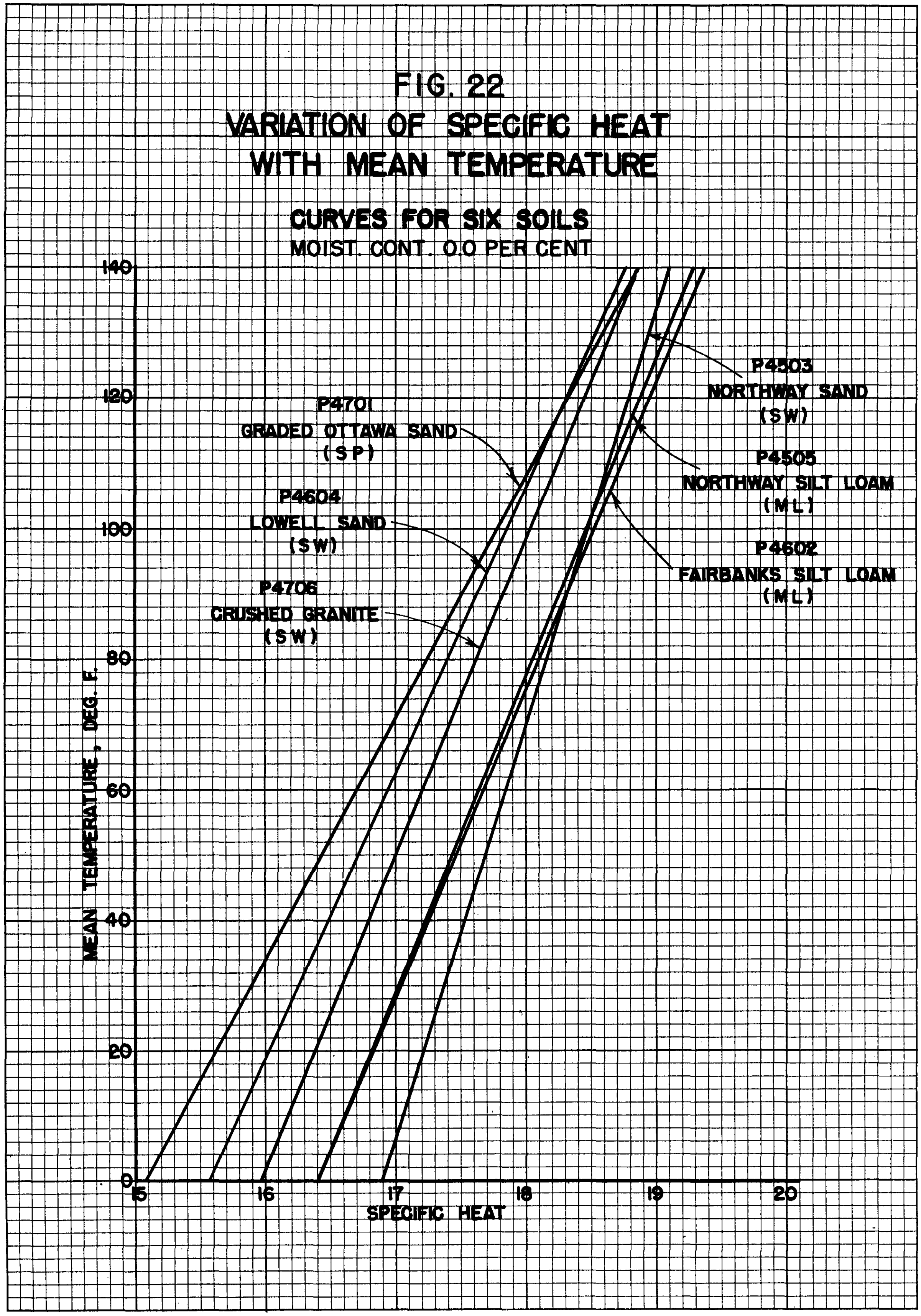


FIG. 22
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
CURVES FOR SIX SOILS
MOIST. CONT. 0.0 PER CENT
P4503
NORTHWAY SAND
(SW)
P4701
GRADED OTTAWA SAND
(SP)
P4505
NORTHWAY SILT LOAM
(ML)
P4604
LOWELL SAND
(SW)
P4602
FAIRBANKS SILT LOAM
(ML)
P4706
CRUSHED GRANITE
(SW)
MEAN TEMPERATURE, DEG. F.
140
120
100
80
60
40
20
0
15
16
17
18
19
20
SPECIFIC HEAT

TABLE XV - SPECIFIC HEAT VALUES: MOIST SOIL AT 70° F.

Soil P4701, Graded Ottawa Sand

Test No.	Method	Moisture Content	Mean Temperature Degrees, F.	SPECIFIC HEAT Moist Soil at Test Temperature	Dry Soil at Test Temperature	Dry Soil at 70°F.	Moist Soil at 70°F.
95	B	1.78	106.5	0.192	0.178	0.169	0.184
65	B	1.85	99.7	0.188	0.173	0.165	0.180
64	B	1.92	99.1	0.187	0.171	0.164	0.180
66	B	1.97	99.3	0.178	0.162	0.155	0.171
92	B	2.06	66.6	0.195	0.178	0.179	0.196
69	C	4.7	95.7	0.227	0.191	0.184	0.221
67	C	4.8	97.2	0.221	0.184	0.176	0.214
68	C	4.9	95.2	0.205	0.166	0.160	0.199
91	B	5.2	76.3	0.228	0.188	0.186	0.226
79	C	5.4	100.0	0.212	0.169	0.161	0.204
77	D	9.4	99.5	0.224	0.151	0.144	0.218
76	D	10.2	98.6	0.239	0.161	0.154	0.232
84	B	10.4	91.7	0.221	0.130	0.126	0.208
94	D	18.73	107.6	0.306	0.176	0.166	0.298
80	C	19.1	82.0	0.299	0.165	0.162	0.296
93	B	19.18	63.7	0.298	0.163	0.165	0.299
89	D	30.1	64.4	0.373	0.184	0.186	0.374
88	D	49.8	61.0	0.461	0.193	0.196	0.463
85	D	75.8	55.7	0.539	0.189	0.193	0.541
87	D	78.7	61.5	0.539	0.176	0.178	0.540
86	D	99.0	64.6	0.594	0.192	0.194	0.595

If it is assumed that the specific heat of a soil-water mixture may be calculated by proportion according to the percentages by weight of the soil and water and the respective specific heats of both components, the specific heat of the soil itself may be determined from that of the mixture. The following formula is used:

$$\text{Specific Heat, Mixture} = \frac{(100 \times \text{Specific Heat Soil}) + (\text{Moist. Cont.} \times 1.0)}{100 + \text{Moisture Content}}$$

Solving:

$$\text{Specific Heat, Soil} = \frac{(\text{Spec. Ht. Mixture})(100 + \text{Moist. Cont.})}{100} - \frac{\text{Moist. Content}}{100}$$

This calculation has been performed and the values are listed in Table XV. Since the tests were run at various mean temperatures, these values have been reduced to a common temperature value of 70 degrees Fahrenheit. The reductions were made by use of the relationship shown in Figure 21. The specific heat of the soil-water mixtures were also recalculated, using the specific heat of the soil at a common temperature, and are listed in Table XV. The latter values have been plotted in Figure 23 for the individual tests, together with a theoretical curve calculated by the above equation and based on a specific heat of 0.170 at 0.0 per cent moisture content. Inspection of this curve shows a fairly good relationship between the test points and the theoretical curve. Some variations are to be expected in the testing of moist soils due to the difficulties encountered in pouring the samples, the variety of test methods used, etc. The tests made at 10 per cent moisture were particularly dffficult, which factor probably accounts for the poor correlation at that point.

The tests would seem to indicate that the specific heat of soil-water mixtures may be calculated according to the proportion by weight of the two components and their respective specific heats.

Effect of Density. - Density was not considered as a factor in the specific heat determinations. All of the soils were tested in a loose condition, being poured into the water in the calorimeter. It is thought that density would have no bearing on the specific heat of a soil.

Effect of Particle Size and Shape. - Tests were made on the three quartz soils: P4701, Graded Ottawa Sand; P4702, 20-30 Ottawa Sand; and P4703, Crushed Quartz, at a mean temperature of 140 degrees. In spite of the differences in particle size and shape of these three samples, the results are almost identical: 0.189, 0.189 and 0.190 respectively. Three specific heat determinations were made on each of these three soils and the extreme range of the nine tests was from 0.188 to 0.191. The Chena River Gravel was tested in two fractions, one finer than 1/4 inch and one larger. The two results were 0.194 and 0.196, an insignificant difference. These results would indicate that such factors as particle size and shape would have very little, if any, effect on specific heat.

Effect of Mineral Composition. - Twelve soils were tested at a mean temperature of approximately 140 degrees. These results, listed in Table V, afford a means of comparing the specific heats of various minerals and a variety of soils. The range is remarkably small, varying from a high of 0.197 for Northway Fine Sand to 0.188 for Lowell Sand. The average is 0.192. The four crushed rock samples: quartz, trap rock, feldspar, and granite, are within a range of 0.189 to 0.193. Thus, the tests do not show any significant differences in the specific heat of the common soils and crushed rocks tested.

Diffusivity. - No tests were made for diffusivity in this research program. However, the values may be calculated for dry soils by the formula:

$$h^2 = \frac{0.08333k}{(\text{Specific Heat})\ (\text{Density})} \qquad \text{(a)}$$

in which h^2 is the diffusivity in feet squared per hour.

For moist, unfrozen soils the diffusivity equation may be written:

$$h^2 = \frac{0.08333k}{\text{Dry Density}\left(\text{Spec. Heat Soil} + \frac{\text{Moisture Content}}{100}\right)} \qquad \text{(b)}$$

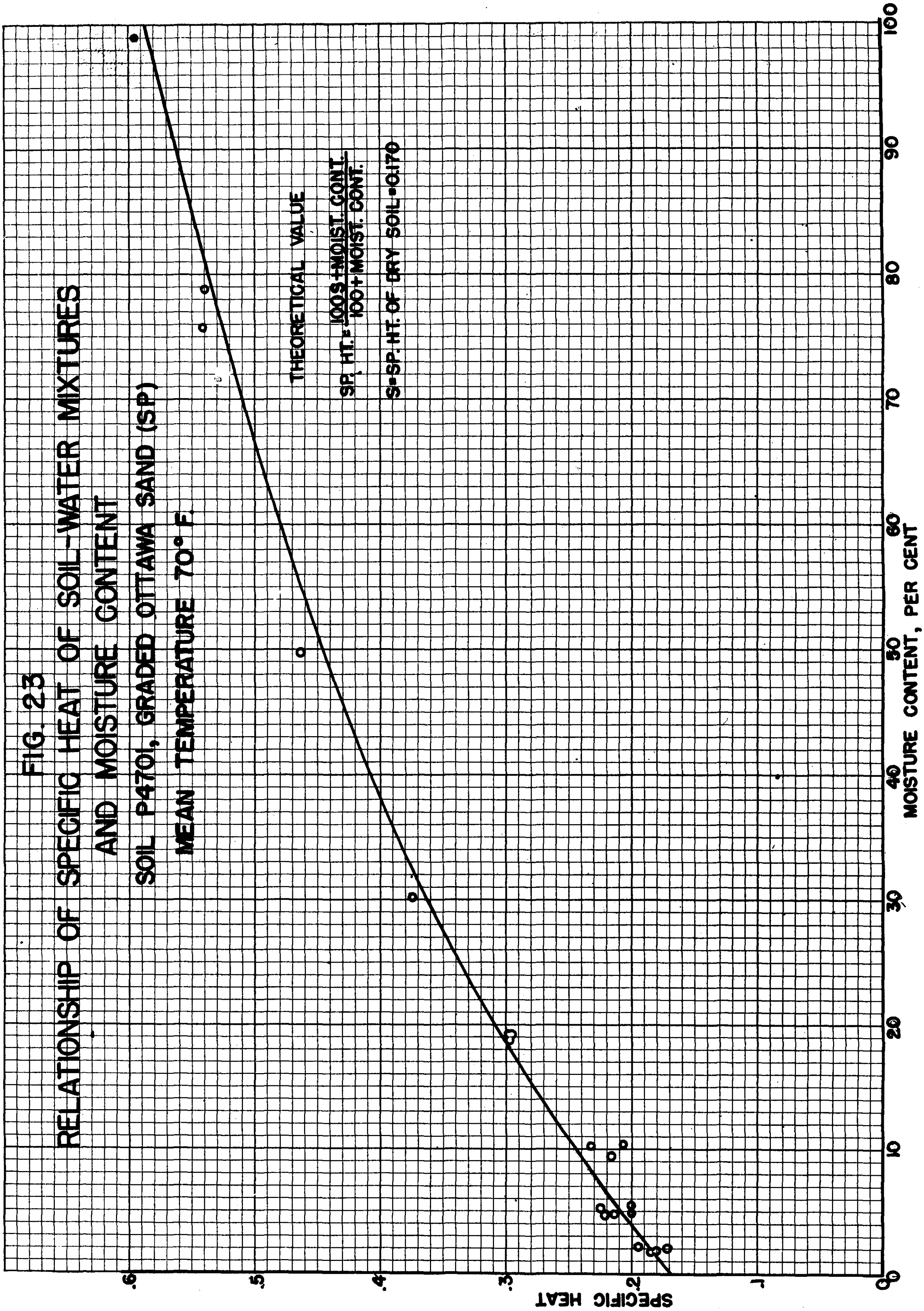


FIG. 23
RELATIONSHIP OF SPECIFIC HEAT OF SOIL-WATER MIXTURES
AND MOISTURE CONTENT
SOIL P4701, GRADED OTTAWA SAND (SP)
MEAN TEMPERATURE 70° F.
THEORETICAL VALUE
SP. HT. = 100S + MOIST. CONT. / 100 + MOIST. CONT.
S = SP. HT. OF DRY SOIL = 0.170
SPECIFIC HEAT
0
.1
.2
.3
.4
.5
.6
MOISTURE CONTENT, PER CENT
0
10
20
30
40
50
60
70
80
90
100

For frozen soils, the equation is:

$$h^2 = \frac{0.08333k}{\text{Dry Density (Spec. Heat Soil} + \frac{\text{Moisture Content}}{100} \cdot 0.5)} \qquad (c)$$

The value 0.5 is the approximate specific heat of ice.

The effect of such items as temperature, moisture content, and density may be predicted by a study of the above formulas.

Effect of Temperature. - In discussing the effect of temperature upon diffusivity, it is also necessary to consider the moisture content of the soil. Considering first temperatures above freezing, it has been previously shown that for both dry and moist soils the conductivity is on the average about 4 per cent higher at 70 degrees than at 40 degrees. This equals a change of approximately 13 per cent per 100 degrees. It has also been shown that the specific heat of a dry soil decreases about 11 per cent for a 100 degree drop in temperature. By inspection of formula (a), it will be noted that a decrease in temperature will cause practically no change in diffusivity. For moist soils, as indicated by an inspection of formula (b), there would be a decrease.

With respect to changes in temperature below freezing, it was shown on Page 34 that the conductivity does not vary by more than 6 per cent, on the average, in a temperature range from 25 to -20 degrees, for all moisture contents. Since the variations of specific heat are also small, the resultant changes in diffusivity for either dry or moist soils would not be great.

Concerning changes from above to below freezing, the change in diffusivity may be more marked. The change in k is chiefly dependent upon moisture content; at optimum moisture content, for example, the frozen soils will have a conductivity on the average 17 per cent greater than the unfrozen. Also, the specific heat of the ice being only 0.5 the denominator of the diffusivity equation (c) is less than that of (b) for a given moisture content. Thus, at a moisture content of 15 per cent, the diffusivity of a soil might increase as much as 50 per cent in becoming frozen; whereas, for a dry soil it would not change. It may be stated that for soils having moisture contents above 6 per cent for sands or somewhat more for the heavier soils, the diffusivity increases appreciably when passing from an unfrozen to a frozen state.

Effect of Moisture Content. - For conductivities at a temperature above freezing, it was shown on Page 46 that doubling the moisture content of a soil resulted in an increase of approximately 30 to 40 per cent in conductivity. Assuming the specific heat of a soil as 0.17, a change of moisture content from 2.5 to 5 per cent would increase the denominator of equation (b) by only 16 per cent; a change from 5 to 10 per cent moisture by 23 per cent; and from 10 to 20 per cent by 37 per cent. Thus, at low or moderate moisture contents, an increase in moisture results in a marked increase in diffusivity. This is not true at high moisture contents, however.

For frozen soils, since the specific heat of ice is only about half that of water and a change in moisture content makes a greater change in conductivity than results in unfrozen soils, the effect of an increase in moisture content is a marked increase in diffusivity.

Effect of Density. - It has been shown that the coefficient of thermal conductivity at 40 degrees increases about 2.8 per cent on the average for each one pound per cubic foot increase in density for all moisture contents. At the range of densities investigated, a one-pound per cubic foot increase in density is equivalent to about one per cent. Thus, by inspection of formulas (a) and (b), it may be seen that an increase in density will cause a slight increase in diffusivity. The same will be true for temperatures other than 40 degrees, including those below freezing.

Effect of Mineral Composition and Particle Size and Shape. - Mineral composition affects diffusivity to about the same degree that it affects conductivity, since it has been shown that the specific heat of all of the materials tested are very nearly the same. Inasmuch as the conductivities of trap rock and quartz may differ by more than 100 per cent, the diffusivities may differ by a like amount.

The same is true for the effect of particle size and shape. Conductivities of quartz samples at equal moisture contents and densities but of different gradings and angularities were found to vary by as much as 50 per cent; diffusivities would thus differ by a like amount.

Thermal Conductivity of Insulating Materials.

Effect of Mean Temperature. - The effect of mean temperature upon thermal conductivity of the pre-cast insulating slabs is shown graphically in Figures 24 and 25. In Figure 24, it will be noted that for the Zonolite slabs there is a decrease in conductivity for a decrease in mean temperature. The decrease for the different slabs amounts to from 5 to 12 per cent for a 100-degree Fahrenheit drop in temperature. The large difference in thermal conductivities of the 1.8 and 1.10 slabs may be attributed to a large difference in densities. The tests on Cell concrete, Figure 25, indicate very little change with respect to variations in mean temperature. Tests made on the 0.8 slabs at a temperature range of from 7 to 175 degrees show a maximum difference of 2 per cent in conductivity values. The 1.0 and 1.2 slabs show only small changes.

Effect of Density. - The thermal conductivity of both the Zonolite and Cell concrete slabs varied with the density. The results on both types of slabs at a mean temperature of 70 degrees are shown in Figure 26. The common curve drawn indicates an increase in conductivity of about 3 per cent per pound per cubic foot increase in density.

There has been included in Figure 26 some additional points for light weight concrete using various types of aggregates. These are taken from the American Society of Heating and Ventilating Engineers Guide, 1948, Page 115, Table 2. Most of the values fall close to the curve drawn and thus tend to substantiate the test data presented.

Effect of Moisture Content. - Since it was not possible to run tests on moist slabs in the apparatus, all slabs were oven-dried before being placed. Consequently, no information was obtained on the effect of moisture content on thermal conductivity. It might be expected, however, that an increase in moisture content would result in an increase in thermal conductivity in much the same manner as occurred for the soils.

Thermal Conductivity of Bituminous Paving Mixture. - The asphalt paving mixture was molded at only one density and was tested in only the dry condition. Consequently, the effect of density and moisture content variations are not evaluated. Such mixtures do not absorb moisture to any marked degree in the field, however; thus, consideration of moisture is not deemed necessary. Also, the variations in density of such materials are not normally great and the single test is therefore quite adequate.

The results of tests for thermal conductivity are given in Table VII, Page 34. The mean temperature effect is shown in Figure 27 and is quite similar to that shown for the Zonolite concrete slabs. Values vary from 9.9 at -20 degrees to 10.3 at 40 degrees.

It is of interest to compare the conductivity of the paving mixture with that of the Chena River Gravel, Soil P4601, which was the aggregate of the mixture. Reference to

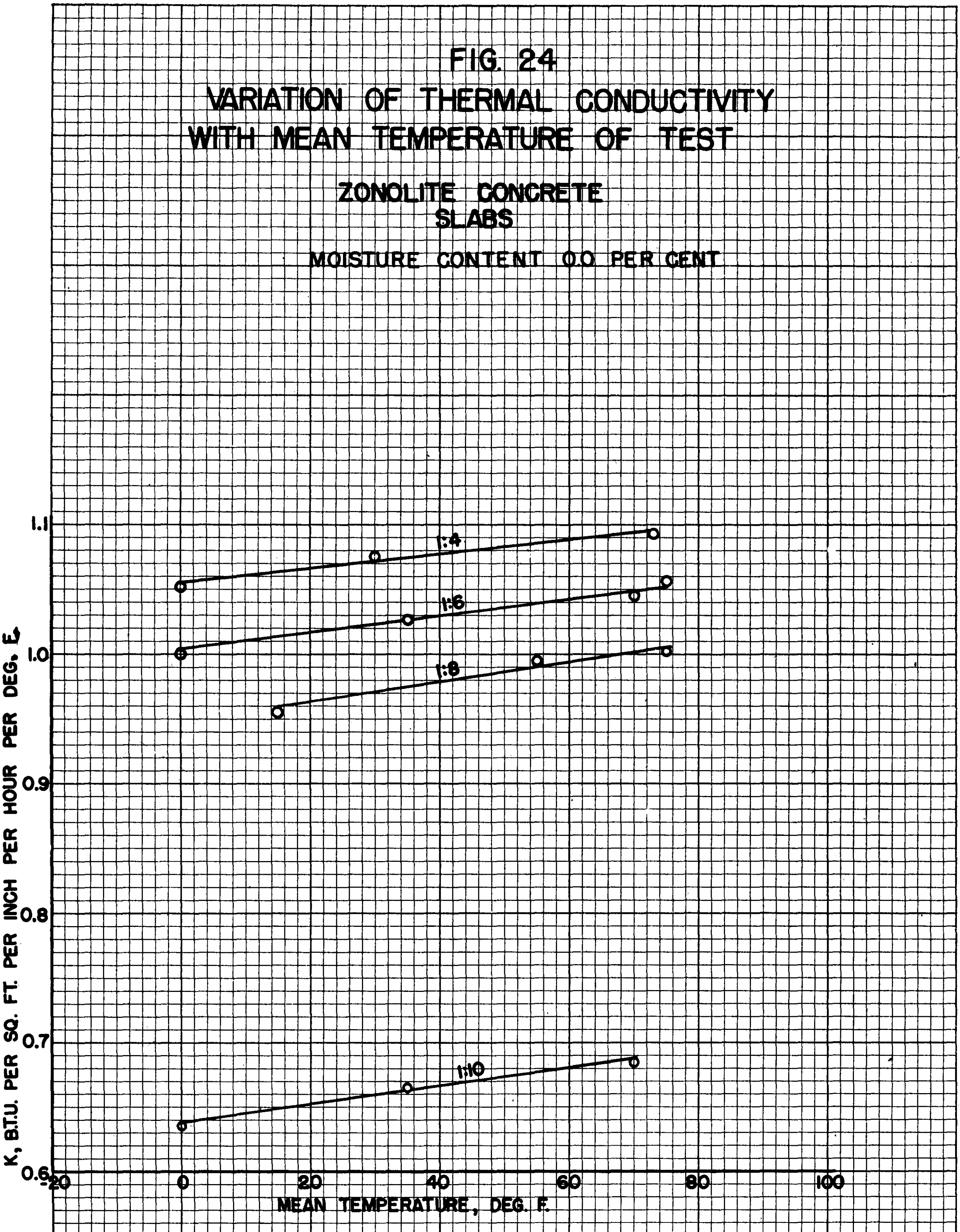


FIG. 24
VARIATION OF THERMAL CONDUCTIVITY
WITH MEAN TEMPERATURE OF TEST
ZONOLITE CONCRETE
SLABS
MOISTURE CONTENT 0.0 PER CENT
1:4
1:6
1:8
1:10
1.1
1.0
0.9
0.8
0.7
0.6
-20
0
20
40
60
80
100
MEAN TEMPERATURE, DEG. F.
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.

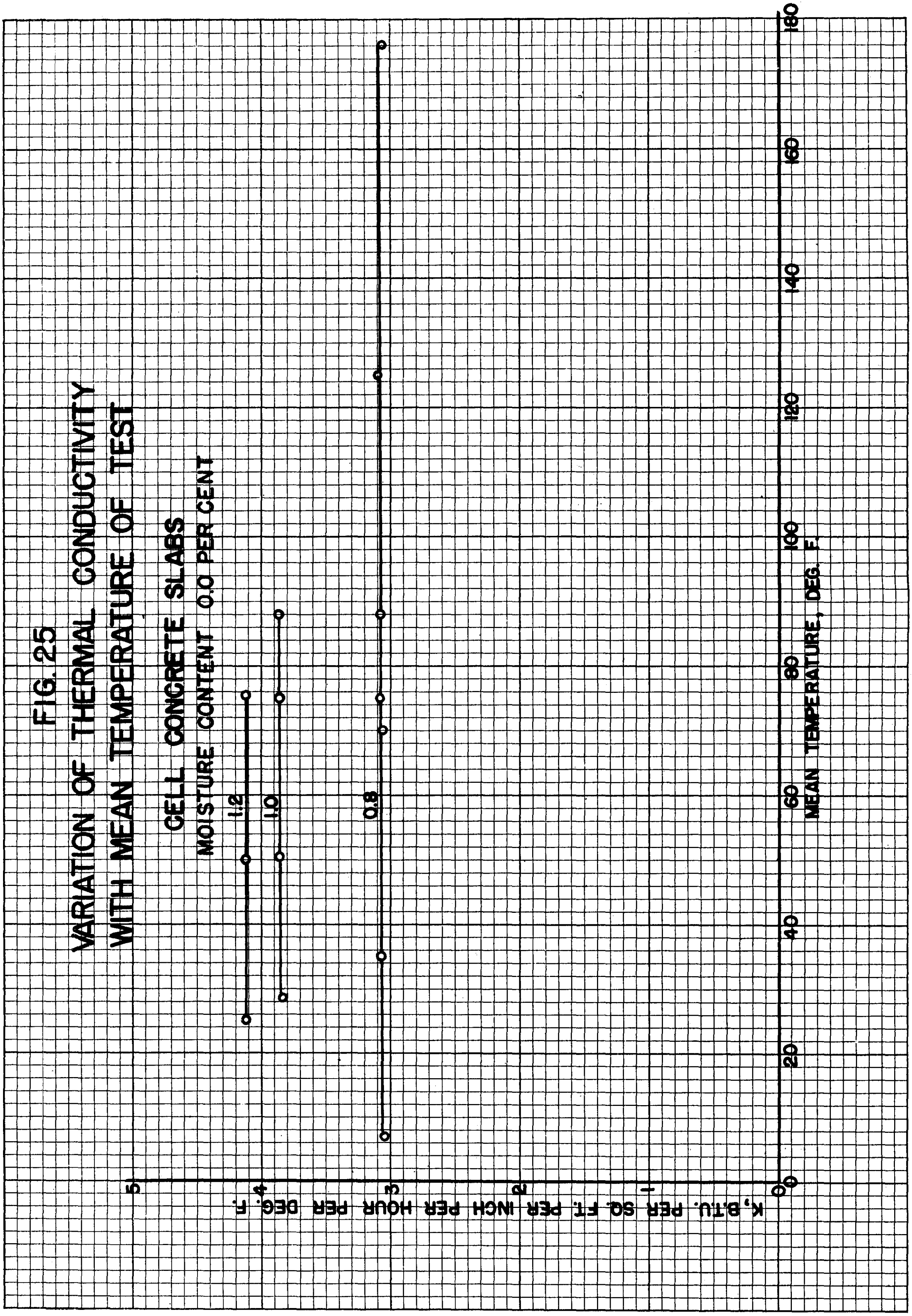


FIG. 25
VARIATION OF THERMAL CONDUCTIVITY
WITH MEAN TEMPERATURE OF TEST
GELL CONCRETE SLABS
MOISTURE CONTENT 0.0 PER CENT
1.2
1.0
0.8
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MEAN TEMPERATURE, DEG. F.
0
1
2
3
4
5
20
40
60
80
100
120
140
160
180

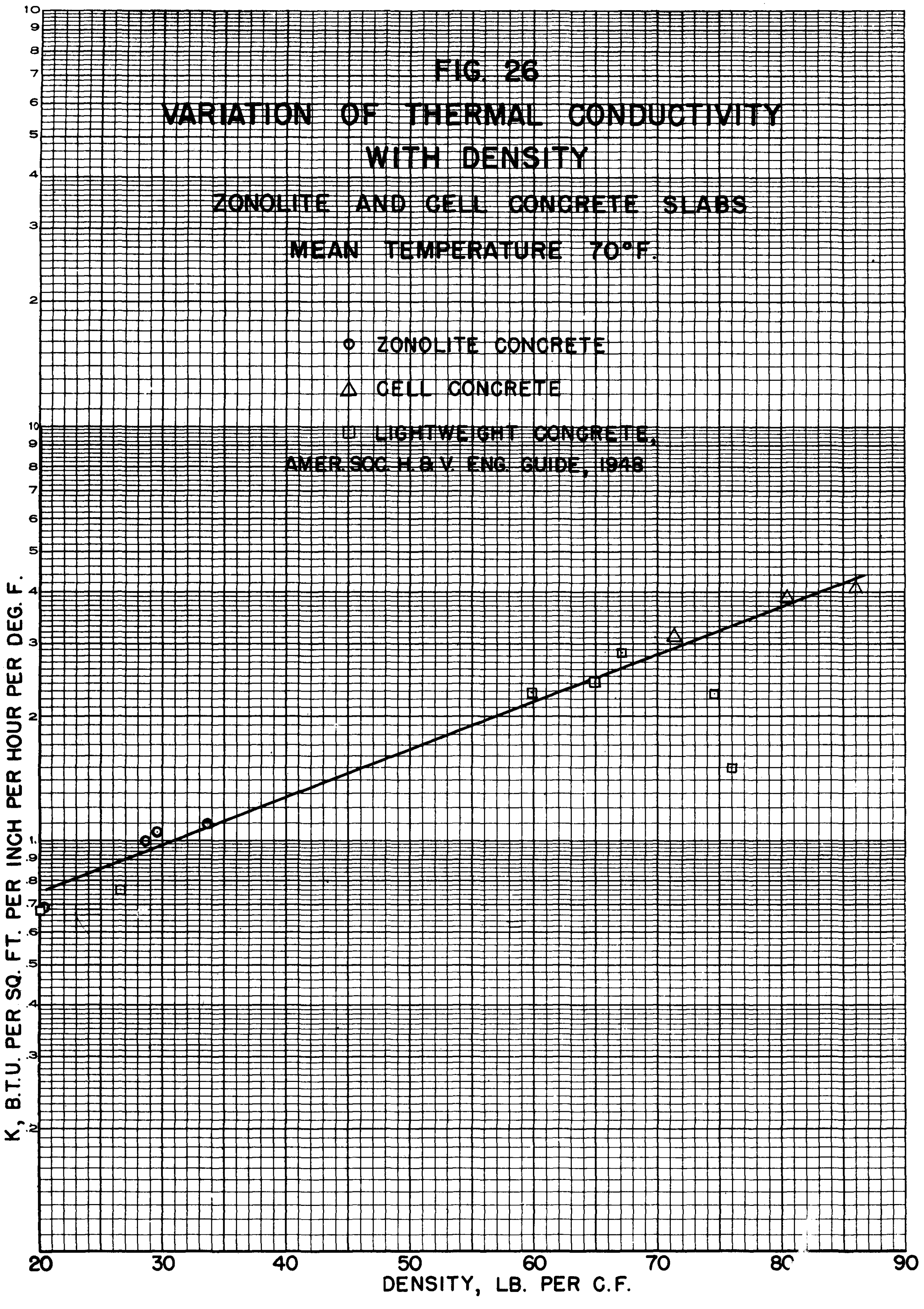


FIG. 26
VARIATION OF THERMAL CONDUCTIVITY
WITH DENSITY
ZONOLITE AND CELL CONCRETE SLABS
MEAN TEMPERATURE 70°F.
ZONOLITE CONCRETE
CELL CONCRETE
LIGHTWEIGHT CONCRETE,
AMER. SOC. H. & V. ENG. GUIDE, 1948
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
20
30
40
50
60
70
80
90

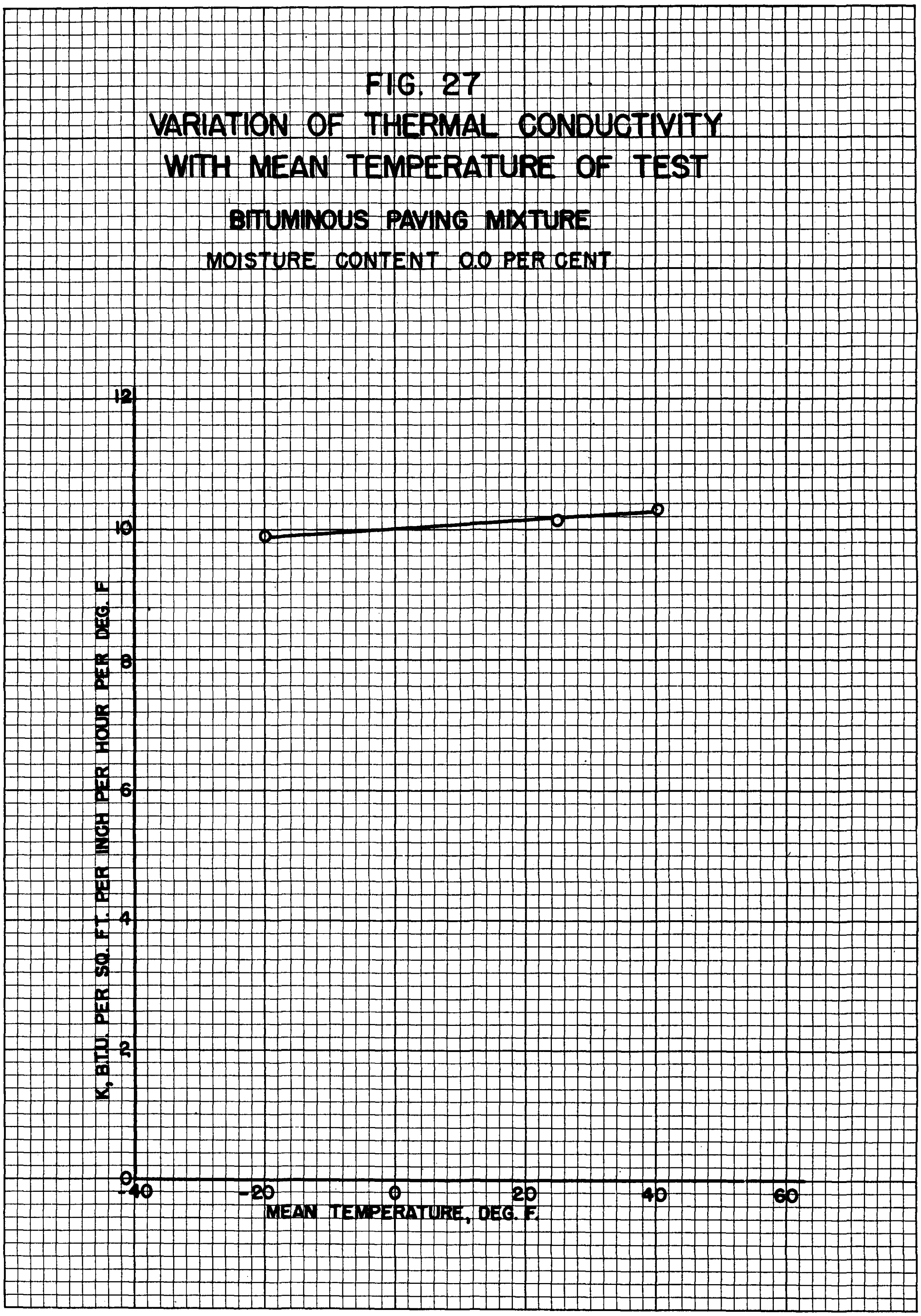


FIG. 27
VARIATION OF THERMAL CONDUCTIVITY
WITH MEAN TEMPERATURE OF TEST
BITUMINOUS PAVING MIXTURE
MOISTURE CONTENT 0.0 PER CENT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F
0
2
4
6
8
10
12
-40
-20
0
20
40
60
MEAN TEMPERATURE, DEG. F.

Figure 53 shows that the dry gravel (0.2 per cent moisture) at a density of 138 pounds per cubic foot would have a conductivity of approximately 8. The paving mixture had a bituminous content of 6 per cent. Tests were not made on the gravel with moisture contents as great as this, but, for moisture contents of about 3 per cent and for densities above 130 pounds per cubic foot, the conductivity values are of the nature of 16 or greater. Thus, one may state that the addition of bituminous material increases the conductivity of the dry aggregate, but not to the same degree that results from an addition of water.

Verification of Results.

Since much of this research has been in a field where there has been very little previous work to guide and to serve as a check, every precaution has been taken to insure reasonably accurate results. The checks available on the work are discussed in the following paragraphs.

Thermal Conductivity of Soil. - The first material tested in the tubular soil apparatus after its completion was a sample of Vermiculite, an expanded mica. This material had previously been tested in the hot plate apparatus at the Engineering Experiment Station. Since identical results were obtained in the two tests, the tubular soil apparatus was assumed to be satisfactory.

During the initial stages of soil testing, it was the practice to run a test at a mean temperature of 70 degrees initially and also to run a check test at the same temperature after tests at several other mean temperatures had been completed. The difference in conductivities in the two tests rarely exceeded 3 per cent. Some difference would be expected because of the rearrangement of moisture occurring during the course of the test.

Thermal conductivity tests were made by the Corps of Engineers, New England Division, by another method on two soils included in the test program at the University of Minnesota; these were: P4604, Lowell Sand, and P4503, Northway Sand.

The results of the New England Division were given in a letter "Results of Comprehensive Report", dated June 9, 1948 from the Office, Chief of Engineers to the District Engineer, St. Paul, Minnesota. The results for Soil P4604 obtained by the New England Division on both frozen and unfrozen samples and the test results at mean temperatures of 40 and 25 degrees at Minnesota are plotted for comparison in Figure 28. A study of this graph will indicate a close agreement between the results of the two laboratories for both frozen and unfrozen samples if the densities are taken into account. For all tests made at similar densities and at approximately equal moisture contents, variations of less than 10% will ordinarily be found.

The results obtained by the New England Division of Soil P4503, Northway Sand, are too meager (only four tests) to make as complete a comparison as for Soil P4604. The values are plotted together with the University of Minnesota test results on the same soil in Figure 29. Inspection of this figure will indicate that the values agree fairly well in general, particularly for the low moisture contents. Some tests seem to differ by about 20%.

Perhaps the most probable source of error in the thermal conductivity tests is the migration of moisture during a run and the consequent unequal distribution of moisture. The possibility of this occurrence was realized at the start of the tests, and, in an effort to hold the amount of migration low, a temperature differential of only 10 degrees between the hot and cold faces was used. The moisture variations at the completion of a test run were usually the greatest in sandy soils. The two Ottawa Sand samples, P4701 and P4702, were about the worst. With these soils, the samples taken near the cold face averaged approximately 0.8 per cent of moisture more than those at the hot face. For many soils, the differences amounted to only 0.2 or 0.3 per cent of moisture. Because of the migration

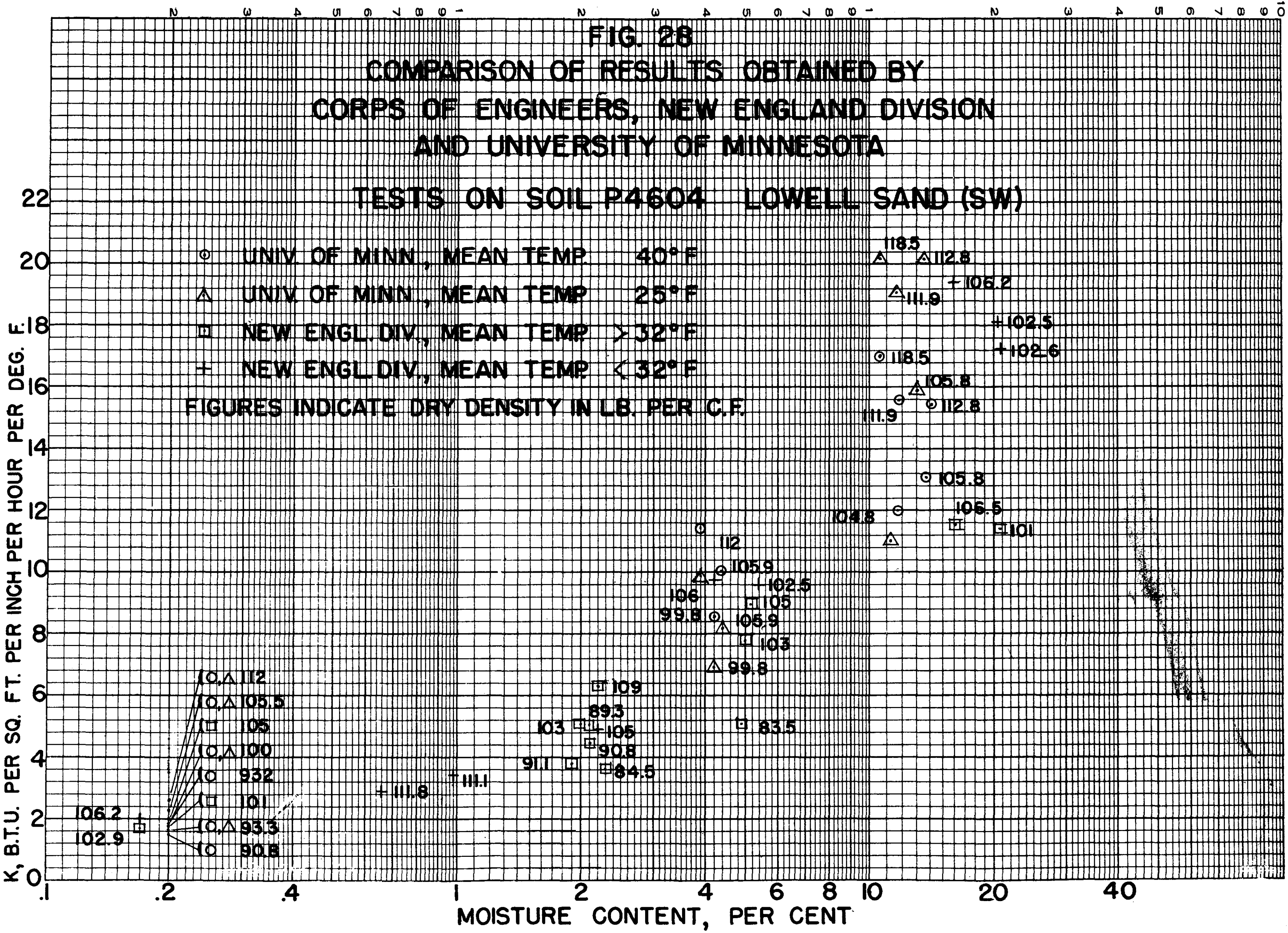


FIG. 28
COMPARISON OF RESULTS OBTAINED BY
CORPS OF ENGINEERS, NEW ENGLAND DIVISION
AND UNIVERSITY OF MINNESOTA
TESTS ON SOIL P4604 LOWELL SAND (SW)
UNIV. OF MINN., MEAN TEMP. 40° F
UNIV. OF MINN., MEAN TEMP. 25° F
NEW ENGL. DIV., MEAN TEMP. > 32° F
NEW ENGL. DIV., MEAN TEMP. < 32° F
FIGURES INDICATE DRY DENSITY IN LB. PER C.F.
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT
0
2
4
6
8
10
12
14
16
18
20
22
.1
.2
.4
1
2
4
6
8
10
20
40
118.5
112.8
106.2
111.9
102.5
102.6
118.5
105.8
112.8
111.9
105.8
106.5
104.8
101
112
105.9
102.5
106
105
99.8
105.9
103
99.8
109
89.3
103
105
90.8
91.1
84.5
83.5
111.1
111.8
112
105.5
105
100
93.2
101
93.3
90.8
106.2
102.9

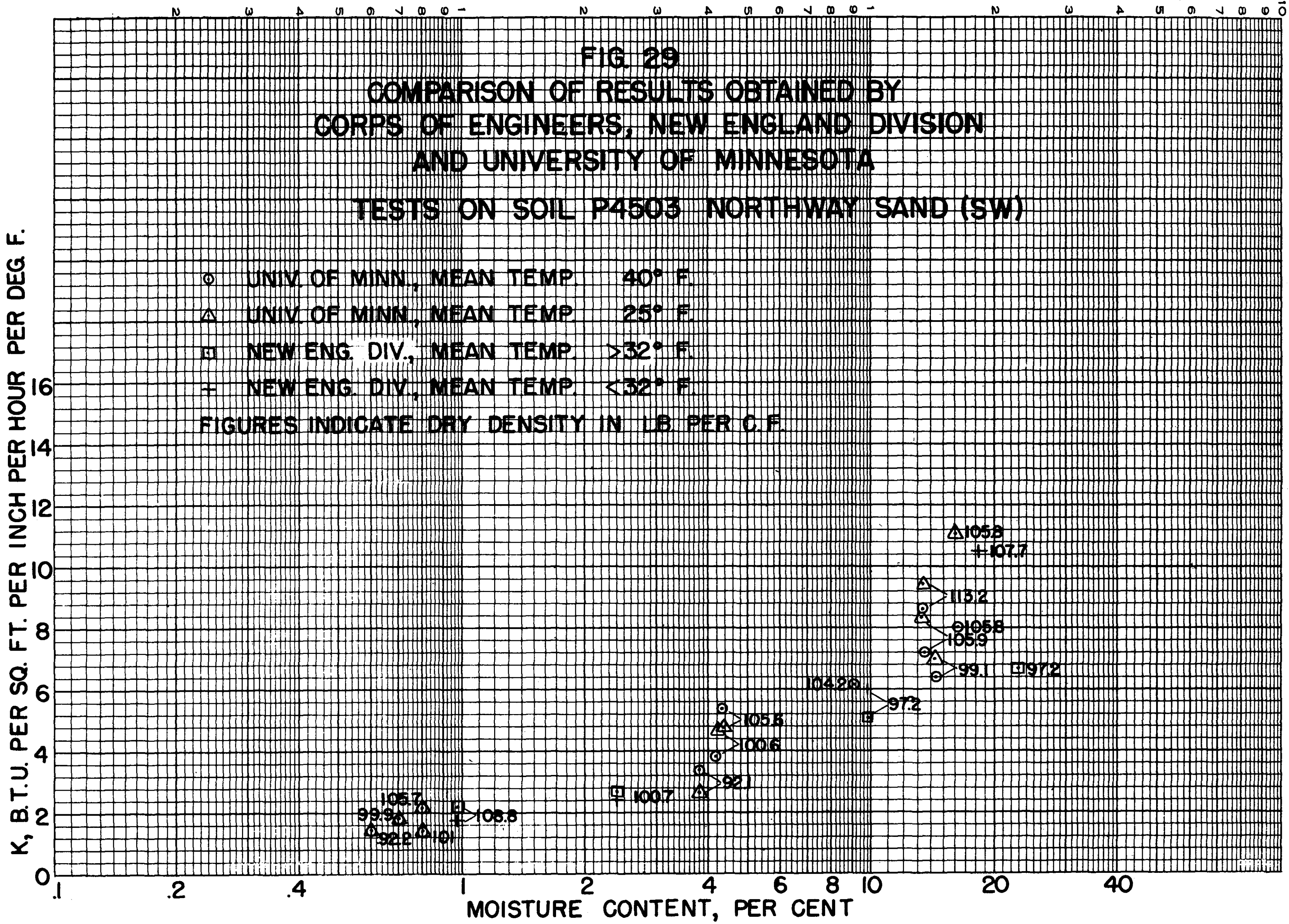


FIG. 29
COMPARISON OF RESULTS OBTAINED BY
CORPS OF ENGINEERS, NEW ENGLAND DIVISION
AND UNIVERSITY OF MINNESOTA
TESTS ON SOIL P4503 NORTHWAY SAND (SW)

which did occur, it is emphasized that many of the moisture contents reported are an average rather than a uniform condition.

Specific Heat. - The method of specific heat determination for soils was developed and corrected by making the initial tests on copper punchings. After the method was fully perfected, the tests on copper gave a specific heat of 0.093 at 140 degrees which checked the value given by handbooks. It was felt, therefore, that the method was satisfactory for soils.

When the specific heat tests were started on soils it was desired to determine them accurately to two decimal places. When it was found that three or more tests could ordinarily be made with a variation of less than 5 in the third decimal place, it was felt that the desired accuracy had been more than attained.

The specific heat values determined were found to lie approximately in the range of those given for common soil minerals in handbooks. Quartz, for example, is given as 0.188 in some tables. The values found by tests in this study checked this very closely.

Thermal Conductivity of Insulating and Paving Materials. - The hot plate apparatus used for determining the thermal conductivity of the pre-cast insulating slabs and bitumino .s paving mixture has been in use for several years for testing various types of insulating material, and it has always proved to be dependable.

Prediction of Thermal Properties.

Thermal Conductivity of Soil. - The thermal conductivity tests on 19 different soils gave a great variety of results; nevertheless, they are useful in formulating predictions of thermal conductivity values for any soil. As noted in Table XIII, the values may vary by more than 100 per cent for two soils at the same moisture content and density, but, by taking into account such items as grading, mineral composition, and other characteristics, the possible error in an estimate may be lowered. Although the test results for all 19 soils are informative, those on eight particular soils are most useful. Of the other 11 soils, 8 were tested only at moisture contents of about 4 per cent or less. One was a peat which could not be compacted to a density greater than 21 pounds per cubic foot, and two (The Northway sands, P4502 and P4503) were of such a unique mineral composition that they would be considered uncommon.

Considering first the conductivities of unfrozen soils, i.e., a mean temperature of 40 degrees, any general overall equation would of necessity be in considerable error for some soils. An inspection of Table XIII will verify this statement. It would seem expedient to divide the soils into two groups: one, the fine grained soils containing, in general, those soils with 50 per cent or more of silt and clay, and two, the sands and sandy soils. Soil P4713, Ramsey Sandy Loam, which contains 47 per cent of silt and clay, has conductivity values more similar to the fine grained soils; whereas Soil P4711, Dakota Sandy Loam, which has 37 per cent of silt and clay, should be included with the sandy soils. The two Northway Sands, P4502, and P4503, actually have conductivity values more similar to the fine grained soils than to the sands and should not be considered as characteristic of ordinary sands.

Considering first the fine textured soils, i.e. P4708, Healy Clay; P4710, Fairbanks Silty Clay Loam; P4602, Fairbanks Silt Loam; P4505, Northway Silt Loam; and also P4713, Ramsey Sandy Loam, a common equation for thermal conductivity may be formulated which yields results not more than about 25 per cent in error for all test results except one and much closer than this in most instances. The equation is a combination of those derived for moisture content and density variations and is as follows:

$$k = [0.9 \log (\text{Moist. Cont}) - 0.2]\ 10^{0.01\gamma}$$

k being for a mean temperature of 40 degrees, and γ being the dry density in pounds per cubic foot. The equation only applies to moisture contents of 7 per cent or greater. A chart of the equation is produced in Figure 30. Its general correctness may be checked by comparing the conductivity values for the fine textured soils in Appendix I with values read from the chart. The k curves of the chart are drawn only up to the 100 per cent saturation line; 50 and 75 per cent saturation lines are also shown on the diagram. These have been calculated for a specific gravity of 2.70.

Figure 30 should serve as an aid in estimating the thermal conductivity value of any soil which contains about 50 per cent or more of silt and clay.

The foregoing equation gave results which are too low for granular soils such as P4709, Fairbanks Sand, P4604, Lowell Sand, and P4601, Chena River Gravel. Soil P4711, Dakota Sandy Loam, also gives higher values. A general equation which best suits such soils is:

$$k = [0.7 \log (\text{Moist. Cont.}) + 0.4]\ 10^{0.01\gamma}$$

k being for a mean of 40 degrees and the moisture content being not less than 1.0 per cent. Conductivity values obtained by this equation check test results very well for the three clean sands or gravel mentioned above. Only 2 of 35 tests have differences of more than 25 per cent. Values from the chart are as much as 50 per cent too great for some tests on the Dakota Sandy Loam.

The equation is charted in Figure 31. This diagram should be used for sandy or gravelly soils of normal composition, i.e., mineralogically they should be predominately quartz. The chart will give too high a result for sandy loam soils or those that contain from 20 to 50 per cent of silt and clay.

As previously noted, the conductivity values for the two Northway sands, P4502 and P4503, agree more closely to the results of the equation advocated for silt and clay soils than to that for sands.

For soils in a frozen condition, the tests at a mean temperature of 25 degrees are considered. Here, again, the soils are divided into two groups, the fine textured and the sandy ones. For frozen soils, the relationship between conductivity and moisture content has been shown to be that of a straight line. (See Figures 12 and 115 to 124). A study of the curves of this relationship shows that both the zero moisture content intercepts and the slopes are a function of the density. For the fine textured soils, the general equation which best fits the data is:

$$k = 0.01(10)^{0.022\gamma} + 0.085(10)^{0.008\gamma}\ (\text{Moist. Content})$$

k being at a mean temperature of 25 degrees and γ being the dry density in pounds per cubic foot. The equation holds for moisture contents from approximately 7 per cent to saturation. Figure 32 is a chart of the equation. This chart may be used for soils which contain about 50 per cent or more of silt and clay. Sandier soils will have conductivity values greater than those of this chart. Values from this diagram check all of the test results for soils P4708, Healy Clay; P4710, Fairbanks Silty Clay Loam; P4602, Fairbanks Silt Loam; P4505, Northway Silt Loam; and P4713, Ramsey Sandy Loam, within 25 per cent, and much closer in most instances.

A general equation for the granular soils, P4709, Fairbanks Sand; P4604, Lowell Sand, P4601, Chena River Gravel; and P4711, Dakota Sandy Loam, is as follows:

$$k = 0.076(10)^{0.013\gamma} + 0.032(10)^{0.0146\gamma}\ (\text{Moist. Content})$$

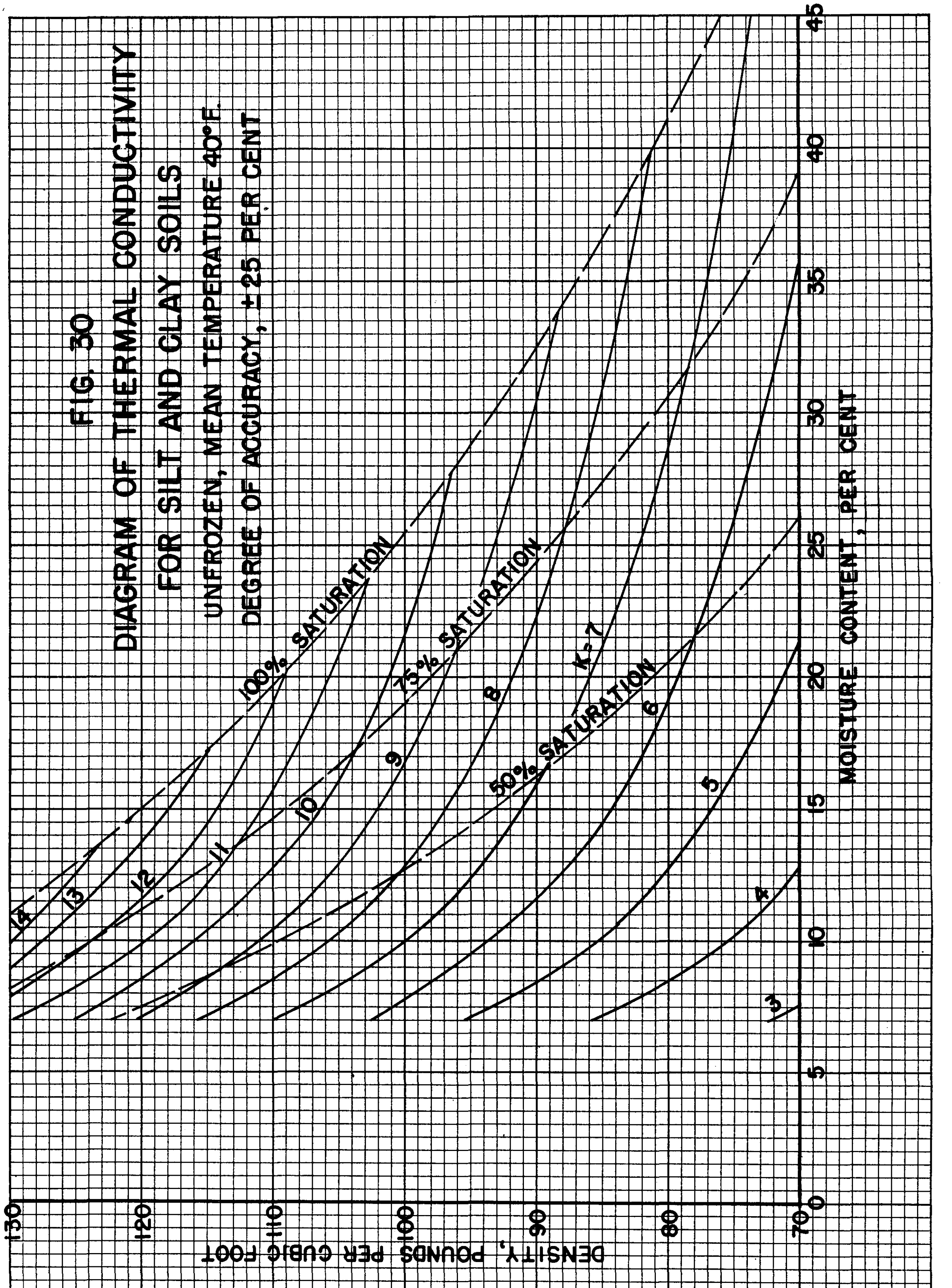


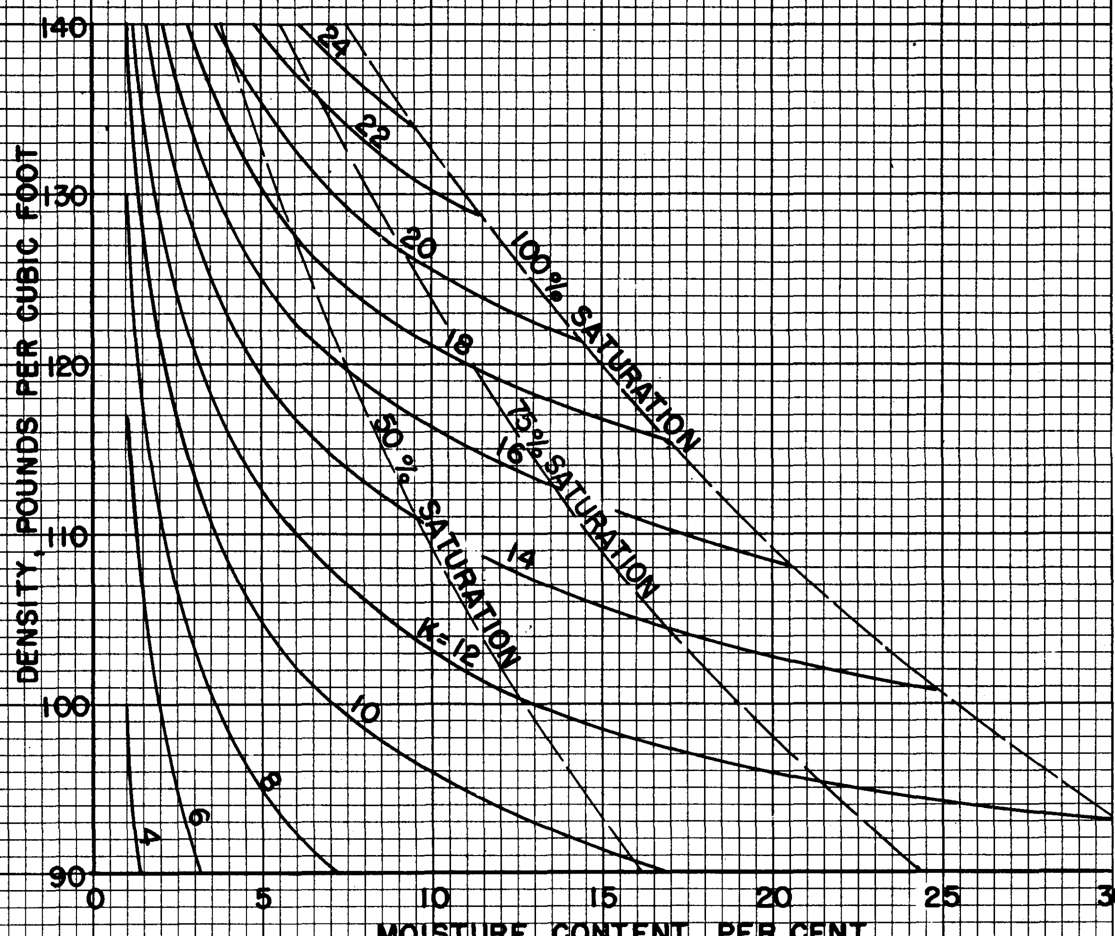
FIG. 30
DIAGRAM OF THERMAL CONDUCTIVITY
FOR SILT AND CLAY SOILS
UNFROZEN, MEAN TEMPERATURE 40°F.
DEGREE OF ACCURACY, ± 25 PER CENT
100% SATURATION
75% SATURATION
50% SATURATION
K=7
14
13
12
11
10
9
8
6
5
4
3
MOISTURE CONTENT, PER CENT
0
5
10
15
20
25
30
35
40
45
DENSITY, POUNDS PER CUBIC FOOT
130
120
110
100
90
80
70

FIG. 31

DIAGRAM OF THERMAL CONDUCTIVITY FOR SANDY SOILS

UNFROZEN, MEAN TEMPERATURE 40°F.

DEGREE OF ACCURACY ± 25 PER CENT



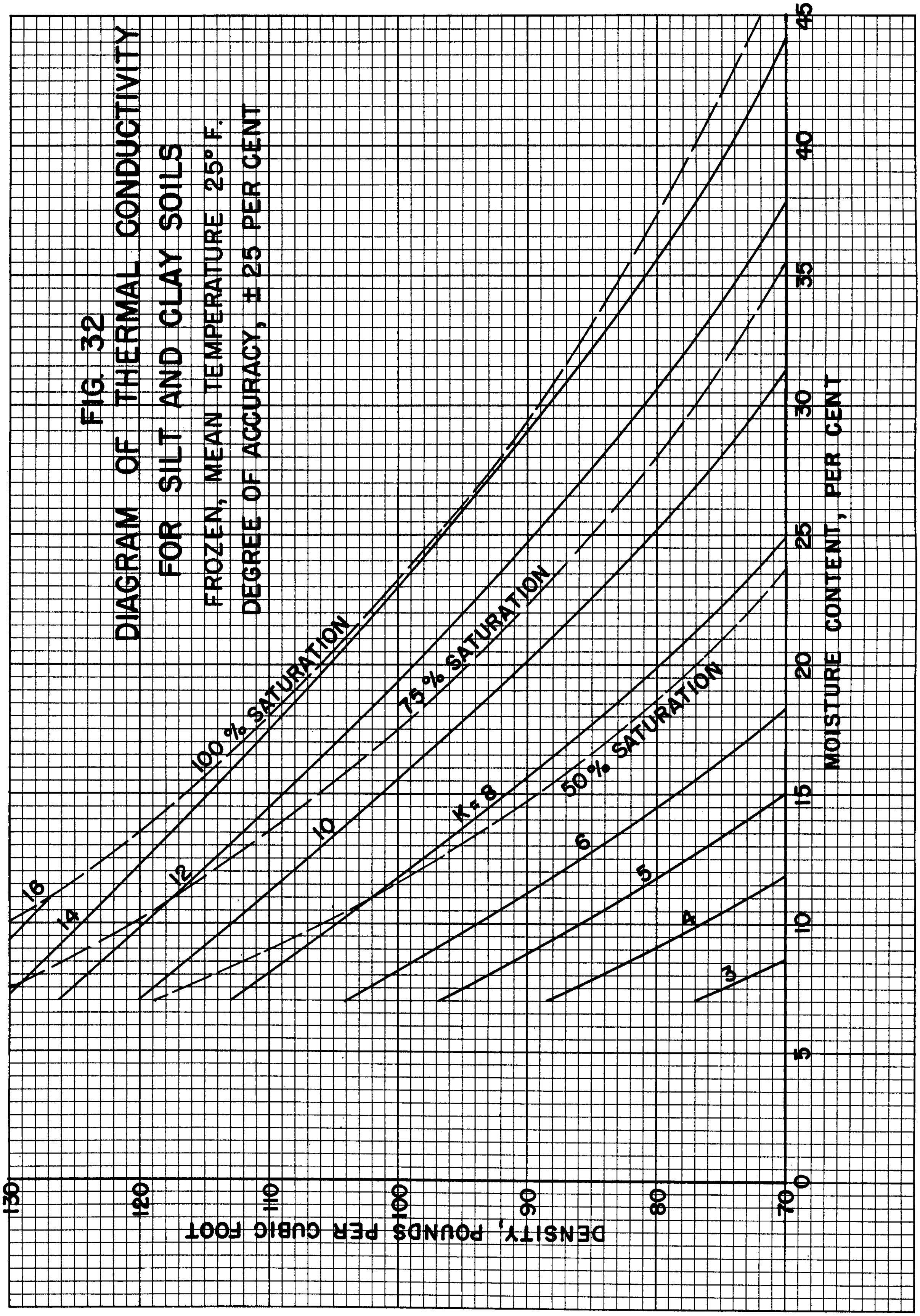


FIG. 32
DIAGRAM OF THERMAL CONDUCTIVITY
FOR SILT AND CLAY SOILS
FROZEN, MEAN TEMPERATURE 25° F.
DEGREE OF ACCURACY, ± 25 PER CENT
100 % SATURATION
75 % SATURATION
50 % SATURATION
K = 8
16
14
12
10
6
5
4
3
MOISTURE CONTENT, PER CENT
0
5
10
15
20
25
30
35
40
45
DENSITY, POUNDS PER CUBIC FOOT
130
120
110
100
90
80
70

k and γ being as before and the moisture content being not less than one per cent. This equation is only slightly different from that for the fine grained soils but gives somewhat greater values of conductivity for a given density and moisture content. Figure 33 is a chart of the equation. Values from this diagram are checked within 25 per cent by thirty-nine of forty-two test results for three of the four enumerated soils, and by eleven of fifteen tests for the other soil. The tests which do not check are essentially at moisture contents of less than 3 per cent. This chart should serve for any other sandy soils of similar mineral composition.

The four charts, Figures 30, 31, 32, and 33 serve as a means of prediction of the thermal conductivity of any soils. Two of the charts are for frozen and two for unfrozen soils; two are for sandy soils and two for silt or clay soils. The division point in texture may be based on the silt and clay contents. Soils with more than 50 per cent of silt and clay are in the fine textured group. Soils which have a somewhat smaller silt and clay content might have conductivity values in the range between those indicated by the two charts. By proper consideration of the texture of the soils, conductivity values with an error of not more than 25 per cent should be obtained.

Since conductivity does not vary much in the range of ordinary air temperatures, and since the same is true for the below freezing range, it should not be necessary to make any changes in the chart values for any normally existent air temperatures.

Specific Heat. - The tests made on the 12 soils all gave such similar results that it would appear to be reasonable to assume the same values for any soil. The values are 0.19 at 140 degrees and 0.16 at 0 degrees. These may be interpolated for other temperatures.

The specific heats of mixtures of soils and water may be calculated by the equation:

$$\text{Specific Heat, Mixture} = \frac{(100 \times \text{Spec. Heat. Soil}) + \text{Moist. Cont.}}{100 + \text{Moisture Content}}$$

the moisture content being expressed as a percentage of the dry weight of the soil.

CONCLUSIONS

Consideration of the test results leads to the following conclusions:

Thermal Conductivity Tests on Soils:

1. The coefficient of thermal conductivity of soils above the freezing point increases slightly with an increase in mean temperature. Values at 70 degrees Fahrenheit average approximately 4 per cent more than those at 40 degrees.

2. In most cases, the coefficient of thermal conductivity does not vary appreciably in a mean temperature range of from +25 to -20 degrees Fahrenheit. At higher moisture contents, the -20 degree value becomes progressively greater than the +25 degree conductivity. For all tests made with moisture contents greater than 20 per cent, the low temperature values average 4 per cent more than the 25-degree results.

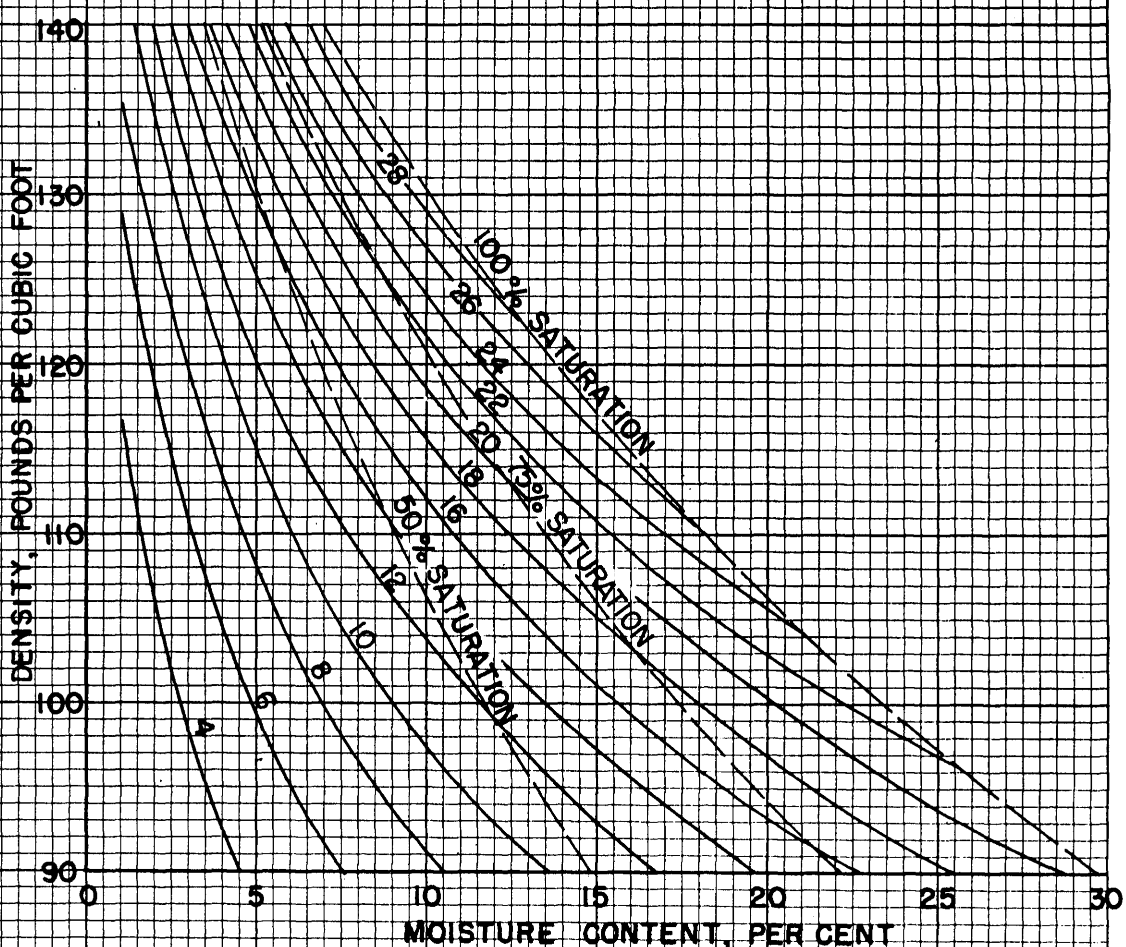
3. The difference in thermal conductivity above and below the freezing point is dependent upon the moisture content of the soil. For air-dry soils there is practically no difference in the two values. For moisture contents up to about 6 per cent in sandy soils or 12 per cent in fine textured soils, the conductivity is lower

FIG. 33

DIAGRAM OF THERMAL CONDUCTIVITY FOR SANDY SOILS

FROZEN, MEAN TEMPERATURE 25°F

DEGREE OF ACCURACY ±25 PER CENT



below freezing than above. With further increases in moisture content, the conductivity of frozen soils becomes progressively greater than that of unfrozen soils. At the modified optimum moisture content, the conductivity below freezing averages about 17 per cent greater than that above freezing. At a moisture content of 5 per cent more than the modified optimum, it is about 35 per cent greater.

4. At a constant moisture content, an increase in density results in an increase in conductivity. The rate of increase is about the same at all moisture contents, and is not markedly different for frozen and unfrozen soils. On the average, for each one-pound per cubic foot increase in density, the conductivity increases 2.8 per cent for unfrozen soils and 3.0 per cent for frozen soils.

5. At a constant density, an increase in moisture content causes an increase in conductivity. This is true up to the point of saturation and holds for frozen as well as unfrozen soils.

6. For saturated, unfrozen soils, the conductivity decreases for a decrease in density. For saturated, frozen soils, the data indicate no well-defined relationship between density and conductivity. Sand soils in such a condition and at densities normally obtainable gave higher conductivities than soils with relatively high silt and clay contents.

7. The thermal conductivity varies, in general, with the texture of soils. At a given density and moisture content, the conductivity is relatively high on coarse textured soils such as gravel or sand; somewhat lower on sandy loam soils; and the lowest on fine textured soils such as silt loam or clay. In the natural position in the field this order would not necessarily hold, since fine textured soils ordinarily exist at higher moisture contents than sandy soils.

8. The thermal conductivity of a soil is dependent upon its mineral composition. Sands with a high quartz content have greater conductivities than sands with high contents of such minerals as plagioclase feldspar and pyroxene, which are constituents of basic rocks. Soils with a relatively high content of kaolinite and other clay minerals have relatively low conductivities. This may be due to the fine texture and is not necessarily the result of the presence of these minerals.

9. The conductivity of crushed rocks of similar gradings vary according to type of rock. The order of conductivities of four crushed materials tested, from least to greatest, is trap rock, granite, potash feldspar, and quartz. The approximate relative magnitudes are 1.0, 1.3, 1.4, and 2.5, respectively.

10. The conductivity of two crushed quartz samples with angular particles was from 20 to 50 per cent greater than two quartz samples with rounded particles. The difference would appear to be due either to the type of contact between the particles or to a difference in the character of the quartz.

11. For purposes of prediction of thermal conductivity, soils should be divided into two groups, sands or sandy soils and silt and clay soils. The line of division, in general, is based upon the silt and clay content: soils with 50 per cent or more of silt and clay are in the fine textured group. The thermal conductivity also differs according to whether the soil is frozen or not. The four equations for these conditions are:

    (1) Silt and clay soils, unfrozen

    $$k = [0.9 \log (\text{Moist. Cont.}) - 0.2]10^{0.01\gamma}$$

(2) Silt and clay soils, frozen

$$k = 0.01\ (10)^{0.022\gamma} + 0.085\ (10)^{0.008\gamma}\ \text{(Moist. Cont.)}$$

(3) Sandy soils, unfrozen

$$k = [0.7 \log \text{(Moist. Cont.)} + 0.4]\ 10^{0.01\gamma}$$

(4) Sandy soils, frozen

$$k = 0.076\ (10)^{0.013\gamma} + 0.032\ (10)^{0.0146\gamma}\ \text{(Moist. Cont.)}$$

In these equations, the thermal conductivity, k, is in British thermal units per square foot per inch per hour per degree Fahrenheit, the moisture content is a per cent of the dry soil weight, and γ is the dry density in pounds per cubic foot. The equations for the silt and clay soils apply for moisture contents of 7 per cent or more; those for the sandy soils, of one per cent or more. The equations for sandy soils are largely based on tests on fairly clean sands. For sandy soils with a relatively high silt and clay content (for example 40 per cent), conductivity values intermediate between those calculated by two equations might be a reasonable prediction. It is expected that judicious use of the equations with an understanding of their limitations will give conductivity values not more than 25 per cent in error.

Specific Heat Tests:

1. The specific heat values of a wide variety of soils differ by only a small amount (about 0.01) and average 0.19 at 140 degrees Fahrenheit.
2. Specific heat values of soil decrease with a decrease in temperature. The change amounts to about 11 per cent for a drop in temperature of 100 degrees Fahrenheit.
3. The specific heat of soil-water mixtures may be calculated by proportion according to the percentage by weight of the two components and the respective specific heats. This statement is based on tests on just one soil.

Diffusivity:

No actual diffusivity tests were conducted. The effect of various factors upon diffusivity can, however, be determined by consideration of the diffusivity formulas and the variation of component parts as presented in this report. The following general conclusions have been arrived at in this manner:

1. Changes in temperature do not cause appreciable changes in diffusivity of a soil unless the temperature change is through the freezing point. In this instance, the diffusivity of soils with high moisture contents will have a marked increase when frozen.
2. At low or moderate moisture contents, an increase in moisture content of either a frozen or an unfrozen soil will cause an increase in diffusivity. This is not necessarily true at high moisture contents.
3. An increase in density of a soil causes a slight increase in diffusivity.

Thermal Conductivity Tests on Insulation Materials:

1. The thermal conductivity of Zonolite concrete slabs varies with the mean temperature. The change in conductivity was found to be from 5 to 12 per cent per

100 degrees Fahrenheit. The conductivity of the Cell concrete slabs showed practically no change with variations in the mean temperature.

2. The conductivity of both types of slabs shows an increase with an increase in density. The average increase in conductivity per pound per cubic foot increase in density was 3 per cent. This is approximately the same value found for soils.

Thermal Conductivity Tests on Bituminous Paving Mixture:

1. The thermal conductivity of a compacted bituminous paving mixture is greater than that of the dry aggregate alone, but is less than that of an aggregate with a moisture content comparable to the bituminous material content.

2. The thermal conductivity varies with mean temperature. The change amounts to about 7 per cent for a temperature change of 100 degrees Fahrenheit.

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APPENDIX I

Test Data

Thermal Conductivity Tests

APPENDIX I - SUMMARY OF THERMAL CONDUCTIVITY TESTS ON SOILS

Dry Density Lbs/Cu. Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs/Cu. Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4601, Chena River Gravel							
119.5	0.2	70.1	4.23	118.2	2.1	70.2	10.52
		39.9	4.03			40.0	9.74
		25.1	4.01			25.0	6.34
		-19.9	3.92			-20.1	5.95
126.7	0.2	70.1	4.79	108.2	3.1	70.1	7.63
		39.9	4.72			40.0	6.99
		25.0	4.69			25.0	4.62
		-20.0	4.65			-20.0	4.34
133.3	0.2	69.9	6.09	119.5	3.2	70.1	12.29
		40.1	6.00			40.1	11.69
		25.0	6.02			25.3	7.50
		-20.2	6.12			-20.0	7.27
115.9	0.7	70.1	4.03	125.3	2.9	70.1	13.55
		40.0	3.77			40.0	12.90
		25.2	3.58			25.1	8.58
		-19.9	3.48			-20.0	8.69
122.7	0.7	70.2	5.38	127.0	3.0	70.0	17.00
		40.3	5.14			40.2	16.56
		24.8	4.81			-19.7	17.76
		-20.0	4.93			25.3	12.07
127.7	0.7	70.1	6.27			-20.1	12.26
		40.0	5.91	111.8	3.8	70.0	9.92
		24.9	5.65			39.9	9.43
		-20.1	5.49			24.9	6.56
130.2	1.6	70.0	15.17			-20.1	6.20
		39.9	14.50	129.3	3.9	70.2	16.55
		25.1	10.09			39.8	16.33
		-19.9	10.08			25.0	14.13
110.0	1.9	70.1	7.85			-20.1	14.38
		40.0	7.03	105.3	5.2	69.9	9.15
		25.0	5.36			40.4	8.73
		-20.0	4.57			25.2	5.80
		70.1	7.81			-19.9	5.63
P4703, Crushed Quartz							
103.9	0.03	69.9	3.08	120.0	0.03	70.0	5.00
		39.9	2.98			40.0	5.00
		24.9	2.96			25.0	4.95
		-20.0	2.84			-20.1	4.94
113.0	0.03	70.0	4.23	103.0	0.7	70.0	6.14
		40.0	4.17			39.9	5.77
		25.0	4.16			24.9	5.07
		-19.9	4.08			-19.7	4.83

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs/Cu. Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4703							
120.0	0.7	70.1	9.94	120.2	3.8	70.1	20.87
	0.6	39.7	9.64		3.7	40.0	21.15
	0.6	24.8	9.06		3.7	25.1	19.48
	0.5	-19.9	8.97		3.6	-19.9	20.49
102.8	1.9	69.9	10.35	102.7	4.3	70.0	13.29
		40.0	9.54		4.3	39.8	12.87
		24.9	7.43		4.2	25.0	9.44
		-20.4	7.12		4.2	-20.0	10.04
119.6	2.1	70.0	16.88				
		40.1	16.39				
		24.9	14.38				
		-20.0	14.67				
P4704, Crushed Trap Rock							
102.6	0.2	70.1	2.06	103.0	1.9	70.0	4.56
		40.0	2.00			40.0	3.93
		24.9	2.00			24.9	3.39
		-20.0	1.94			-20.0	3.31
120.0	0.2	70.0	3.33	120.3	1.7	70.1	5.30
		39.8	3.27			40.0	4.66
		24.8	3.27			24.9	4.25
		-19.9	3.20			-20.1	4.25
103.0	1.0	70.0	2.96	103.2	3.8	70.0	5.78
	1.0	40.0	2.65			40.0	5.11
	0.9	25.0	2.53			25.0	4.51
	0.9	-20.0	2.44			-19.9	4.71
119.8	1.1	70.1	4.87	120.3	3.7	70.0	7.44
	1.1	40.0	4.49			39.9	6.88
	1.0	25.0	4.20			24.9	6.58
	1.0	-19.9	4.11			-20.1	6.55
P4705, Crushed Feldspar							
103.0	0.08	70.0	2.78	120.1	0.05	70.0	3.91
		40.1	2.74			39.9	3.92
		24.9	2.73			25.0	3.91
		-20.0	2.66			-19.9	3.89
112.0	0.07	70.0	3.19	102.8	1.1	69.9	4.60
		40.0	3.13		1.1	40.1	4.33
		24.9	3.19		1.0	25.0	3.81
		-19.8	3.09		1.0	-20.2	3.68

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4705							
111.7	1.1	70.0	5.92	111.3	2.6	70.0	7.19
		40.0	5.31			40.0	6.60
		24.9	4.77			25.0	6.02
		-20.0	4.65			-20.1	5.87
119.7	0.9	70.0	6.39	103.1	3.9	70.0	7.01
		40.0	6.01		3.9	40.1	6.40
		25.0	5.61		3.8	25.0	5.58
		-19.9	5.53		3.8	-20.2	6.20
102.9	2.1	70.0	6.33	111.8	4.1	70.1	8.41
		39.9	5.64		4.1	40.0	7.89
		24.9	4.81		4.0	25.0	7.09
		-20.1	4.68		4.0	-20.0	7.02
120.2	1.8	69.9	8.08	119.9	4.1	69.9	9.63
		40.1	7.53			40.0	9.43
		25.0	7.29			25.1	9.37
		-20.1	7.61			-20.1	9.48
P4706, Crushed Granite							
106.1	0.07	70.1	2.23	120.4	1.7	70.0	7.44
		40.0	2.23		1.7	40.0	6.71
		25.0	2.18		1.6	24.9	5.77
		-20.0	2.15		1.6	-20.0	5.62
120.0	0.09	69.9	3.27	102.4	2.6	69.9	6.29
		39.7	3.24		2.5	39.9	5.61
		24.8	3.21		2.4	24.9	4.76
		-19.9	3.17		2.3	-19.9	4.54
103.0	0.7	70.0	2.95	120.1	3.9	69.9	9.96
	0.7	40.0	2.73			39.9	9.58
	0.6	24.9	2,50			25.0	9.08
	0.6	-20.1	2.42			-20.0	9.30
119.9	0.7	70.0	5.21	102.9	4.1	70.1	6.67
		40.0	4.90		4.1	40.1	6.09
		25.0	4.53		4.0	25.0	4.88
		-20.1	4.35		4.0	-20.2	4.80
103.2	1.5	70.0	5.08				
	1.5	40.0	4.38				
	1.4	25.0	3.47				
	1.4	-20.0	3.29				
P4702, Standard Ottawa Sand 20-30							
97.6	0.014	69.8	1.77	107.6	0.013	70.1	2.42
		39.9	1.70			39.9	2.39
		24.9	1.68			25.1	2.39
		-19.8	1.62			-19.9	2.34

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4702							
97.7	0.6	70.1	3.12	107.6	1.0	69.9	6.47
	0.6	39.9	2.99			40.0	6.56
	0.6	24.7	2.16			24.9	3.91
	0.5	-19.9	1.99			-19.9	3.74
97.3	1.6	70.2	5.29	108.1	1.5	69.9	13.11
	1.5	39.9	5.31		1.5	40.0	12.52
	1.5	25.1	2.37		1.4	24.9	4.08
	1.4	-20.0	2.15		1.4	-20.0	5.50
108.7	1.8	70.1	13.42				
	1.7	40.1	12.78				
	1.7	24.8	4.57				
	1.6	-19.9	4.42				
	1.6	64.9	10.46				
P4701, Graded Ottawa Sand							
96.7	0.02	69.9	1.76	97.2	1.7	70.3	5.28
		40.1	1.68		1.7	40.0	5.19
		25.0	1.66		1.6	24.9	3.63
		-19.8	1.62		1.6	-20.1	3.43
102.1	0.02	69.9	2.05	108.2	1.8	69.8	7.75
		39.9	2.00		1.7	40.0	7.72
		25.0	1.99		1.7	24.9	5.11
		-20.2	1.95		1.6	-20.0	5.06
107.2	0.02	70.2	2.54	108.3	5.7	69.9	15.09
		40.0	2.53		5.3	39.9	14.72
		25.0	2.54		4.9	24.7	8.41
		-20.1	2.54		4.5	-20.0	8.44
96.9	0.8	69.9	3.55	97.2	5.8	70.0	11.27
	0.7	39.9	3.27		5.4	40.1	10.83
	0.7	25.0	3.09		5.0	25.4	5.10
	0.6	-19.8	2.92		4.6	-19.6	4.78
107.9	0.8	70.0	4.75				
	0.7	40.0	4.47				
	0.7	25.0	4.10				
	0.6	-20.0	5.99				
P4714, Fine Crushed Quartz							
97.0	0.02	70.1	2.59	106.6	0.02	69.8	3.30
		39.8	2.55			39.9	3.28
		25.2	2.50			25.2	3.28
		-20.1	2.48			-20.4	3.27
102.0	0.02	70.2	2.86	97.6	1.1	70.0	5.69
		40.0	2.84		1.0	40.0	5.41
		25.3	2.85		1.0	25.1	4.88
		-19.9	2.83		0.9	-19.9	4.59

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4714							
108.3	0.7	70.1	6.14	107.7	4.3	70.1	14.70
	0.7	40.3	5.93			39.8	15.21
	0.6	25.0	5.64	97.2	4.7	70.1	11.71
	0.6	-20.0	5.50		4.6	39.7	12.00
98.0	1.8	69.9	9.62		4.5	25.1	10.53
		39.9	9.41		4.4	-20.0	10.29
		24.9	8.64				
		-19.8	8.39				
107.0	2.0	70.0	11.28				
	2.0	39.9	11.39				
	1.9	25.2	10.66				
	1.9	-19.7	10.48				
P4709, Fairbanks Sand							
106.6	0.2	69.8	2.32	107.0	2.5	70.0	9.50
		40.1	2.29		2.5	40.0	8.49
		25.1	2.26		2.4	25.0	5.98
		-20.1	2.19		2.4	-20.2	5.81
113.0	0.2	70.0	2.64	112.8	2.6	69.9	10.90
		40.4	2.62		2.6	40.0	10.03
		25.1	2.59		2.5	25.1	7.12
		-19.8	2.51		2.5	-19.9	8.65
120.4	0.2	69.8	3.70	120.5	2.6	70.2	13.06
		39.8	3.61			39.7	12.42
		24.9	3.60			25.2	10.48
		-19.6	3.44			-20.1	10.93
107.1	1.2	70.0	4.43	117.3	5.4	70.0	15.91
	1.2	40.1	4.01			40.4	15.43
	1.1	25.1	3.78	107.1	5.9	69.8	11.11
	1.1	-20.0	3.63		5.9	39.9	10.88
112.8	1.3	70.1	6.13		5.8	25.1	8.81
	1.3	40.2	5.60		5.8	-20.0	9.48
	1.2	25.0	4.93	112.9	6.3	69.9	14.40
	1.2	-20.1	5.04		6.2	40.0	14.08
119.6	1.3	70.1	6.78		6.0	25.3	11.06
	1.3	39.9	6.36		5.9	-20.1	11.33
	1.2	25.2	5.60	119.7	6.2	70.3	15.33
	1.2	-20.0	5.51		6.1	39.7	15.20
123.2	1.3	69.9	9.05		6.0	25.1	13.58
	1.3	40.1	8.34		5.9	-20.0	14.06
	1.2	25.2	7.66				
	1.2	-20.0	7.63				

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4709			
107.3	10.7	69.8	14.60
		39.8	14.43
		25.4	15.54
		-19.7	15.29
120.4	10.6	70.4	17.67
	10.5	40.0	17.63
	10.4	25.1	22.20
	10.3	-20.1	22.98
112.0	11.9	69.9	16.05
	11.8	39.9	15.92
	11.7	25.0	18.54
	11.6	-20.2	18.82
113.8	14.2	24.6	22.63
107.4	17.6	25.1	25.15
P4604, Lowell Sand			
90.8	0.2	69.8	1.55
		39.9	1.49
93.3	0.3	70.0	1.70
		40.1	1.63
		25.0	1.62
		3.0	1.54
93.2	0.2	70.0	1.70
		39.6	1.63
100.0	0.2	69.8	1.91
		40.1	1.88
		24.9	1.85
		- 0.1	1.80
		-20.0	1.81
105.5	0.2	70.1	2.32
		40.0	2.27
		3.1	2.20
		25.1	2.27
112.0	0.2	25.0	2.53
		10.1	2.48
		2.2	2.50
		40.3	2.53
		55.3	2.52
		70.2	2.54
		85.2	2.55
		39.9	2.54
99.8	4.1	70.1	9.16
		39.7	8.50
		24.9	6.49
		0.0	6.18
		-19.9	6.34
		70.6	8.98
105.9	4.4	70.1	10.55
		40.0	10.13
		25.1	8.19
		0.0	8.01
		-20.0	8.32
		70.2	10.48
112.0	3.9	70.0	12.00
		40.0	11.49
		24.9	9.86
		0.1	9.73
		-20.2	10.08
		70.3	12.05
104.8	12.2	70.1	12.44
	11.8	40.0	12.08
	11.3	25.0	11.1**
	10.9	- 0.1	12.09
	10.4	-19.9	16.58
	10.0	70.2	12.12
105.4	11.8	70.2	13.52
	11.0	40.1	13.59
	11.2	24.9	15.02
	11.4	0.3	17.49
	11.6	- 0.1	16.35
	11.7	-20.1	18.66
	11.6	-20.2	21.23
111.9	12.0	70.1	15.75
	11.8	39.9	15.64
	11.6	25.1	18.94
	11.4	2.2	18.58
	11.2	70.3	15.30
	10.8	-19.8	22.90
112.2	11.8	69.9	15.55
	11.7	40.0	15.35
	11.6	25.3	20.04
	11.5	0.2	19.67
	11.4	-20.0	20.42
	11.2	70.3	15.08
118.5	10.8	70.0	17.46
	10.7	39.8	17.15
	10.6	25.2	21.33
	10.5	10.2	21.43
	10.3	70.0	17.01

*k in Btu's per square foot per inch per hour per degree F..
**Good balance not obtained.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4604			
105.8	14.4	70.0	13.52
	13.7	40.0	13.14
	13.0	25.2	15.97
	12.3	0.0	15.68
	11.6	-20.0	16.27
	10.9	70.2	13.27
112.8	14.6	70.0	15.77
	14.0	40.1	15.44
	13.4	25.0	21.01
	12.8	70.4	15.20
	12.2	3.1	23.07
98.9	17.7	25.1	18.84
104.4	17.7	39.9	15.21
		24.6	22.84
P4503, Northway Sand			
92.2	0.6	69.9	1.43
		40.0	1.40
		24.8	1.39
		- 4.9	1.33
99.9	0.7	70.3	1.79
		40.2	1.77
		-20.2	1.72
101.0	0.8	70.2	1.85
		39.9	1.76
		24.9	1.77
		10.3	1.71
105.7	0.8	70.0	2.05
		40.2	2.00
		24.9	2.00
		- 0.1	1.93
		-20.0	1.95
92.1	3.9	69.9	4.15
	3.8	40.1	3.43
	3.8	25.2	2.71
	3.7	0.1	2.55
	3.7	-20.1	2.57
	3.6	70.5	4.01
100.6	4.1	70.0	5.27
		40.5	4.72
		25.1	3.92
		00.3	3.97
		-20.1	4.16
105.6	4.3	70.3	5.70
		40.0	5.42
		25.3	4.71
		0.0	4.73
		-20.1	4.91
104.2	9.5	70.1	6.56
	9.2	39.9	6.16
	8.8	15.4	5.61
	8.5	- 5.0	5.41
	8.2	69.7	6.39
99.1	14.8	70.2	6.67
	14.6	40.3	6.46
	14.4	25.2	6.99
	14.2	0.2	6.85
	14.0	-20.1	7.10
	13.8	70.0	6.78
105.9	14.0	70.1	7.66
	13.6	40.1	7.27
	13.2	25.3	8.40
	12.8	- 0.2	8.09
	12.4	-20.2	8.25
	12.0	70.4	7.48
113.2	13.5	70.2	8.70
	13.3	40.2	8.35
	13.1	25.1	9.86
	12.9	0.1	9.78
	12.7	-20.0	10.05
	12.5	70.0	8.38
105.8	17.0	70.0	8.44
	16.5	39.8	8.12
	16.0	24.9	11.17
	15.5	- 0.3	11.12
	15.0	-20.1	11.47
	14.5	70.3	8.28
97.9	21.8	24.9	10.92

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4502, Northway Fine Sand							
97.4	0.5	69.8	1.48	102.7	5.2	70.1	6.26
		40.1	1.44			39.8	6.01
		24.9	1.43			25.0	5.92
		-19.9	1.38			-20.3	6.33
102.7	0.5	70.1	1.69	109.8	5.2	70.1	7.10
		39.9	1.62			40.2	6.93
		24.9	1.65			24.9	6.93
		-20.0	1.61			-20.0	6.99
110.3	0.5	69.8	2.07	102.7	10.9	70.0	7.70
		39.9	2.06			40.2	7.54
		24.7	2.08			24.9	8.76
		-20.3	2.07			-20.1	8.64
103.1	2.0	69.8	2.94	110.3	11.2	70.0	8.50
		39.8	2.72			39.8	8.66
		24.9	2.62			25.2	10.52
		-19.8	2.57			-20.0	10.59
						39.9	8.61
110.0	1.9	70.2	3.26			69.9	8.76
		40.1	3.04				
		25.0	2.98	116.1	11.4	69.8	9.77
		-20.0	3.01		11.4	40.2	9.49
					11.3	25.0	11.89
109.8	2.1	70.3	3.80		11.3	-19.8	12.11
		40.0	3.45				
		25.2	3.32	110.2	13.9	70.1	9.82
		-20.1	3.33		13.9	39.9	9.57
					14.0	24.9	13.06
97.6	5.1	70.0	5.90		14.0	-20.2	13.17
		40.3	5.52				
		25.1	5.24				
		-20.0	5.12				
P4711, Dakota Sandy Loam							
84.4	2.0	70.2	1.80	119.9	2.1	70.2	6.21
	1.9	40.1	1.70			40.1	6.12
	1.9	25.2	1.73			24.8	6.12
	1.8	-20.0	1.65			-20.1	6.19
99.9	2.1	70.2	3.28	110.3	3.4	70.1	5.67
		40.1	3.19		3.4	40.1	5.47
		25.0	3.18		3.3	25.1	5.29
		-20.2	3.14		3.3	-19.8	5.33
110.1	2.0	70.0	3.91	120.3	3.7	70.0	9.30
	1.9	40.0	3.84		3.6	39.7	8.94
	1.9	24.9	3.78		3.5	24.9	8.77
	1.8	-19.7	3.79		3.4	-20.4	8.91

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4711							
130.1	3.6	70.3	11.72	137.0	6.4	70.0	19.08
	3.5	40.2	11.45		6.3	40,0	18.88
	3.5	24.9	11.42		6.2	24.9	20.28
	3.4	-20.0	12.01		6.1	-20.0	22.12
122.9	4.0	69.8	9.62	120.1	8.9	70.1	14.98
	4.0	40.0	9.14		8.9	40.0	15.01
	3.9	25.2	8.97		8.8	25.0	17.22
	3.9	-19.8	9.04		8.8	-20.2	16.66
120.1	4.9	70.2	10.67	129.6	9.3	69.8	18.28
		39.7	10.25		9.3	39.9	18.31
		24.9	9.55		9.2	25.1	21.09
		-20.1	9.76		9.2	-19.8	22.99
131.8	5.0	70.0	15.90	119.5	13.9	69.8	16.03
	4.9	40.0	15.75		13.6	39.7	16.39
	4.9	25.0	16.31		13.3	24.6	22.01
	4.8	-20.0	17.66		13.0	-20.1	24.04
133.1	5.0	69.9	16.29	109.6	18.4	25.1	21.17
	4.9	20.0	15.98				
	4.9	25.0	16.84				
	4.8	-20.0	17.97				
P4713, Ramsey Sandy Loam							
87.6	2.6	70.3	1.78	119.0	6.9	70.2	10.76
		40.3	1.72		6.8	39.8	10.51
		25.4	1.71		6.8	24.9	10.45
		-20.1	1.65		6.7	-20.1	10.50
100.5	2.7	70.2	3.70	99.5	9.5	70.1	8.35
		40.0	3.62		9.4	40.2	7.74
		25.3	3.60		9.2	25.1	6.86
		-20.1	3.58		9.1	-19.8	7.02
108.8	3.0	70.0	4.79	109.5	9.5	70.1	10.63
	2.9	39.9	4.72			40.1	10.31
	2.7	25.3	4.71			25.0	8.60
	2.6	-20.4	4.71			-20.2	8.62
99.2	6.8	70.1	5.94	119.5	9.4	69.9	12.11
	6.6	40.2	5.63			39.8	12.01
	6.4	25.1	5.39			24.8	10.45
	6.2	-19.9	5.56			-20.1	10.57
109.5	6.4	69.9	8.24	126.1	9.7	70.1	16.70
	6.3	40.2	7.99		9.6	40.0	16.49
	6.2	24.7	7.89		9.6	25.0	17.43
	6.1	-20.1	8.08		9.5	-20.0	19.32

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4713			
100.2	13.8	70.4	9.63
	13.7	39.9	8.88
	13.7	25.2	9.56
	13.6	-20.0	8.93
110.5	13.4	69.9	11.72
	13.3	40.1	11.44
	13.1	25.0	12.50
	13.0	-20.0	12.52
121.1	12.9	69.8	14.89
	12.8	39.9	14.78
	12.7	25.0	17.29
	12.6	-20.0	19.23
99.2	18.3	70.0	10.40
	18.0	40.1	10.10
	17.8	24.9	12.96
	17.5	-20.2	14.06
109.5	18.6	70.5	12.35
	18.3	39.9	12.22
	18.1	25.0	16.58
	17.8	-19.9	18.38
P4505, Northway Silt Loam			
74.7	1.8	70.1	1.03
	1.8	40.2	1.00
	1.8	24.9	0.99
	1.7	0.1	0.96
	1.7	-20.2	0.98
	1.7	70.3	1.03
84.0	1.7	70.0	1.26
		40.1	1.21
		25.0	1.20
		0.1	1.19
		-20.4	1.18
90.3	1.4	70.0	1.32
		40.1	1.29
		25.1	1.29
		- 0.3	1.26
		-20.2	1.30
		69.9	1.32
96.9	1.7	70.0	1.66
		39.8	1.62
		24.8	1.63
		0.1	1.61
		-20.4	1.59
		70.0	1.65
97.3	6.7	70.2	4.21
	6.6	40.1	3.77
	6.6	25.1	3.65
	6.5	0.1	3.49
	6.5	-19.9	3.53
	6.4	70.3	3.90
89.3	16.6	70.3	5.68
	16.5	40.4	5.27
	16.4	24.9	6.50
	16.3	- 0.1	6.60
	16.2	-20.0	6.72
	16.1	70.2	5.55
96.2	16.4	70.0	6.52
	16.4	40.0	6.25
	16.4	25.2	7.54
	16.3	0.0	7.51
	16.3	-20.0	8.11
	16.3	70.2	6.43
113.8	14.6	69.9	9.34
	14.5	40.1	8.81
	14.4	25.0	10.58
	14.4	0.1	10.68
	14.3	-20.0	11.07
	14.2	69.8	9.22
90.7	23.1	70.0	6.92
	23.0	39.9	6.75
	22.9	24.9	8.92
	22.9	0.1	8.76
	22.8	-19.7	9.03
	22.7	69.9	6.71
98.0	22.7	70.0	7.74
	22.5	40.1	7.15
	22.3	25.0	10.67
	22.1	0.0	10.85
	21.9	-20.1	11.17
	21.7	70.0	7.62

*k in Btu's per square foot per inch per hour per degree F.

P4602, Fairbanks Silt Loam

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
70.0	2.4	68.9	1.09
		39.8	1.10
		25.0	1.10
		0.1	1.06
		-20.6	1.04
		69.9	1.12
82.4	2.3	70.2	1.55
	2.3	40.0	1.52
	2.3	24.9	1.52
	2.2	0.5	1.48
	2.2	-19.8	1.51
	2.2	70.0	1.55
83.2	7.6	70.1	3.32
		40.1	3.07
		25.0	2.93
		0.2	2.90
		-19.9	2.89
93.5	7.4	70.5	4.71
	7.4	39.9	4.29
	7.3	25.1	4.20
	7.3	0.0	4.06
	7.3	-20.7	4.13
	7.3	70.2	4.25
100.9	9.1	70.1	6.91
	9.0	40.1	6.57
	8.9	24.9	6.60
	8.8	0.1	6.37
	8.7	-20.0	6.51
	8.6	70.7	6.67
94.4	13.8	69.8	7.02
	13.8	40.0	6.66
	13.8	25.0	7.28
	13.7	0.3	7.02
	13.7	-20.0	7.07
	13.7	70.2	6.90

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
103.7	15.0	70.0	9.69
	15.1	40.1	9.56
	15.2	25.0	12.07
	15.3	0.1	12.74
	15.4	-19.7	13.07
109.4	15.6	70.0	12.28
	15.5	40.0	11.77
	15.4	25.0	14.60
	15.3	- 0.4	15.04
	15.2	-20.1	15.69
	15.1	70.0	11.84
93.3	21.1	70.0	8.71
		39.9	8.49
		25.0	11.35
		0.2	10.98
		-19.1	11.22
		70.1	8.47
101.9	21.1	70.2	11.16
	20.8	40.1	10.82
	20.5	24.9	14.66
	20.3	0.5	14.30
	20.1	-19.9	14.54
	19.9	70.1	10.84
83.8	23.8	70.4	7.20
		40.0	6.98
		25.1	9.47
		0.1	8.72
		-19.8	8.71
93.3	24.6	70.4	9.93
	24.4	40.0	9.55
	24.2	24.9	13.23
	24.0	- 0.1	13.77
	23.8	-20.5	14.20
	23.6	70.1	9.63
85.7	29.7	24.7	14.31
81.4	34.1	24.9	14.16
76.5	39.0	24.8	16.32

P4710, Fairbanks Silty Clay Loam

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
57.7	2.4	69.9	0.95
		40.2	0.95
		25.0	0.97
		-20.0	0.94
69.8	2.5	70.2	1.36
		40.0	1.33
		24.8	1.31
		-20.2	1.27

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent.	Mean Temp. Deg. F.	k*
P4710							
79.8	2.6	70.0	1.67	89.8	18.1	70.5	7.48
	2.5	40.1	1.64		18.0	40.1	7.16
	2.4	24.8	1.63		17.8	24.7	8.85
	2.3	-20.4	1.62		17.7	-20.2	9.20
79.4	6.7	69.8	3.30	102.0	18.0	70.0	9.56
	6.7	39.8	2.98		17.9	40.1	9.35
	6.6	25.0	2.91		17.8	25.0	11.76
	6.6	-19.7	2.88		17.7	-20.3	12.65
88.8	7.0	70.3	4.02	79.7	25.4	70.4	6.61
	6.9	39.7	3.73		25.2	40.3	6.25
	6.9	25.2	3.62		25.0	24.6	8.33
	6.8	-20.0	3.48		24.8	-20.1	8.41
80.1	12.4	70.2	4.98	89.6	25.5	70.0	8.31
	12.3	40.1	4.47		25.4	40.0	8.17
	12.3	25.0	4.38		25.3	25.0	11.07
	12.2	-19.9	4.24		25.2	-20.0	11.44
90.1	12.4	69.9	6.26	94.7	25.4	69.7	9.32
	12.3	39.9	5.90		25.0	39.8	9.47
	12.2	25.0	6.03		24.7	24.9	12.82
	12.1	-20.1	5.98		24.3	-20.1	13.52
100.9	12.6	70.0	8.01	90.3	30.3	70.1	8.44
	12.5	40.1	7.68		30.0	40.1	8.48
	12.4	24.8	8.33		29.7	25.2	13.23
	12.3	-20.2	8.61		29.4	-20.0	13.92
80.3	17.6	70.1	6.02	81.2	36.7	69.8	8.59
		40.0	5.62			40.0	8.69
		24.9	6.47	79.5	37.3	24.9	13.51
		-20.2	6.46				
P4708, Healy Clay							
64.0	3.2	70.1	1.14	84.9	6.8	70.0	3.13
	3.2	39.9	1.08		6.7	39.8	2.90
	3.1	24.8	1.06		6.6	24.7	2.85
	3.1	-19.9	1.06		6.5	-19.8	2.80
73.9	3.2	70.0	1.42	93.0	6.6	69.9	4.29
	3.2	40.0	1.41		6.4	40.0	4.11
	3.1	25.0	1.38		6.2	25.1	4.05
	3.1	-19.9	1.34		6.0	-19.9	3.93
84.2	3.0	70.2	2.10	83.9	10.8	69.9	4.94
	3.0	40.0	2.06		10.7	40.3	4.43
	3.1	25.1	2.07		10.6	24.7	4.31
	3.1	-19.9	2.04		10.5	-20.1	4.25

*k in Btu's per square foot per inch per hour per degree F.

Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*	Dry Density Lbs./Cu.Ft.	Moist. Cont. Per Cent	Mean Temp. Deg. F.	k*
P4708							
93.9	10.9	69.9	6.42	93.5	22.5	69.7	9.50
	10.8	40.4	6.12		22.3	39.9	9.36
	10.8	25.4	6.15		22.1	25.1	11.27
	10.7	-19.9	6.24		21.9	-20.1	12.78
83.9	17.2	70.1	7.00	103.8	21.8	69.9	10.76
		39.7	6.59		21.6	40.1	10.70
		24.8	6.57		21.4	24.8	13.75
		-20.1	6.62		21.2	-20.3	15.16
94.0	17.0	70.0	8.61	71.7	35.7	70.0	6.24
		39.8	8.28		35.0	40.1	5.71
		25.0	8.82		34.4	25.0	9.71
		-20.0	9.18		33.7	-20.4	10.63
108.2	15.7	70.0	11.51	80.6	35.4	70.0	8.88
	15.5	39.9	11.30		34.8	40.1	8.78
	15.3	25.2	13.05		34.3	25.1	13.17
	15.1	-19.9	13.97		33.7	-19.3	14.61
83.6	22.6	70.0	6.73				
	22.7	40.0	6.33				
	22.8	24.9	7.23				
	22.9	-20.0	7.13				
P4707, Fairbanks Peat							
13.9	10.4	70.0	0.39	24.8	170.0	70.2	3.10
		40.1	0.36			40.0	3.12
		24.9	0.35			25.0	7.72
		-19.2	0.31**			-20.0	8.51
21.7	9.3	69.7	0.48	7.4	271.0	69.9	1.27
		40.1	0.46			40.0	0.94
		25.0	0.46			25.1	1.51
		-19.5	0.32**			-20.2	1.38
7.5	112.0	70.1	0.82	14.5	284.0	69.7	2.90
		40.1	0.63			40.1	2.78
		25.4	0.66			25.0	6.94
		-20.0	0.62			-20.0	7.07
14.3	109.0	70.1	1.20	17.8	277.0	70.3	3.26
		40.0	0.95			39.9	3.10
		24.9	1.14			24.7	8.81
		-20.2	1.12			-20.3	9.83
21.0	113.0	70.0	2.00	14.3	174.0	69.7	2.04
		39.9	1.75			39.9	1.72
		25.0	2.43			24.9	2.99
		-19.8	2.18			-19.8	2.57
8.1	176.0	70.2	0.92	20.7	185.0	70.2	2.77
		40.2	0.69			40.0	2.57
		24.9	0.83			25.2	5.65
		-19.8	0.18			-19.6	4.87

*k in Btu's per square foot per inch per hour per degree F.

**Poor run; one balancing couple off; values are too low.

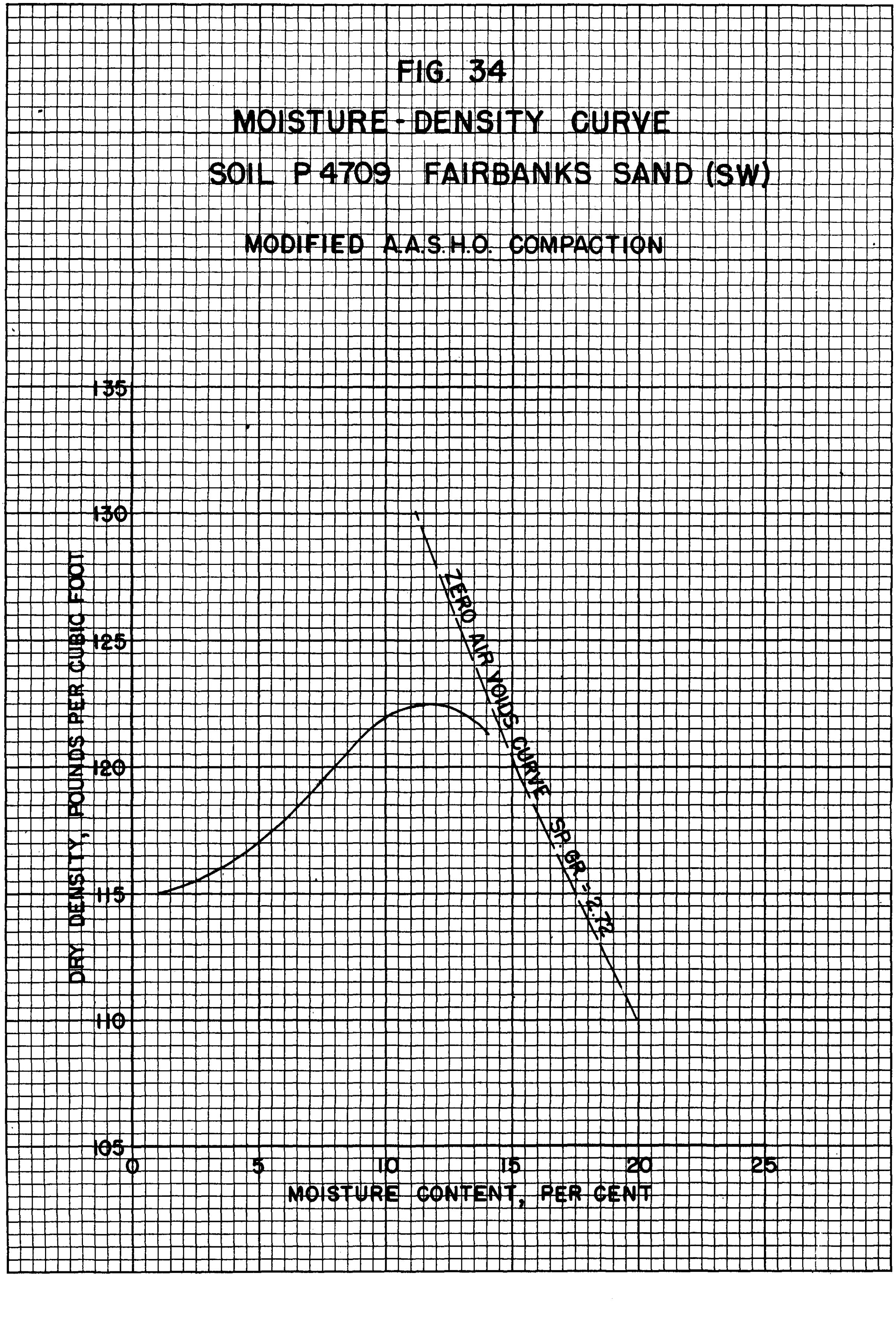


FIG. 34
MOISTURE - DENSITY CURVE
SOIL P 4709 FAIRBANKS SAND (SW)
MODIFIED A.A.S.H.O. COMPACTION
ZERO AIR VOIDS CURVE SP. GR. = 2.72
DRY DENSITY, POUNDS PER CUBIC FOOT
135
130
125
120
115
110
105
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

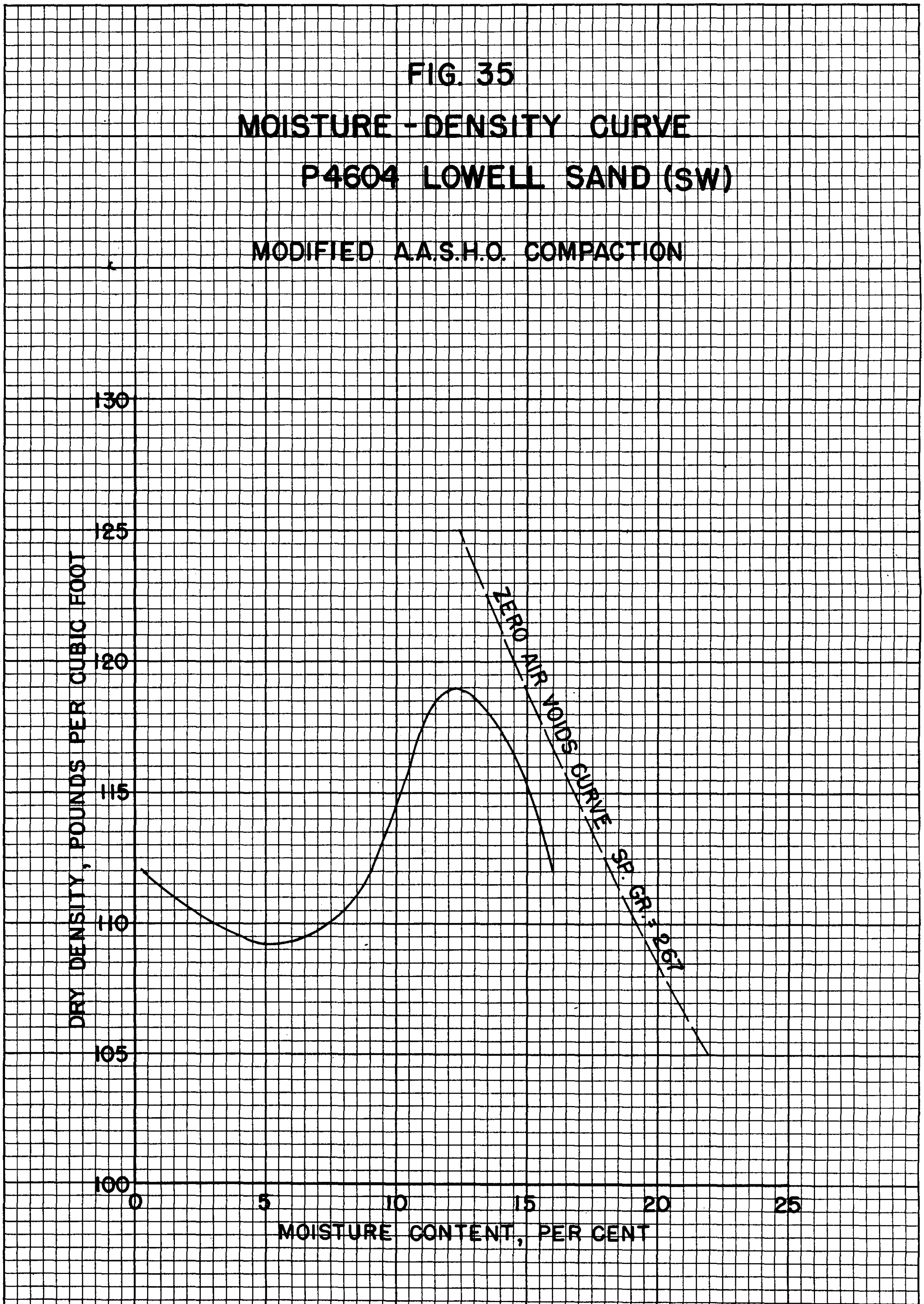


FIG. 35
MOISTURE - DENSITY CURVE
P4604 LOWELL SAND (SW)
MODIFIED A.A.S.H.O. COMPACTION
ZERO AIR VOIDS CURVE SP. GR. = 2.67
DRY DENSITY, POUNDS PER CUBIC FOOT
130
125
120
115
110
105
100
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

FIG. 36

MOISTURE - DENSITY CURVE

SOIL P 4503 NORTHWAY SAND (SW)

MODIFIED A.A.S.H.O. COMPACTION

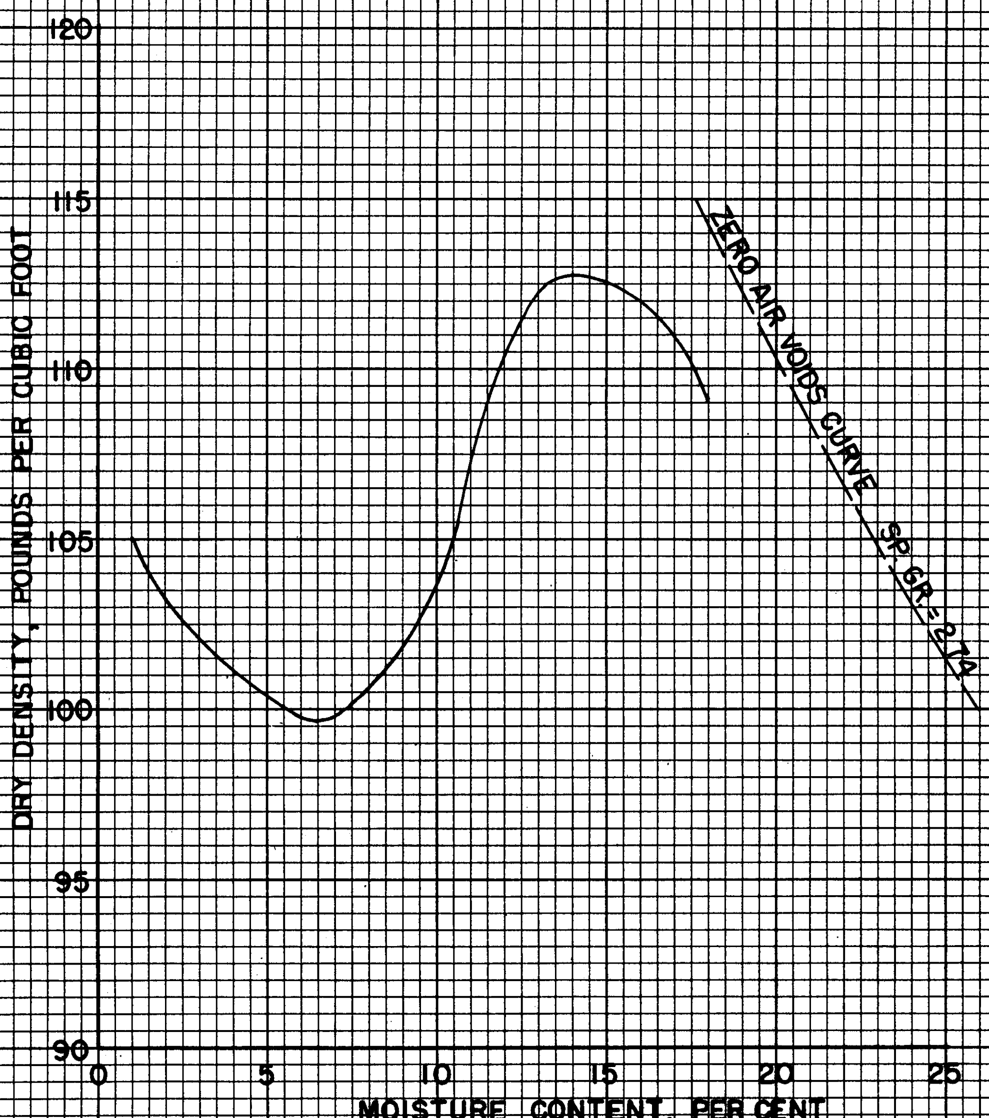
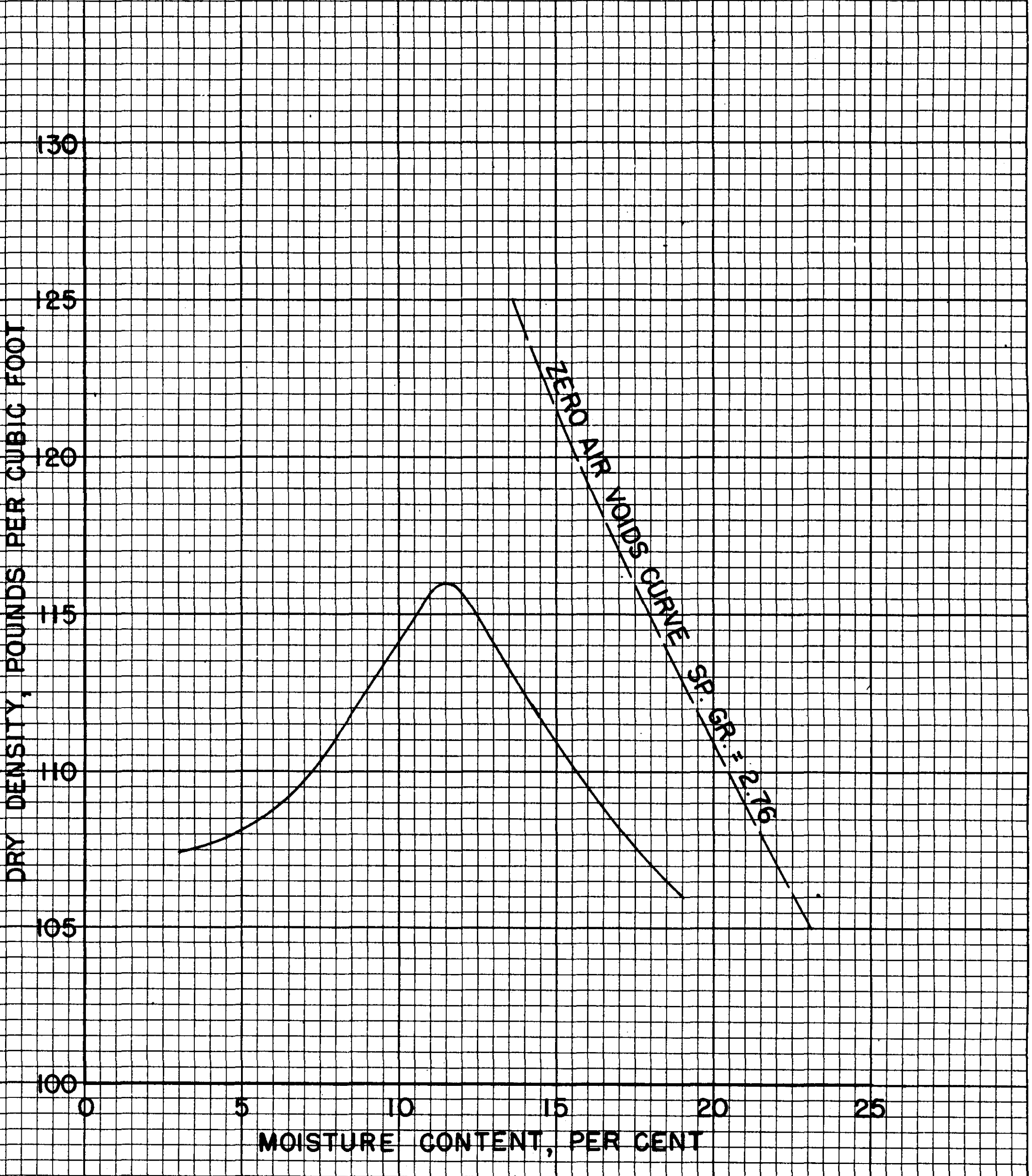


FIG. 37

MOISTURE - DENSITY CURVE

SOIL P4502 NORTHWAY FINE SAND (SP)

MODIFIED A.A.S.H.O. COMPACTION



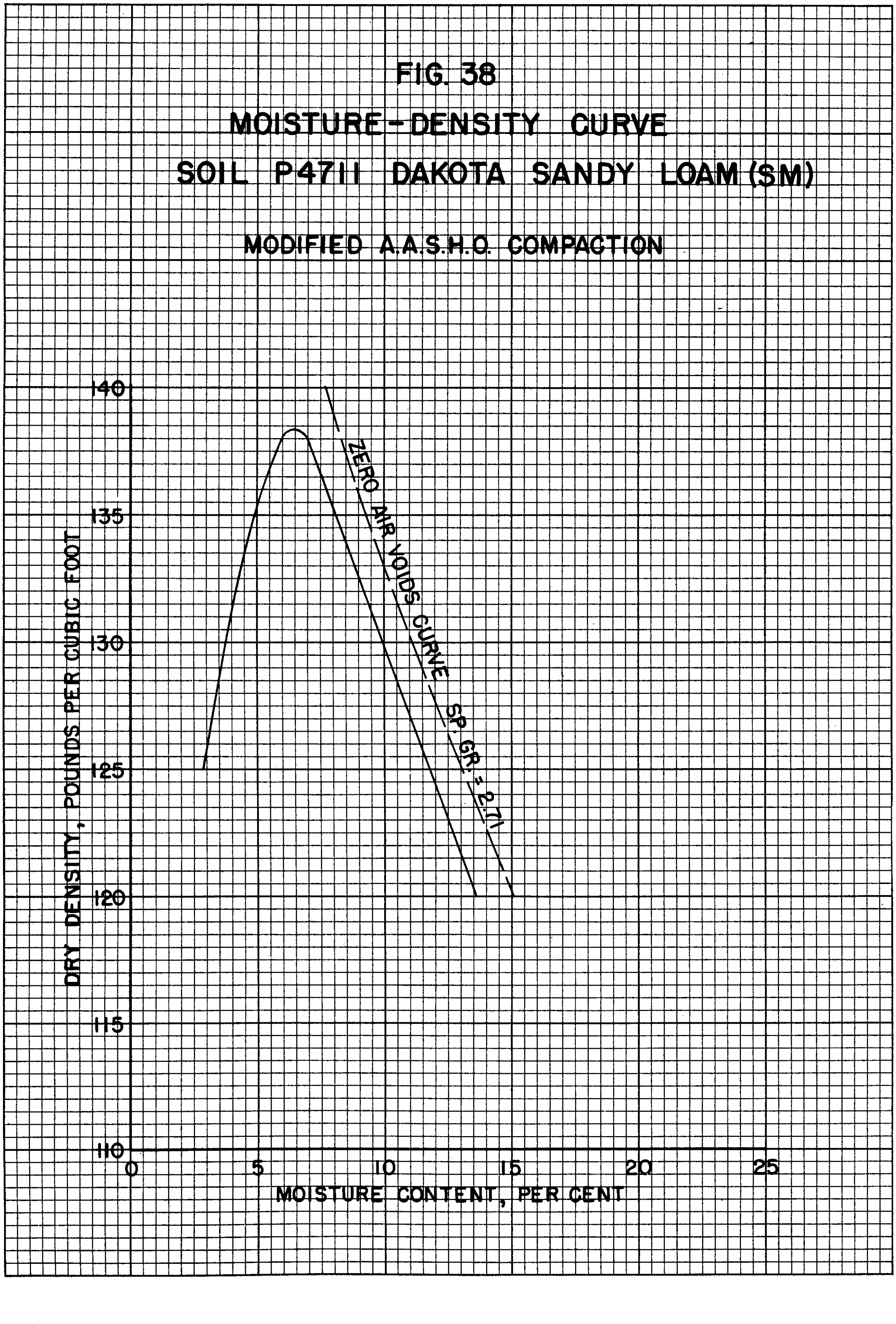


FIG. 38
MOISTURE-DENSITY CURVE
SOIL P4711 DAKOTA SANDY LOAM (SM)
MODIFIED A.A.S.H.O. COMPACTION
ZERO AIR VOIDS CURVE SP. GR. = 2.71
DRY DENSITY, POUNDS PER CUBIC FOOT
140
135
130
125
120
115
110
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

FIG. 39

MOISTURE-DENSITY CURVE

SOIL P 4713 RAMSEY SANDY LOAM (CL)

MODIFIED A.A.S.H.O. COMPACTION

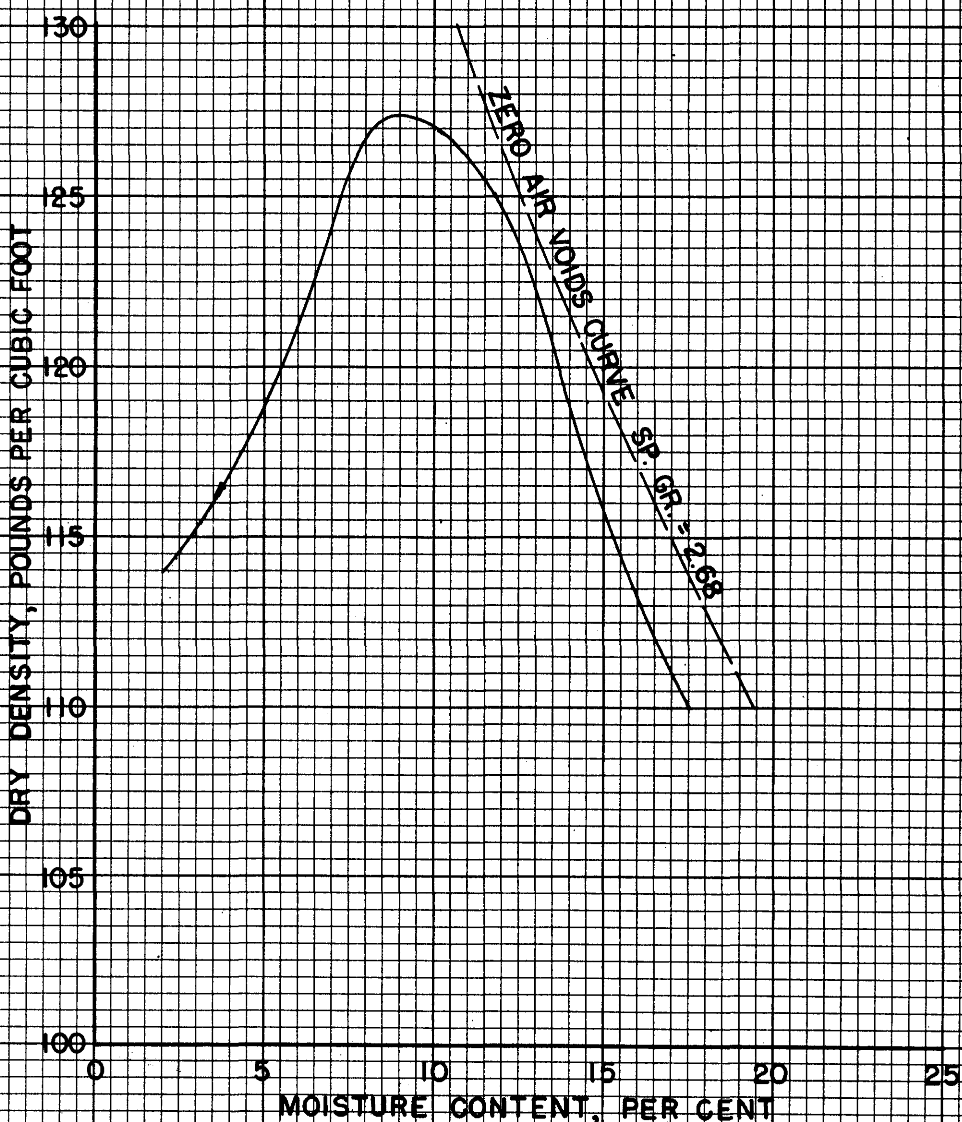
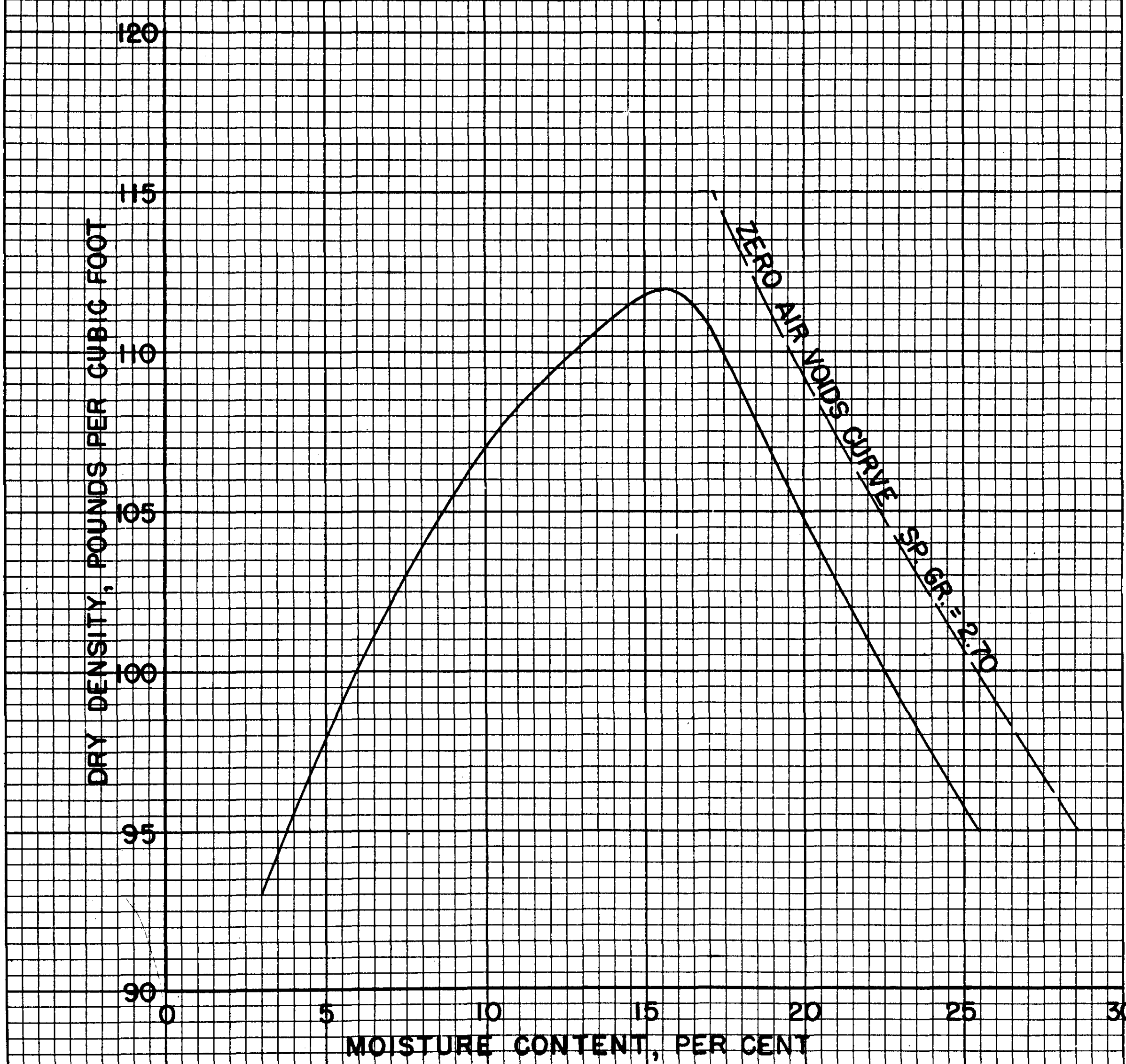


FIG. 40

MOISTURE - DENSITY CURVE

SOIL P4505 NORTHWAY SILT LOAM (ML)

MODIFIED A.A.S.H.O. COMPACTION



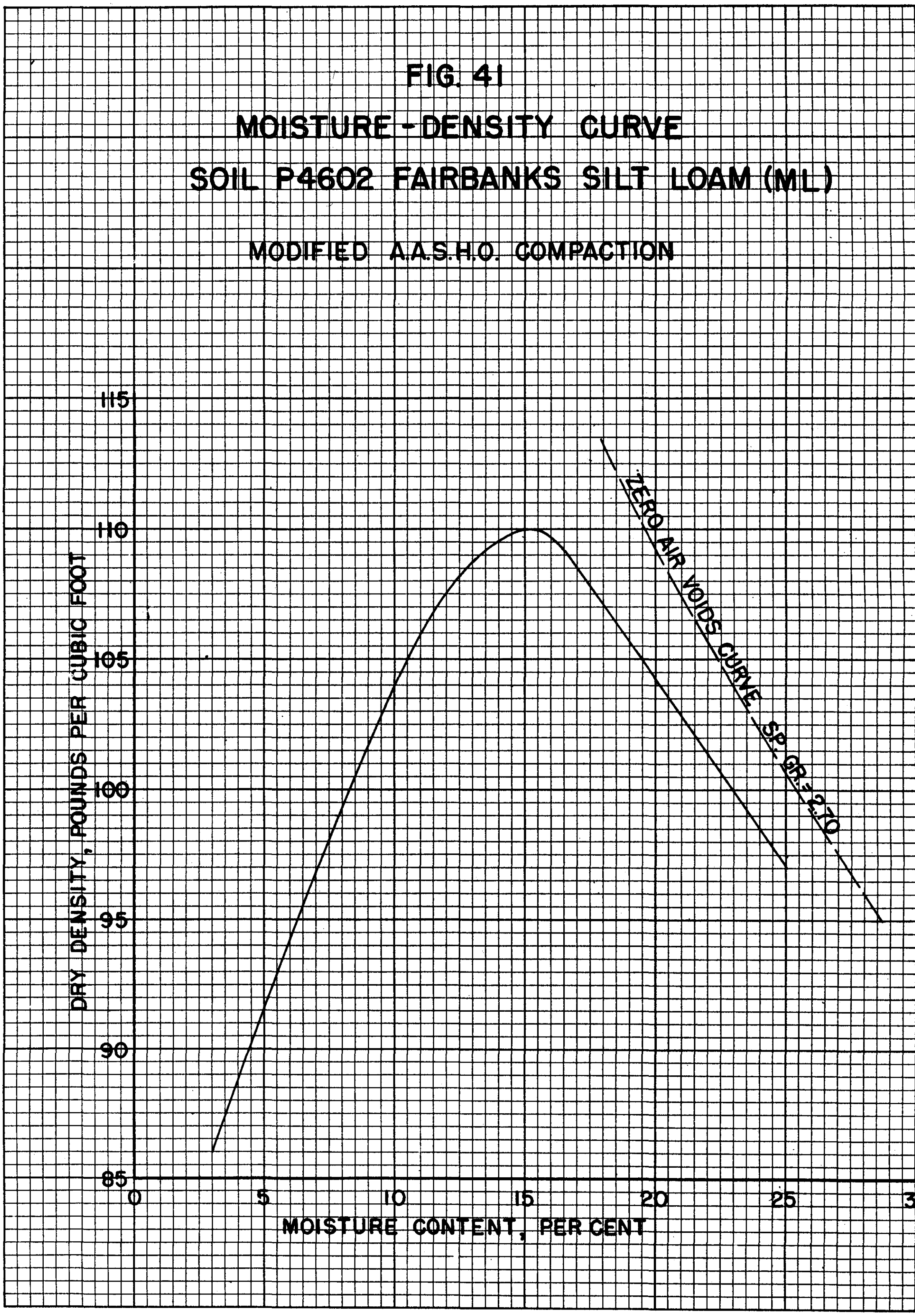


FIG. 41
MOISTURE - DENSITY CURVE
SOIL P4602 FAIRBANKS SILT LOAM (ML)
MODIFIED A.A.S.H.O. COMPACTION
ZERO AIR VOIDS CURVE SP. GR.=2.70
DRY DENSITY, POUNDS PER CUBIC FOOT
115
110
105
100
95
90
85
0
5
10
15
20
25
30
MOISTURE CONTENT, PER CENT

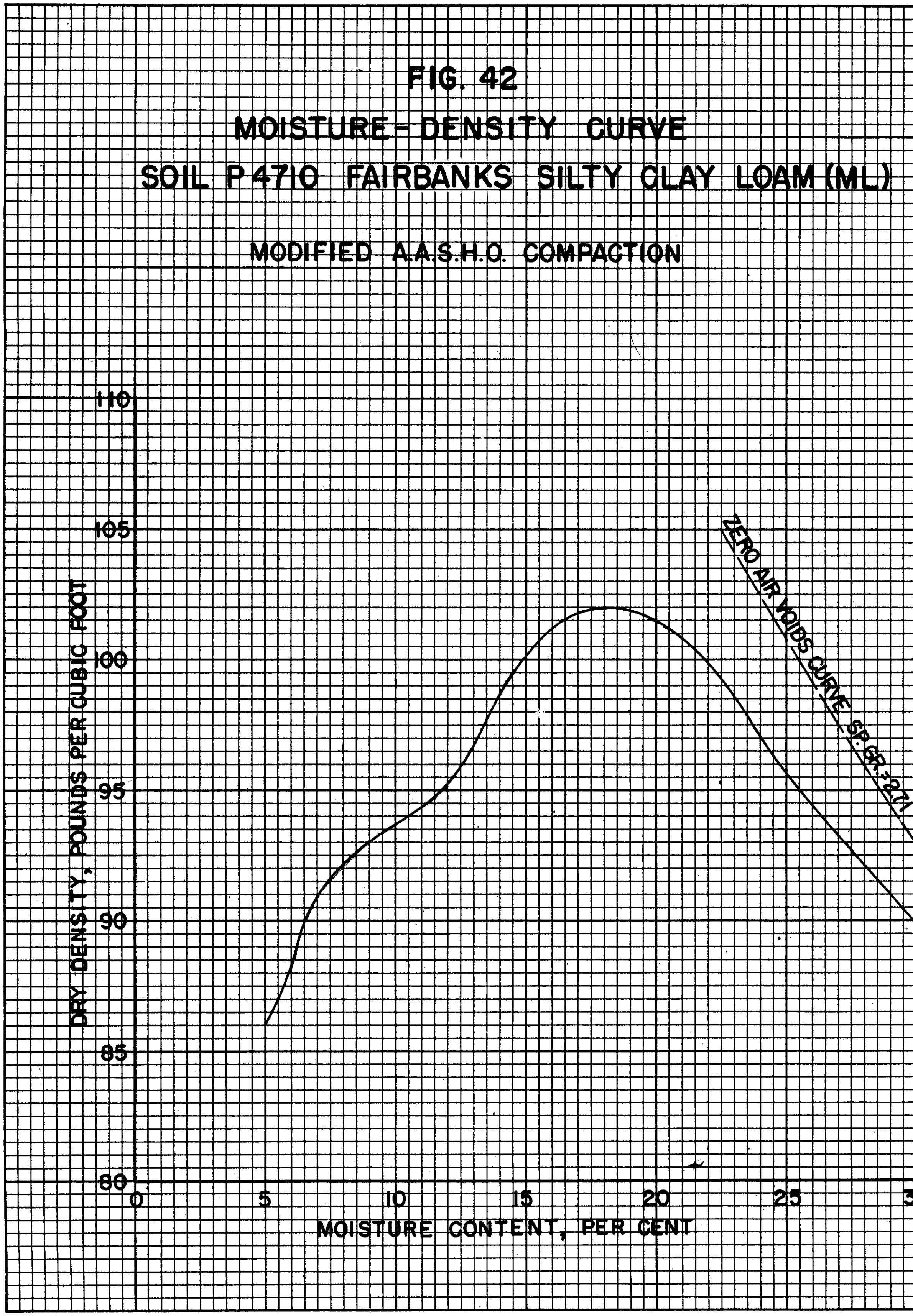


FIG. 42
MOISTURE - DENSITY CURVE
SOIL P 4710 FAIRBANKS SILTY CLAY LOAM (ML)
MODIFIED A.A.S.H.O. COMPACTION
ZERO AIR VOIDS CURVE SP. GR. = 2.71
DRY DENSITY, POUNDS PER CUBIC FOOT
110
105
100
95
90
85
80
0
5
10
15
20
25
30
MOISTURE CONTENT, PER CENT

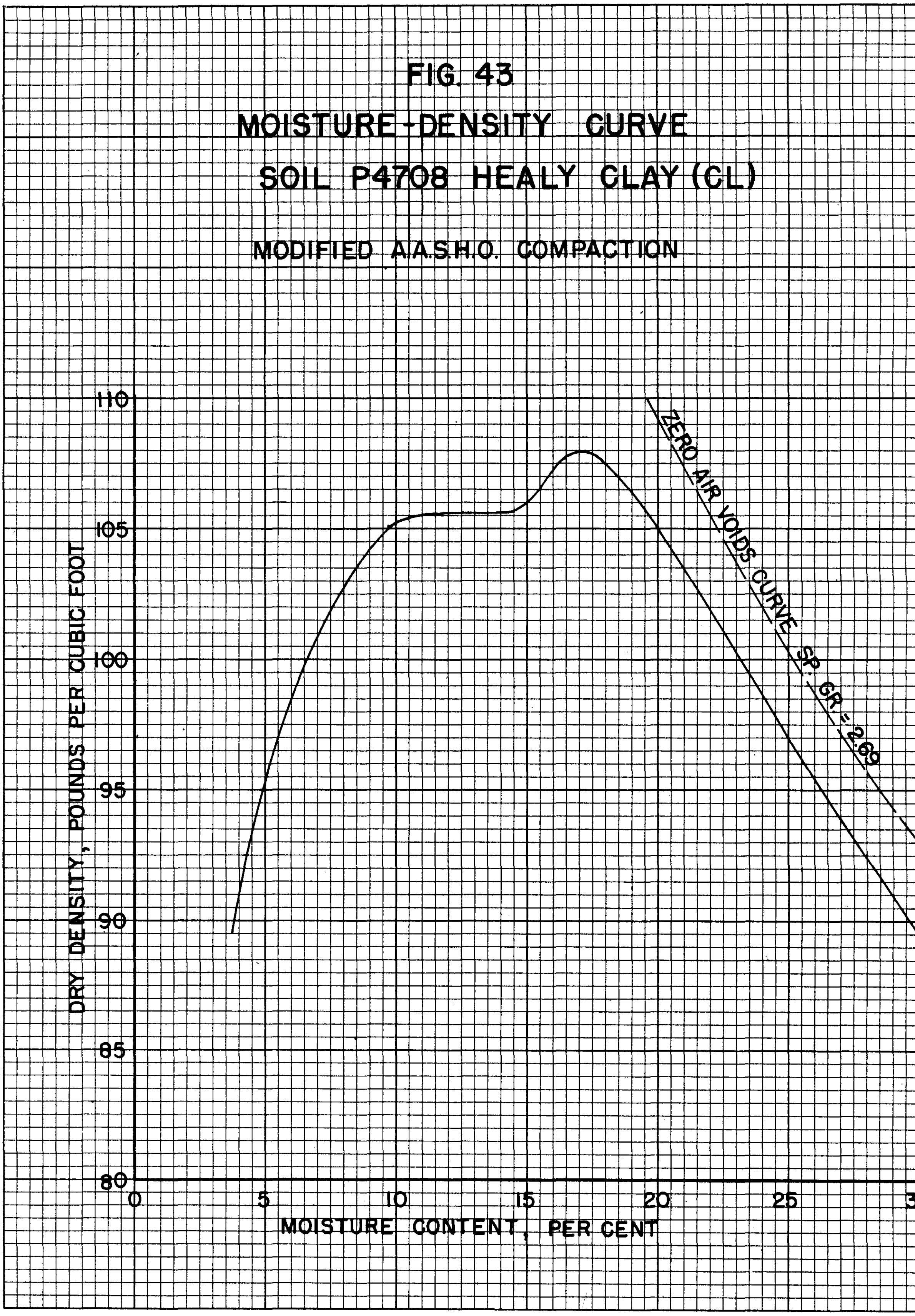


FIG. 43
MOISTURE-DENSITY CURVE
SOIL P4708 HEALY CLAY (CL)
MODIFIED A.A.S.H.O. COMPACTION
DRY DENSITY, POUNDS PER CUBIC FOOT
MOISTURE CONTENT, PER CENT
ZERO AIR VOIDS CURVE SP. GR. = 2.69
110
105
100
95
90
85
80
0
5
10
15
20
25
30

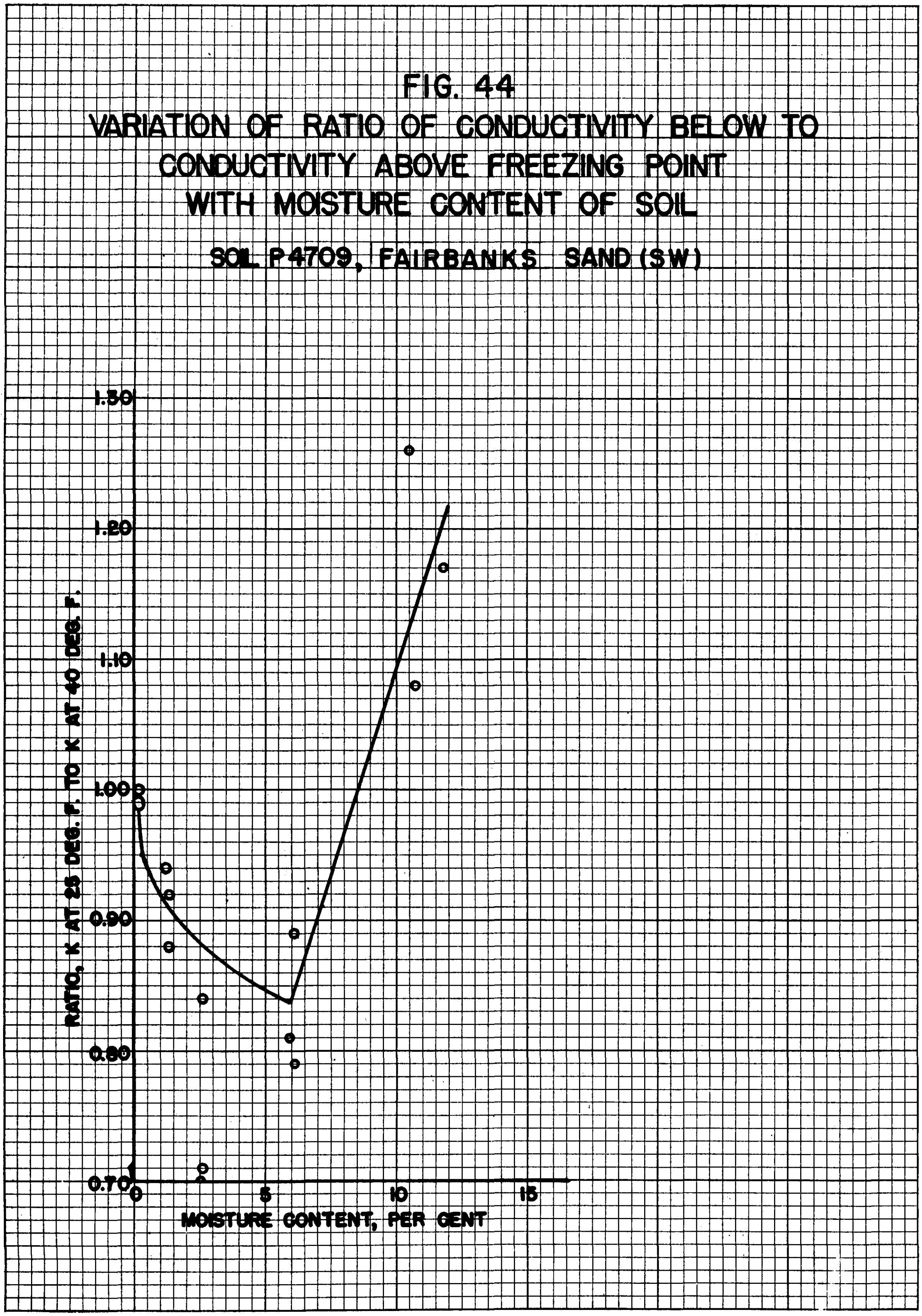


FIG. 44
VARIATION OF RATIO OF CONDUCTIVITY BELOW TO
CONDUCTIVITY ABOVE FREEZING POINT
WITH MOISTURE CONTENT OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
RATIO, K AT 25 DEG. F. TO K AT 40 DEG. F.
1.30
1.20
1.10
1.00
0.90
0.80
0.70
0
5
10
15
MOISTURE CONTENT, PER CENT

FIG. 45

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4604, LOWELL SAND (SW)

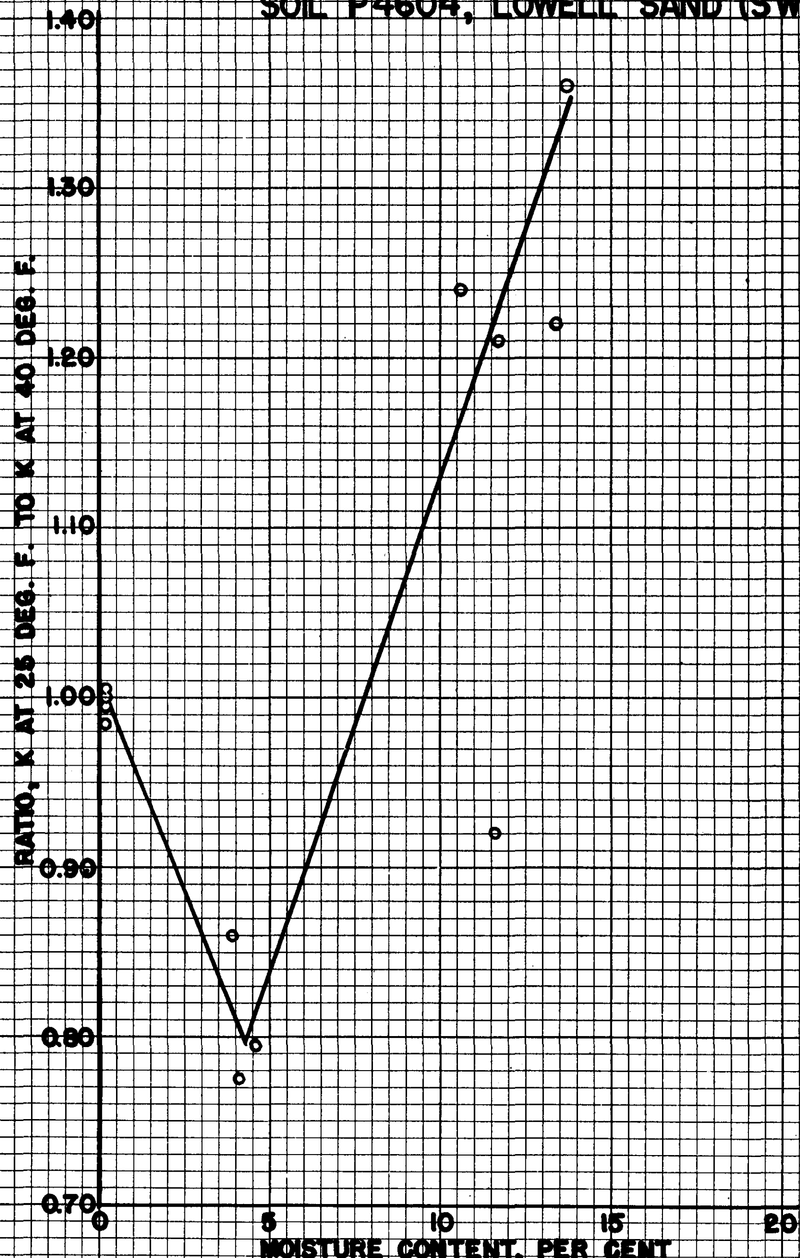


FIG. 46

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4503, NORTHWAY SAND (SW)

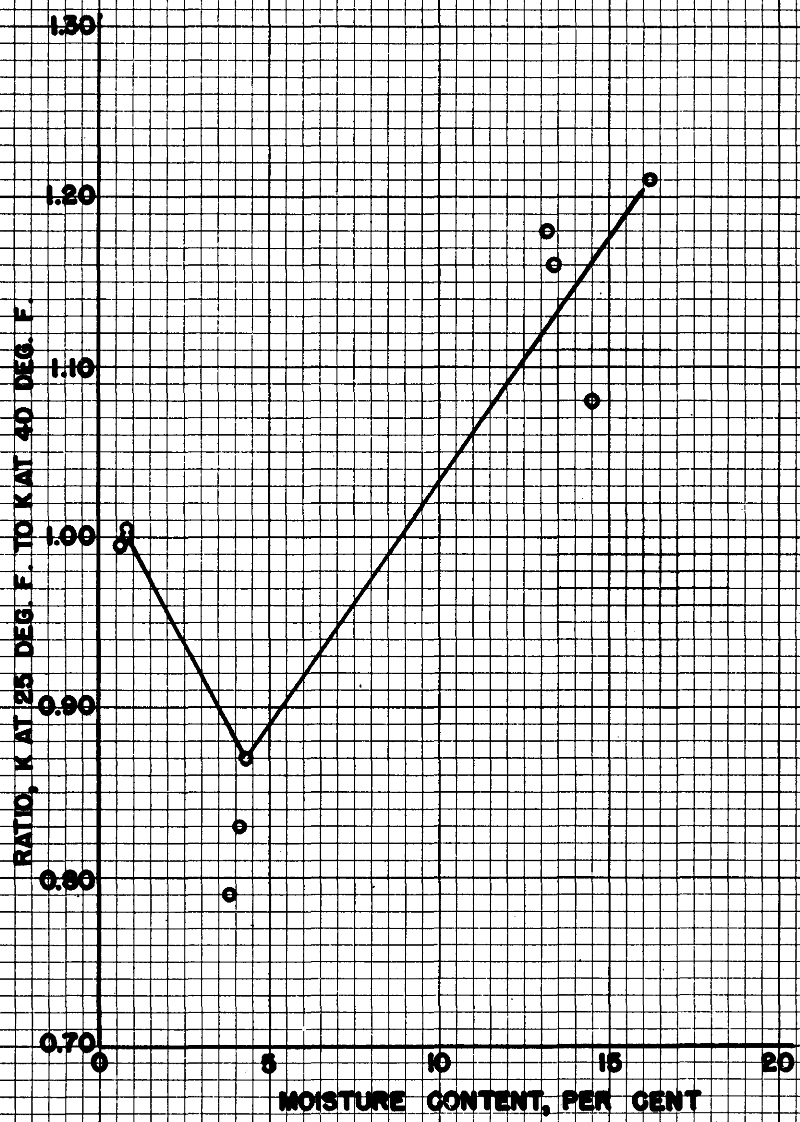


FIG. 47
VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4502, NORTHWAY FINE SAND (SP)

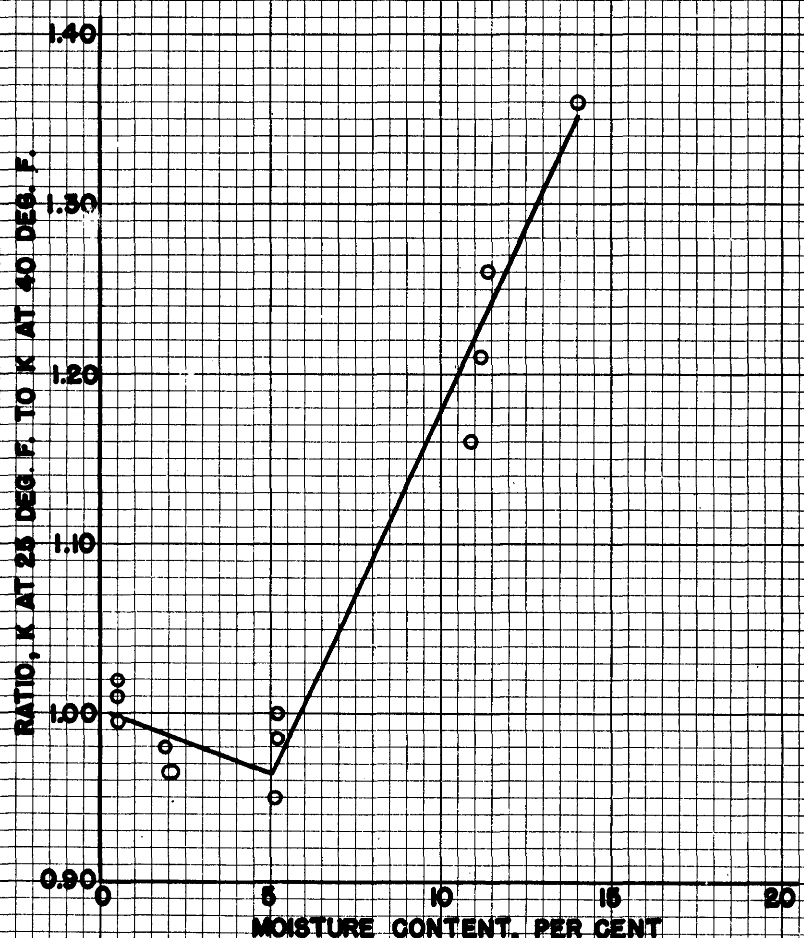


FIG. 48

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4711, DAKOTA SANDY LOAM (SM)

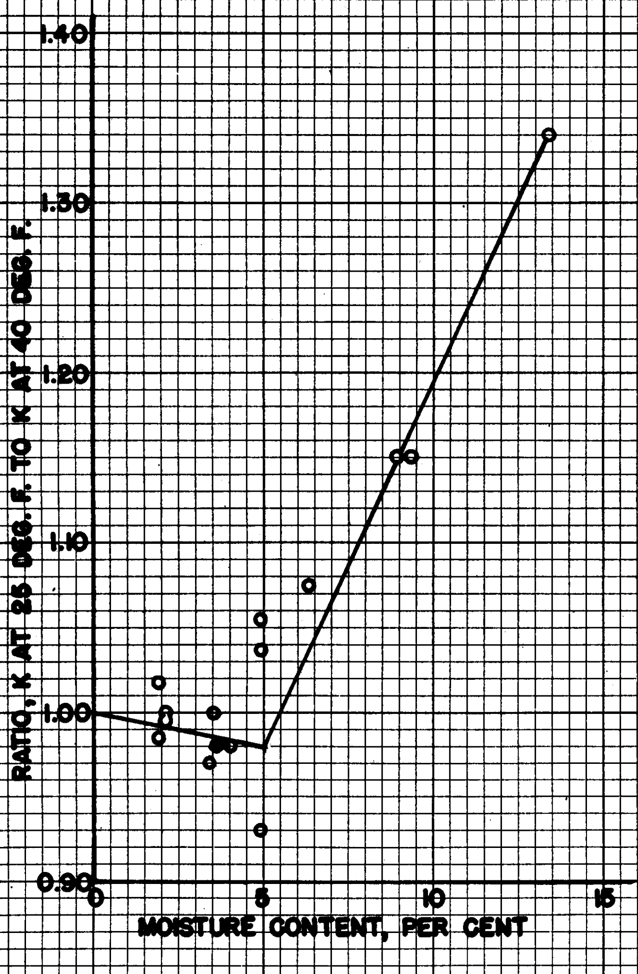
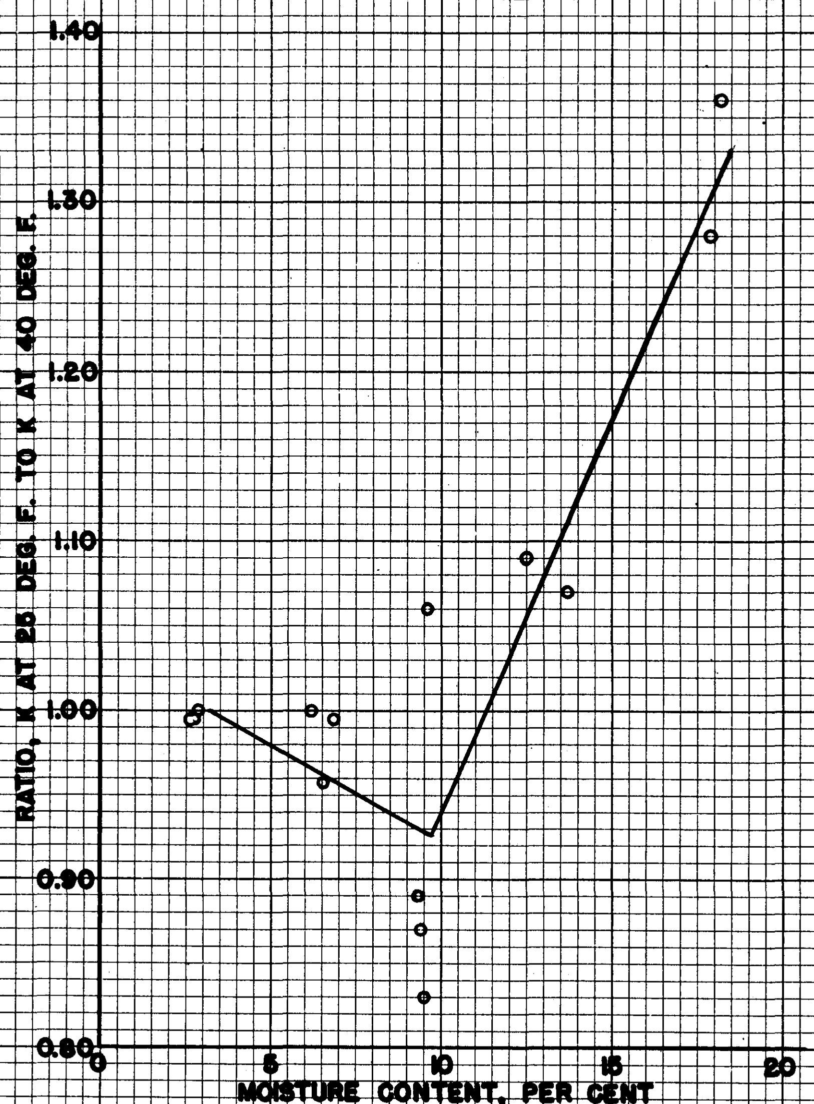


FIG. 49

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4713, RAMSEY SANDY LOAM (CL)



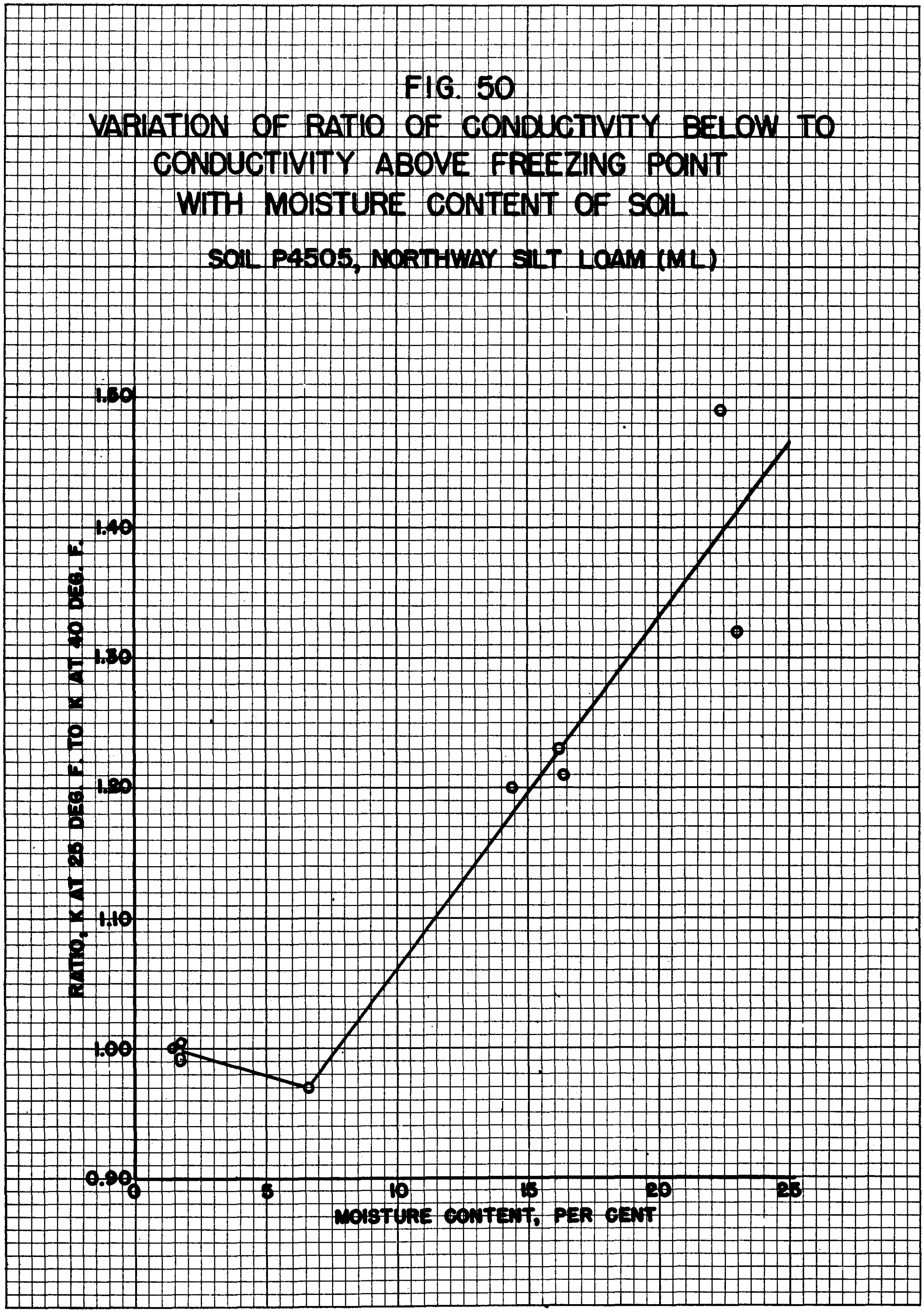


FIG. 50
VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL
SOIL P4505, NORTHWAY SILT LOAM (ML)
RATIO, K AT 25 DEG. F. TO K AT 40 DEG. F.
1.50
1.40
1.30
1.20
1.10
1.00
0.90
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

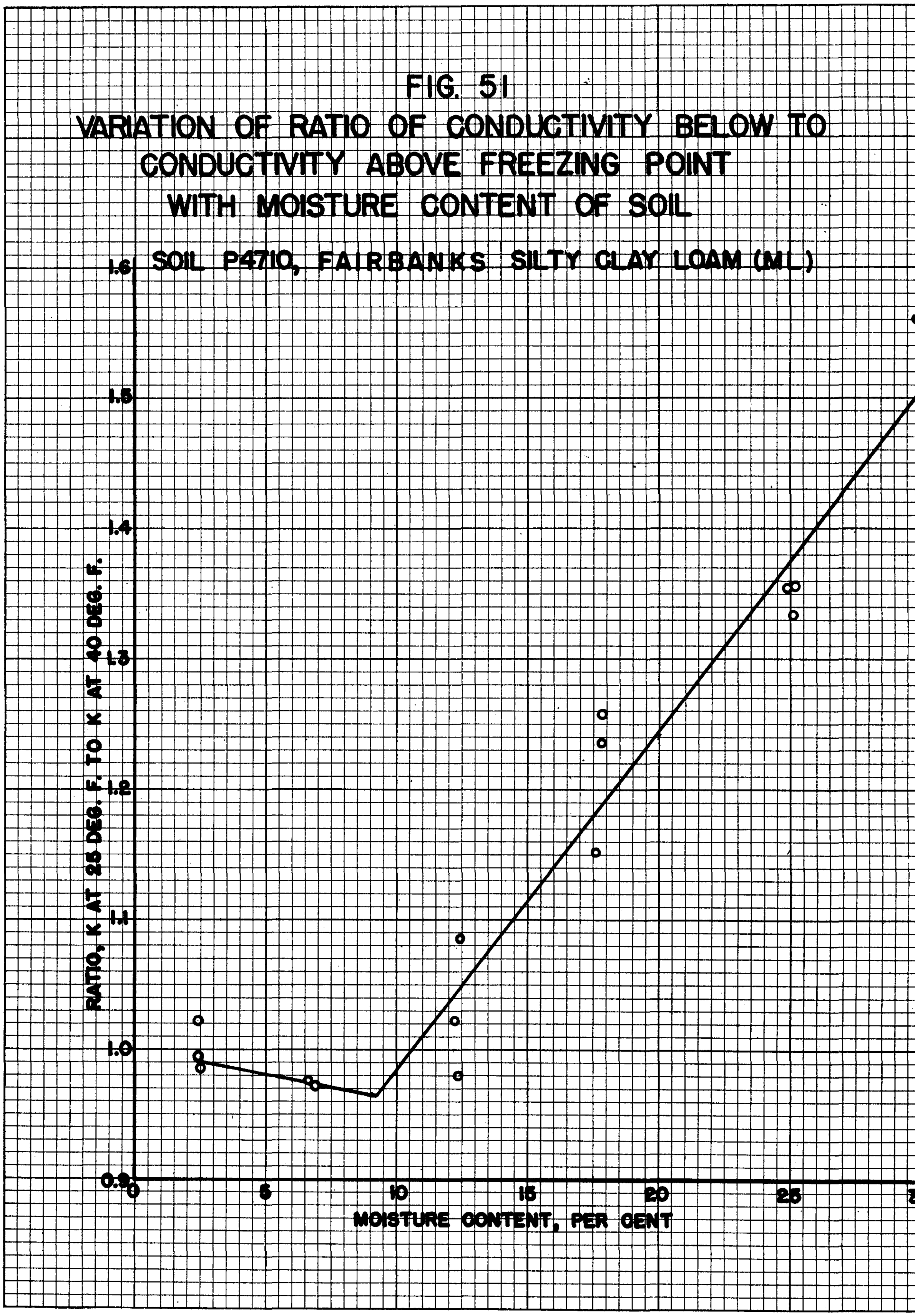
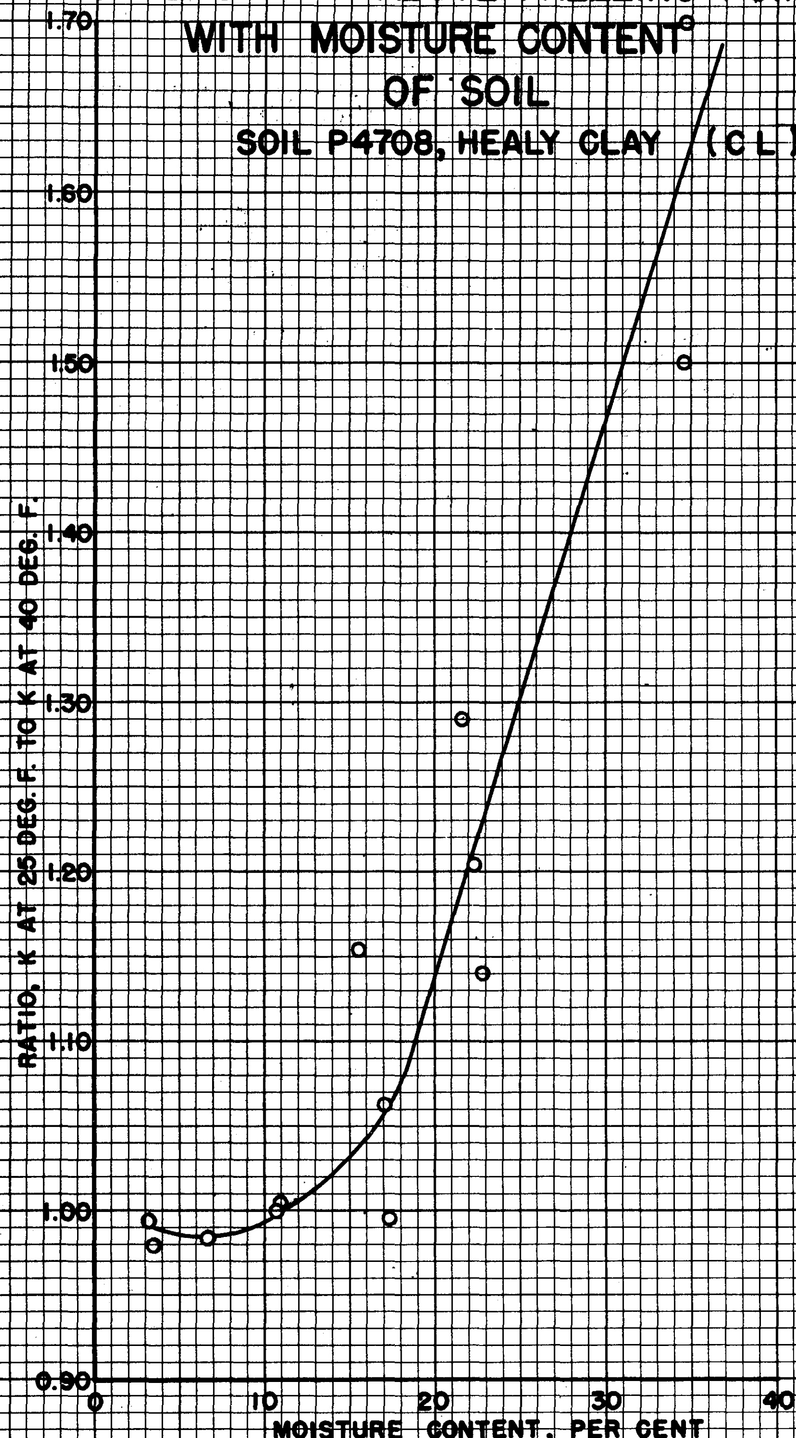


FIG. 51
VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
RATIO, K AT 25 DEG. F. TO K AT 40 DEG. F.
MOISTURE CONTENT, PER CENT
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0
5
10
15
20
25
30

FIG. 52

VARIATION OF RATIO OF CONDUCTIVITY BELOW TO CONDUCTIVITY ABOVE FREEZING POINT WITH MOISTURE CONTENT OF SOIL

SOIL P4708, HEALY CLAY (CL)



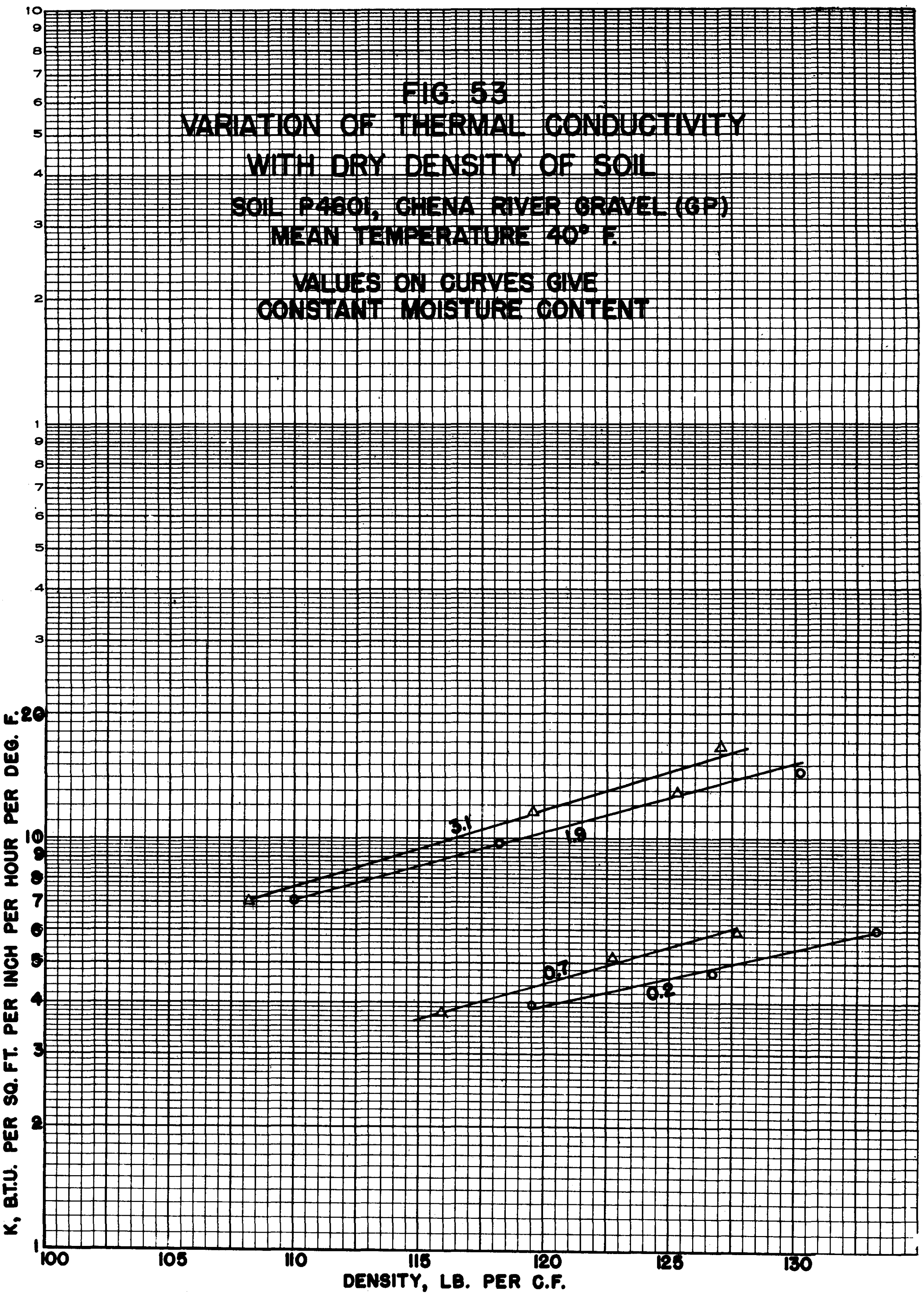


FIG. 53
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4601, CHENA RIVER GRAVEL (GP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
3.1
1.9
0.7
0.2
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120
125
130

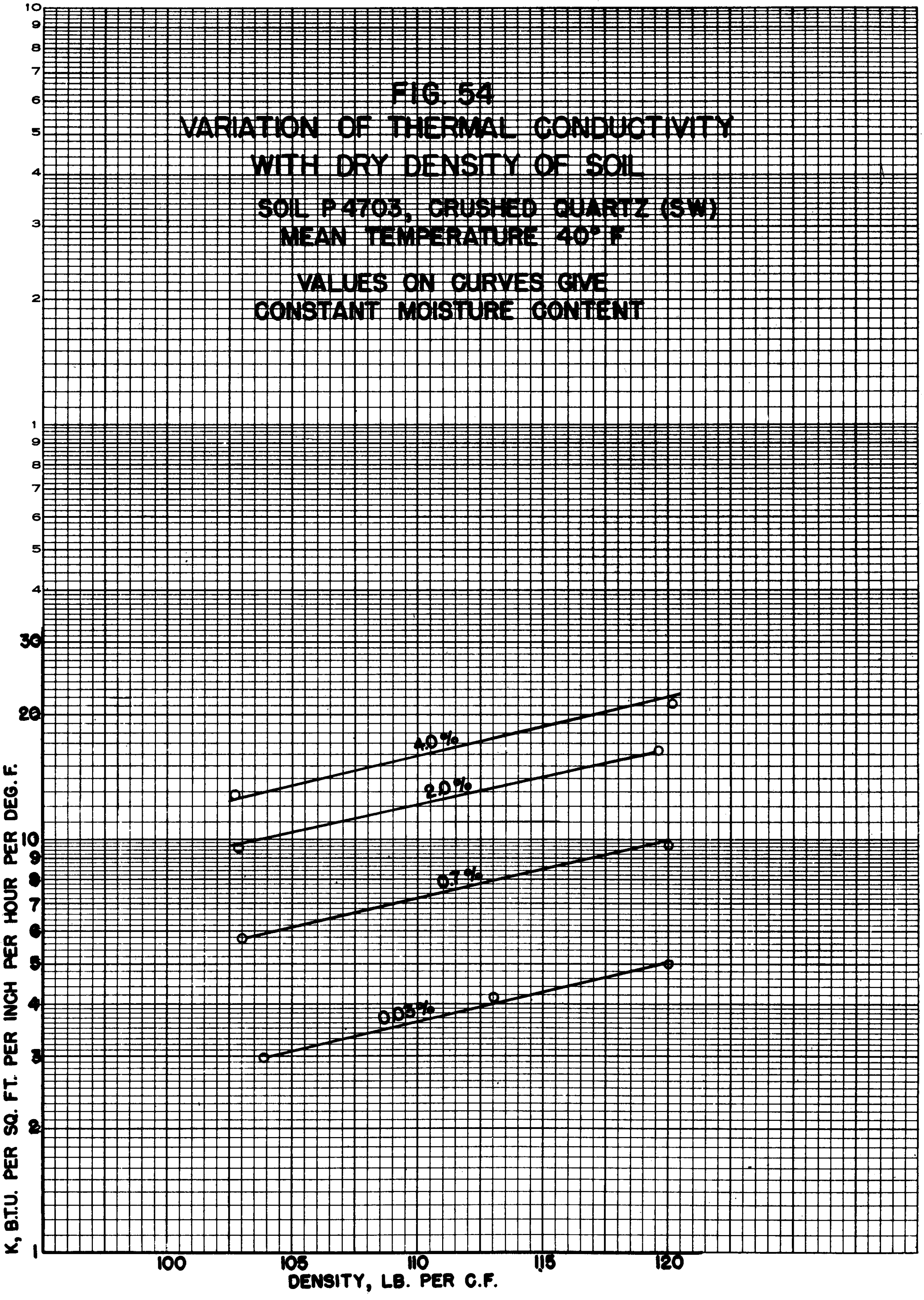


FIG. 54
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4703, CRUSHED QUARTZ (SW)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
4.0%
2.0%
0.7%
0.03%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

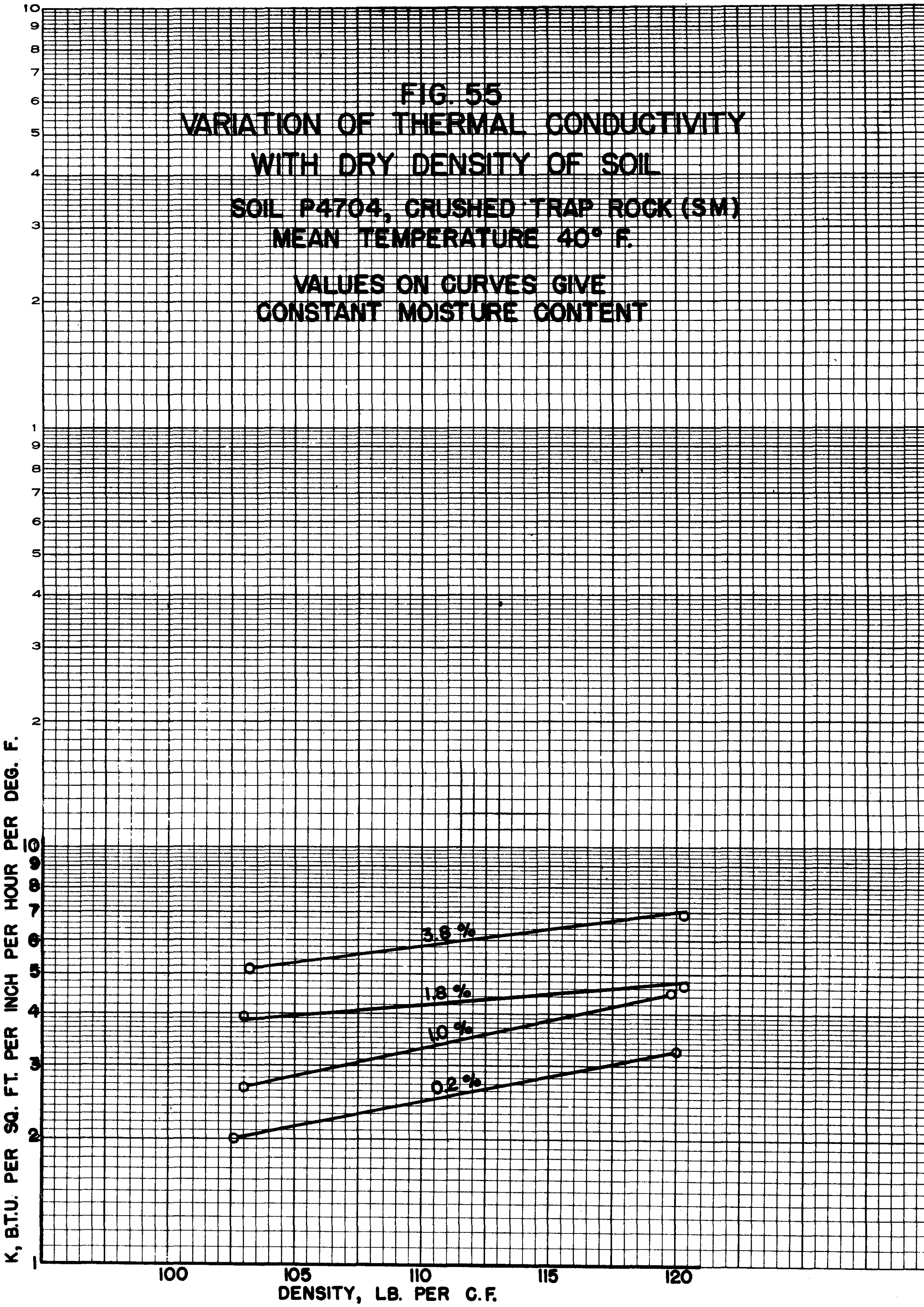


FIG. 55
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4704, CRUSHED TRAP ROCK (SM)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
3.8 %
1.8 %
1.0 %
0.2 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

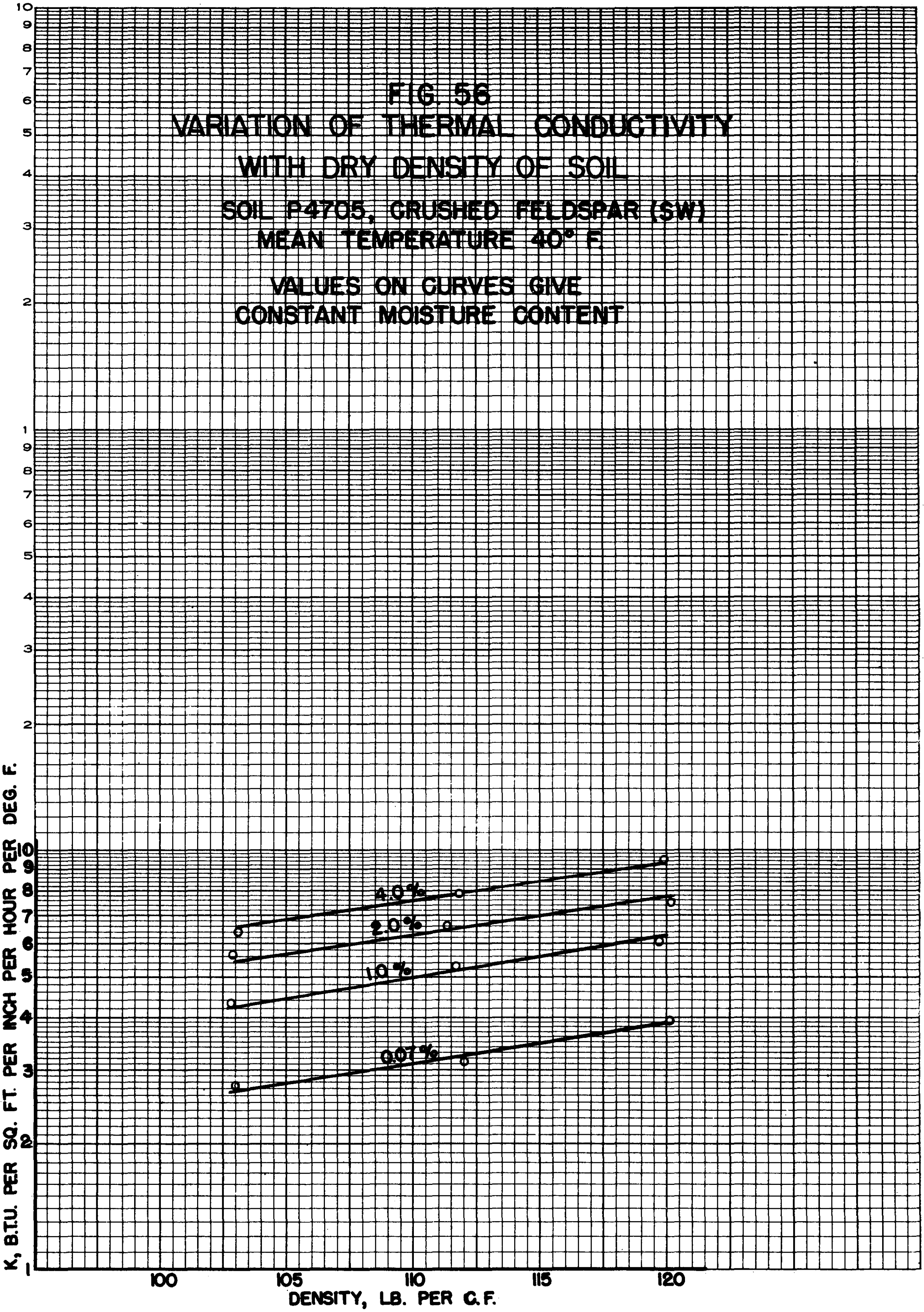


FIG. 56
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4705, CRUSHED FELDSPAR (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
4.0%
2.0%
1.0%
0.07%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

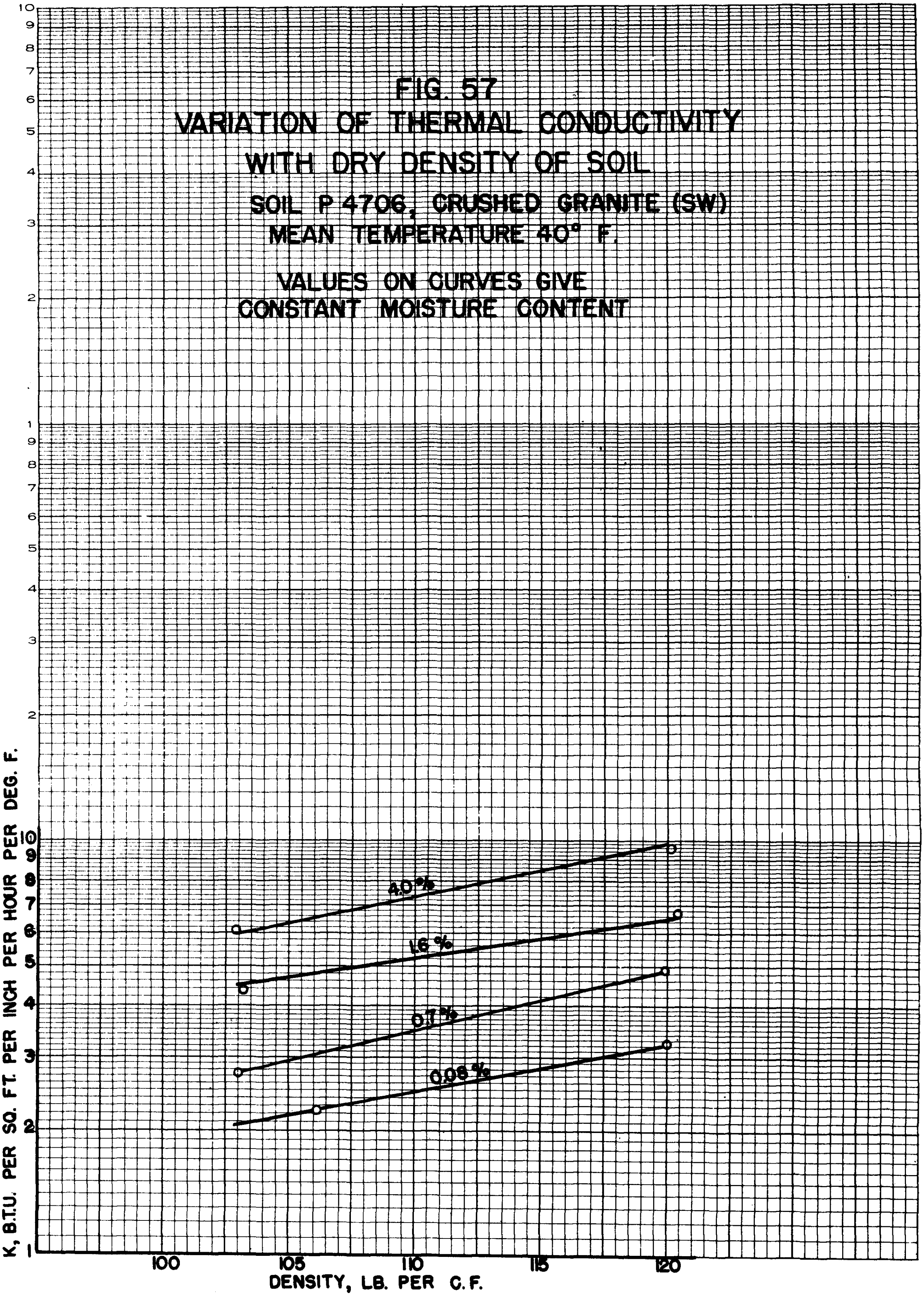


FIG. 57
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4706, CRUSHED GRANITE (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
40 %
16 %
0.7 %
0.08 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

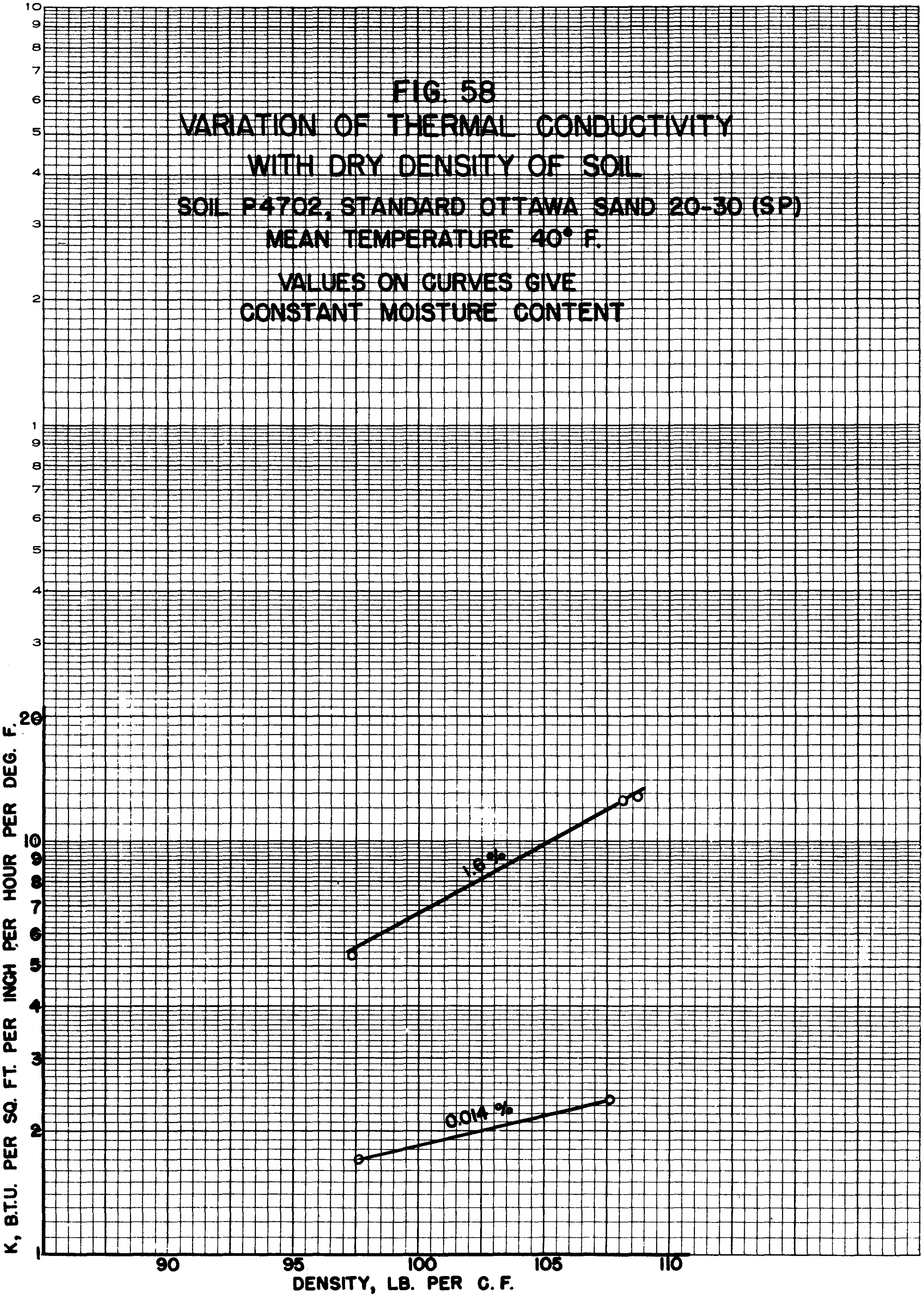


FIG. 58
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4702, STANDARD OTTAWA SAND 20-30 (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
1.6 %
0.014 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C. F.
90
95
100
105
110

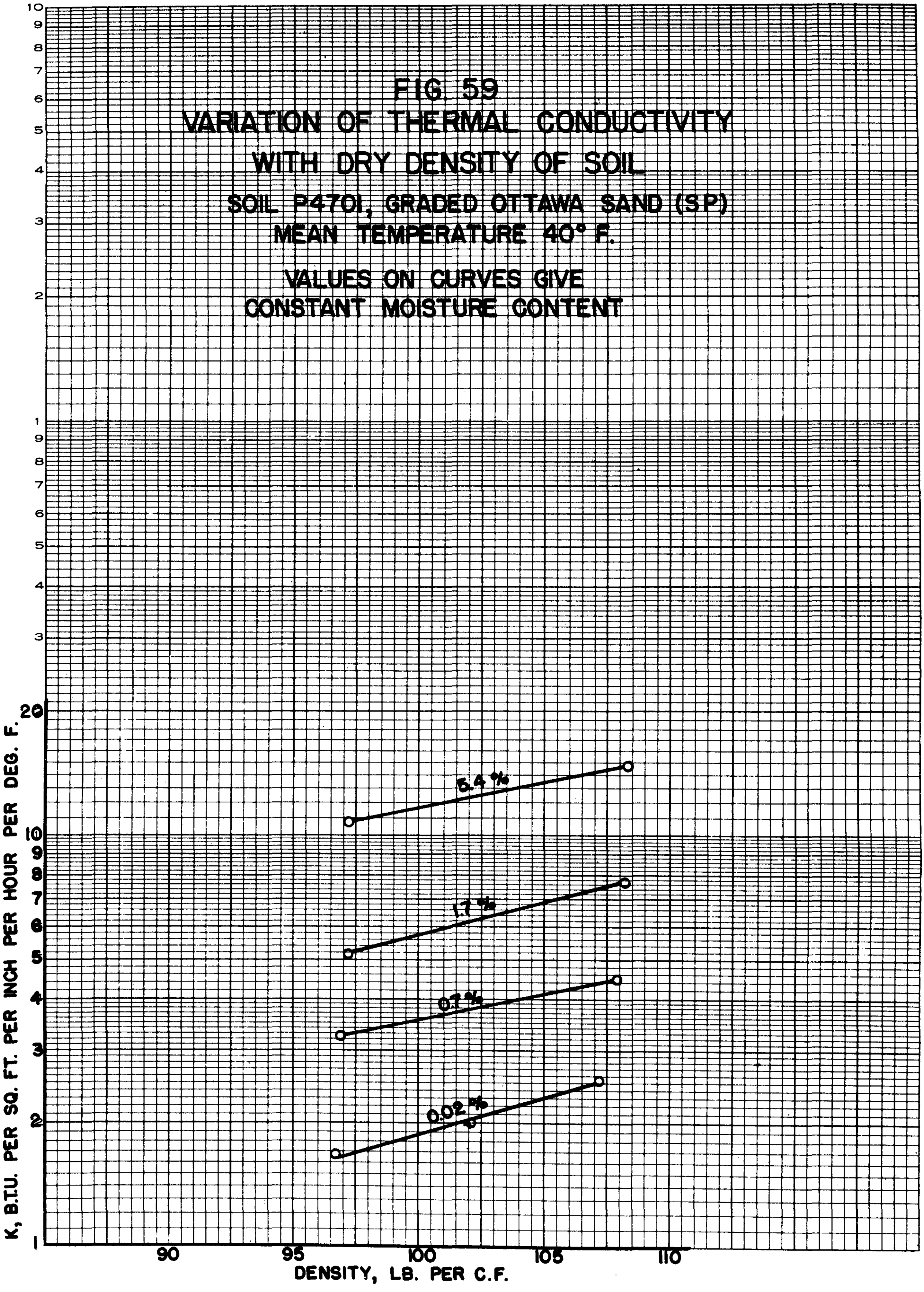


FIG. 59
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4701, GRADED OTTAWA SAND (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
5.4 %
1.7 %
0.7 %
0.02 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110
1
2
3
4
5
6
7
8
9
10
20

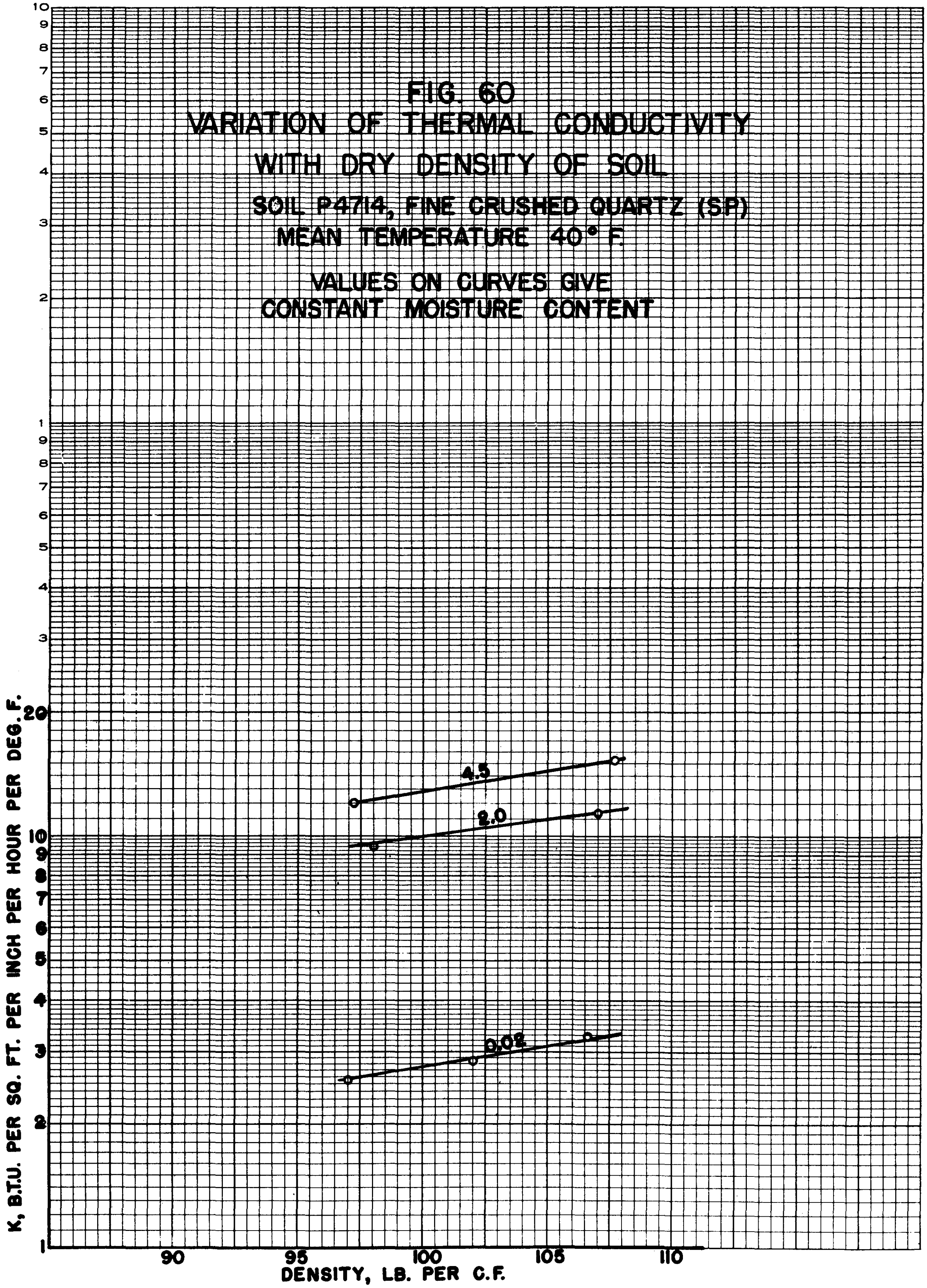


FIG. 60
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4714, FINE CRUSHED QUARTZ (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
4.5
2.0
0.02
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110

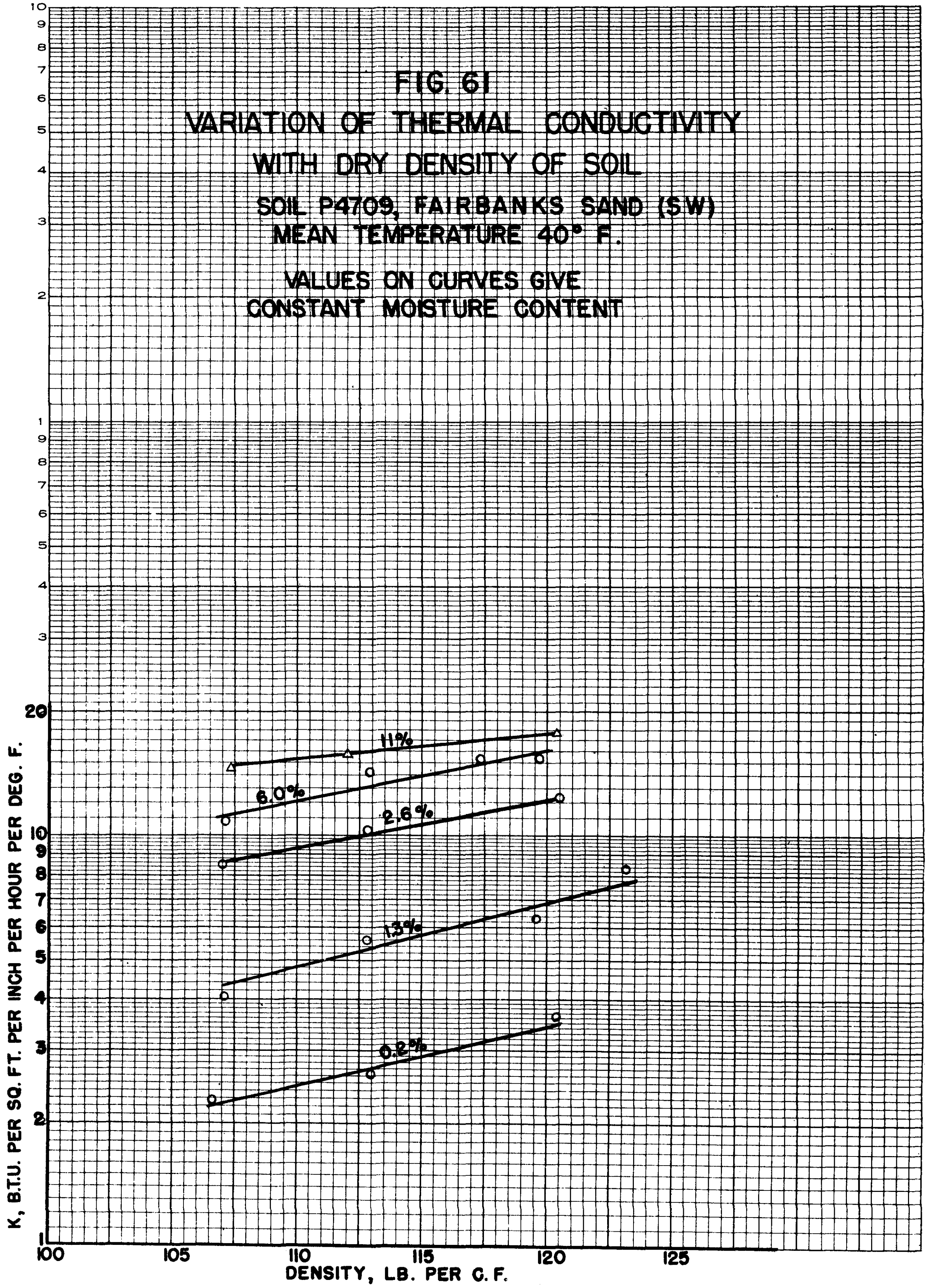


FIG. 61
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
11%
6.0%
2.6%
13%
0.2%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120
125

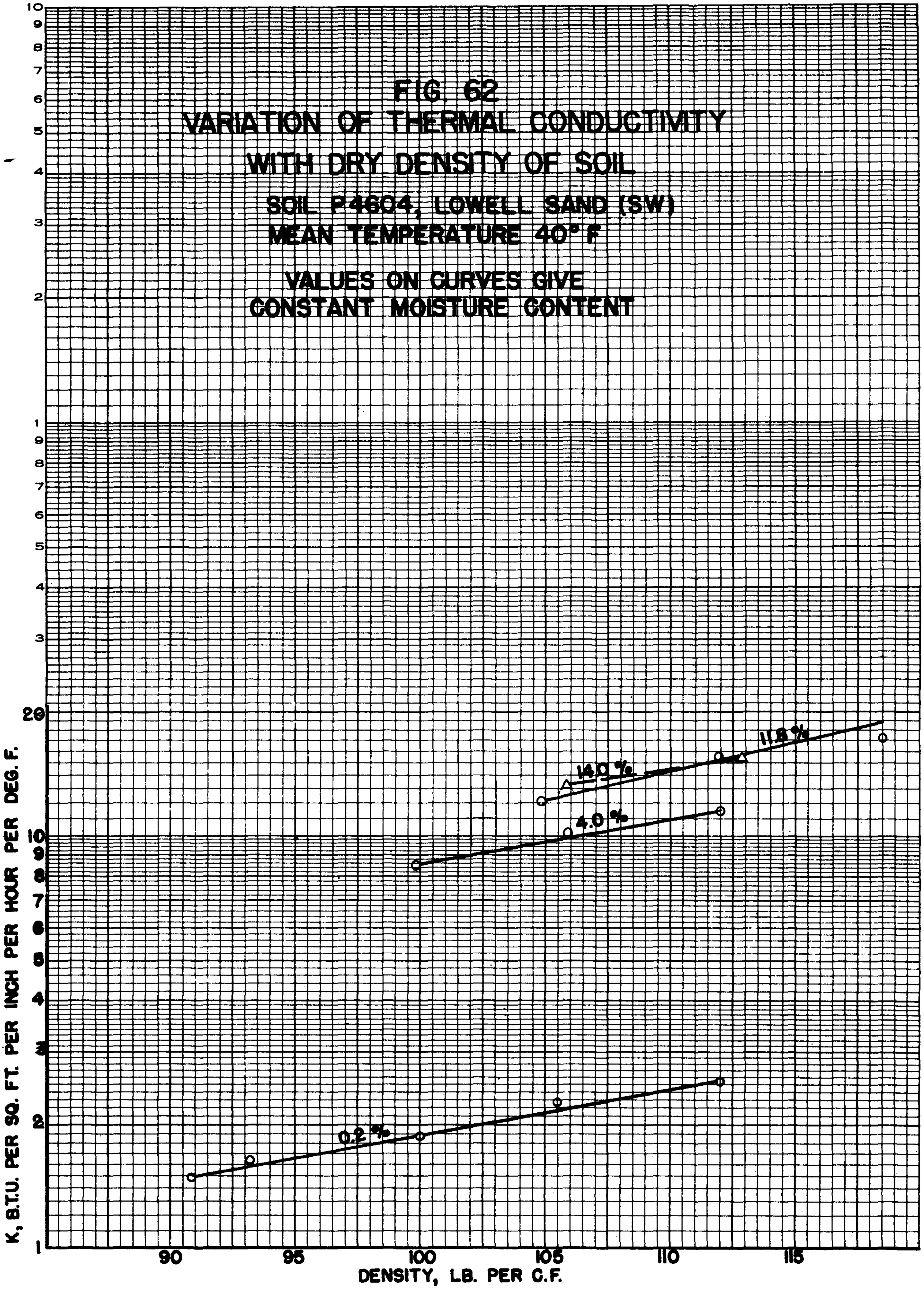
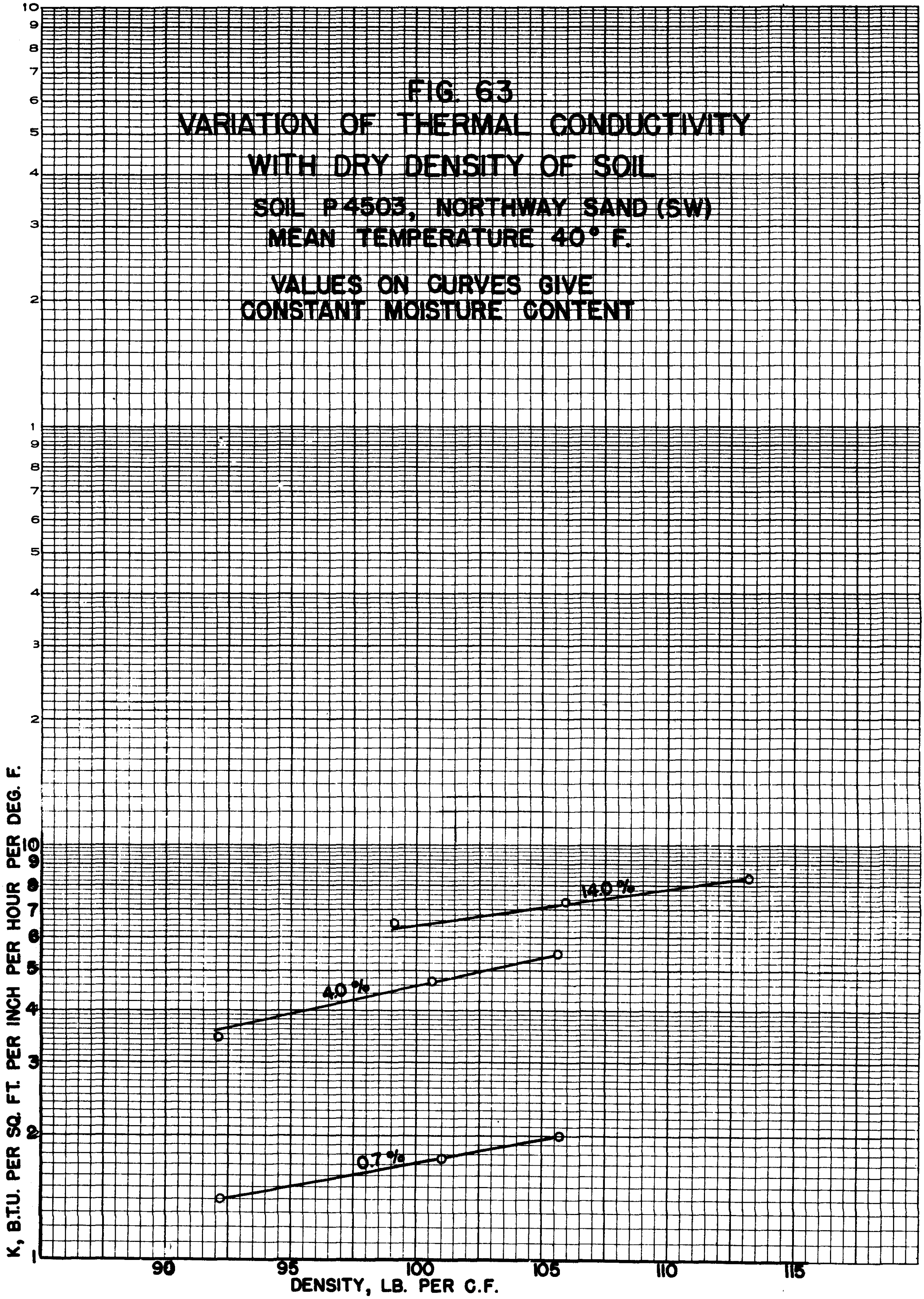


FIG. 62
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4604, LOWELL SAND (SW)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
11.8 %
14.0 %
4.0 %
0.2 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110
115

FIG. 63
VARIATION OF THERMAL CONDUCTIVITY WITH DRY DENSITY OF SOIL
SOIL P 4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 40° F.

VALUES ON CURVES GIVE CONSTANT MOISTURE CONTENT



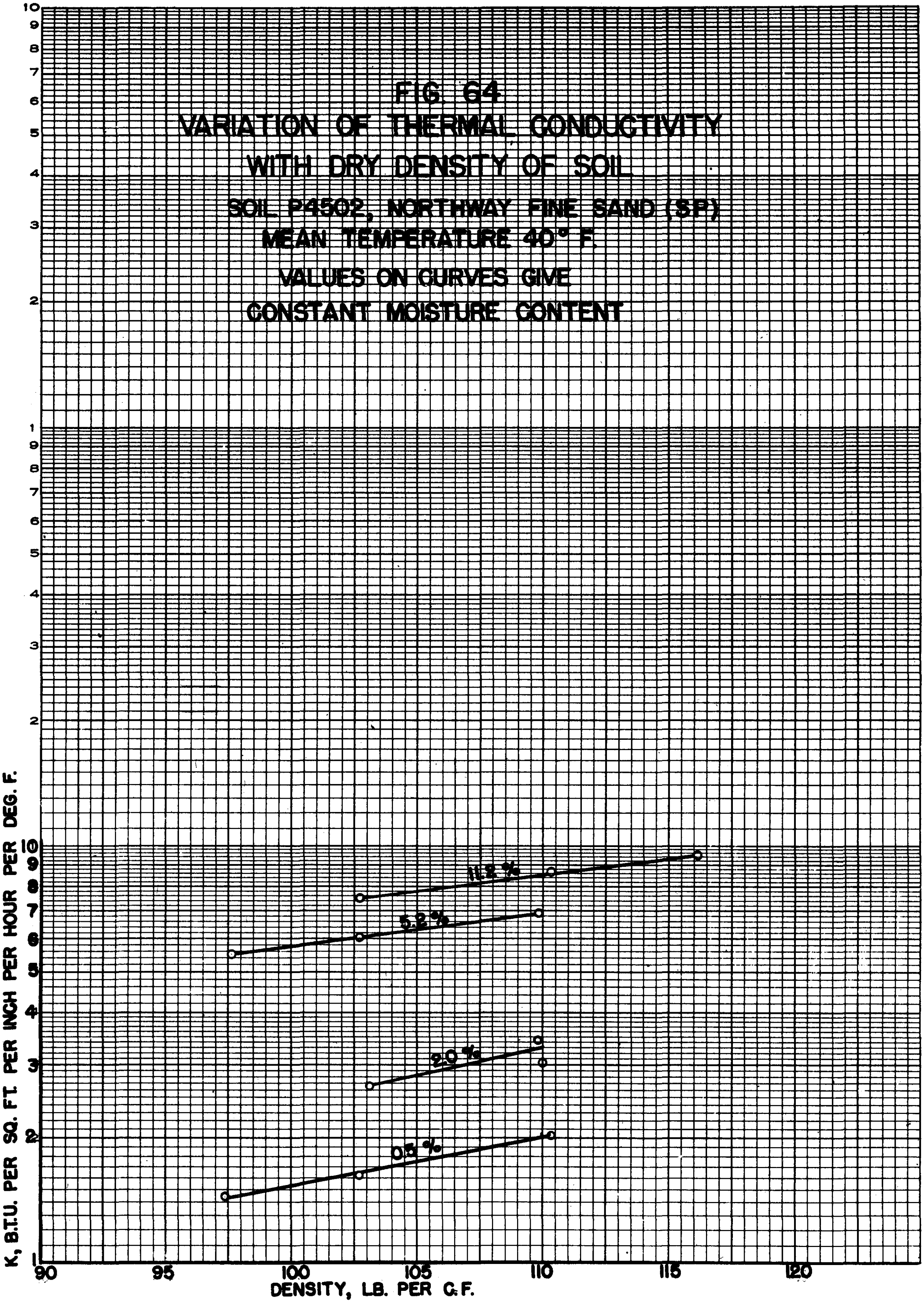


FIG. 64
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
11.2 %
5.2 %
2.0 %
0.5 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110
115
120

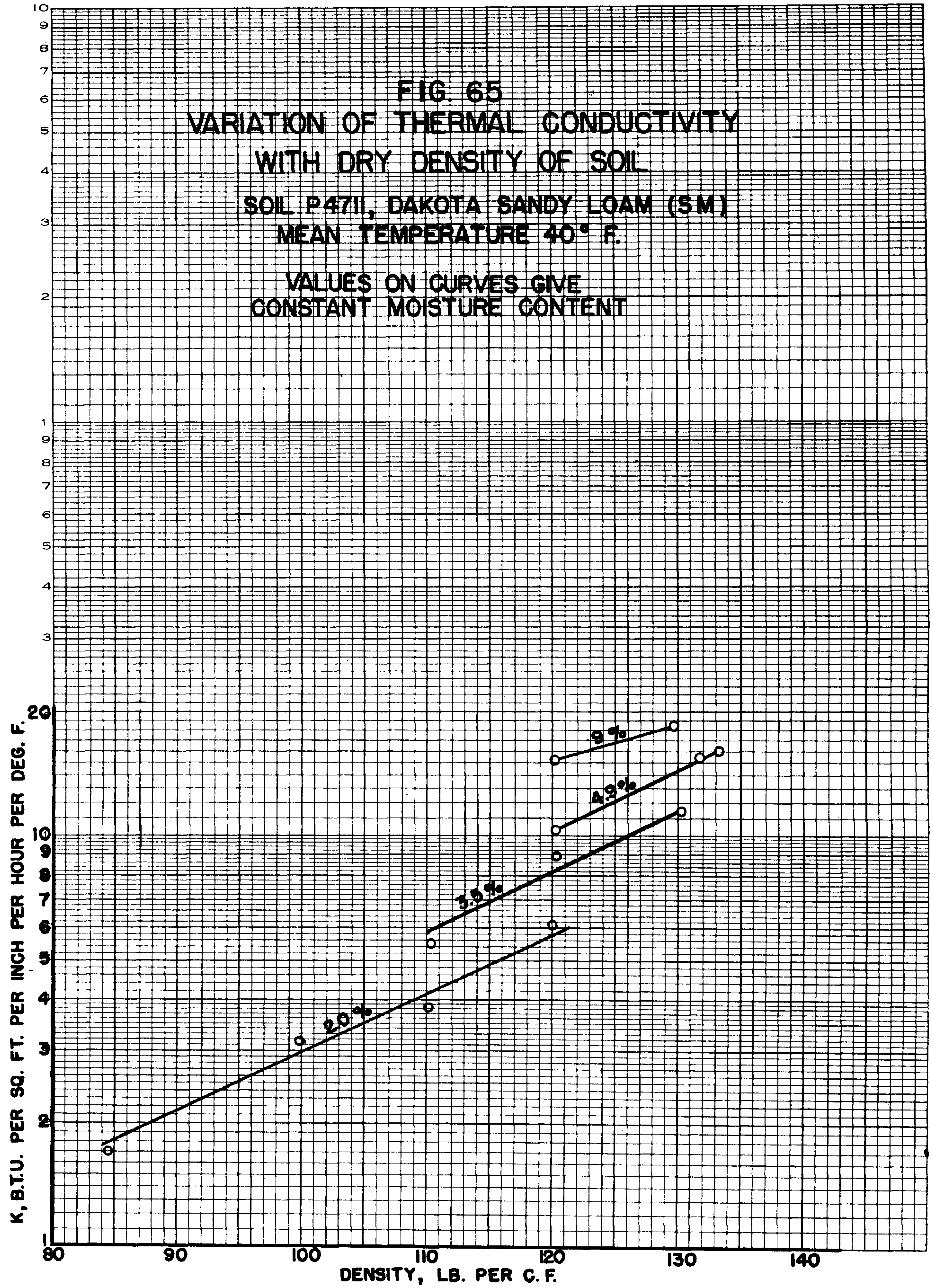


FIG. 65
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
9%
4.9%
3.5%
20%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
80
90
100
110
120
130
140
1
2
3
4
5
6
7
8
9
10
20

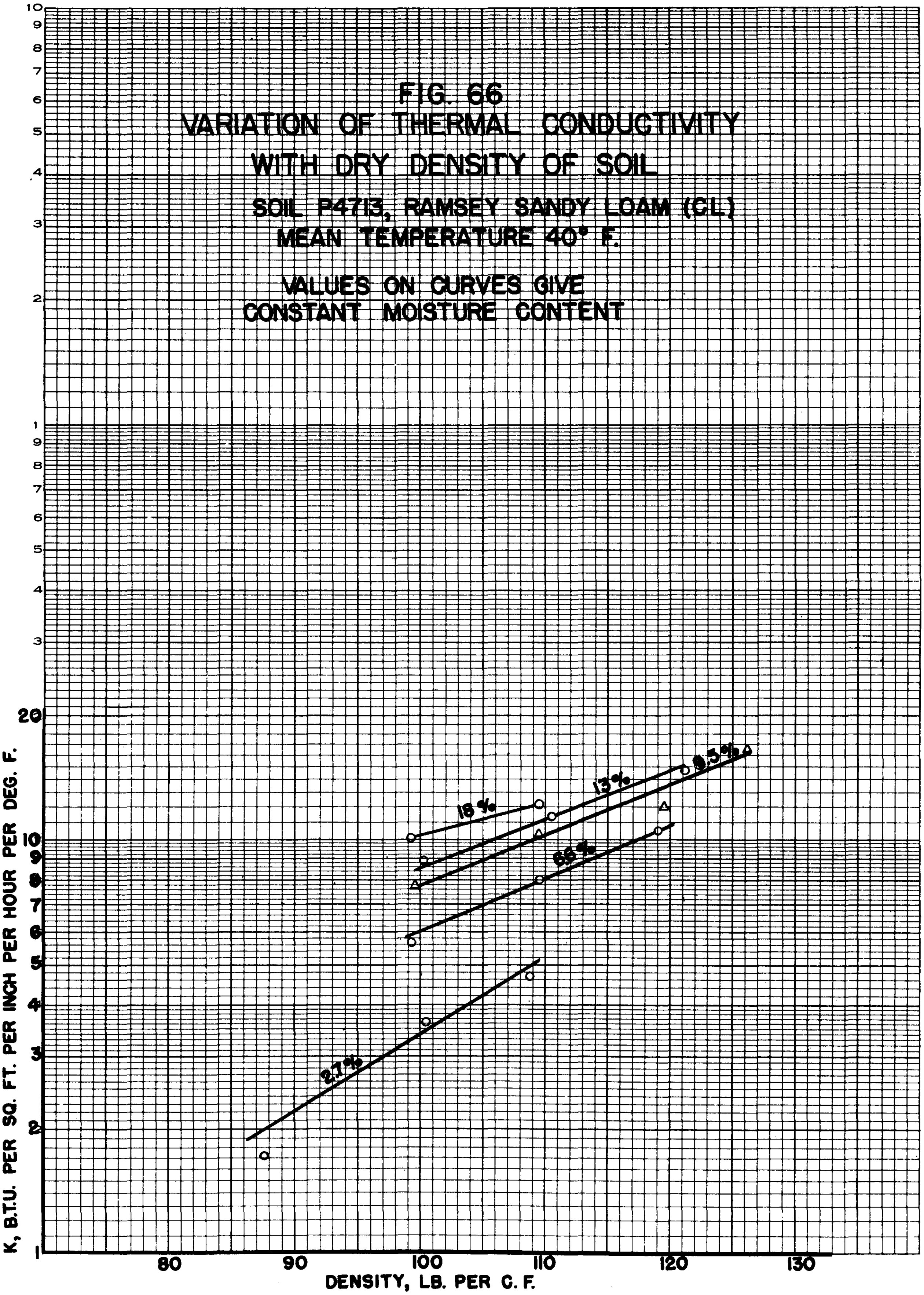


FIG. 66
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
18%
13%
9.5%
6.6%
2.7%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C. F.
80
90
100
110
120
130

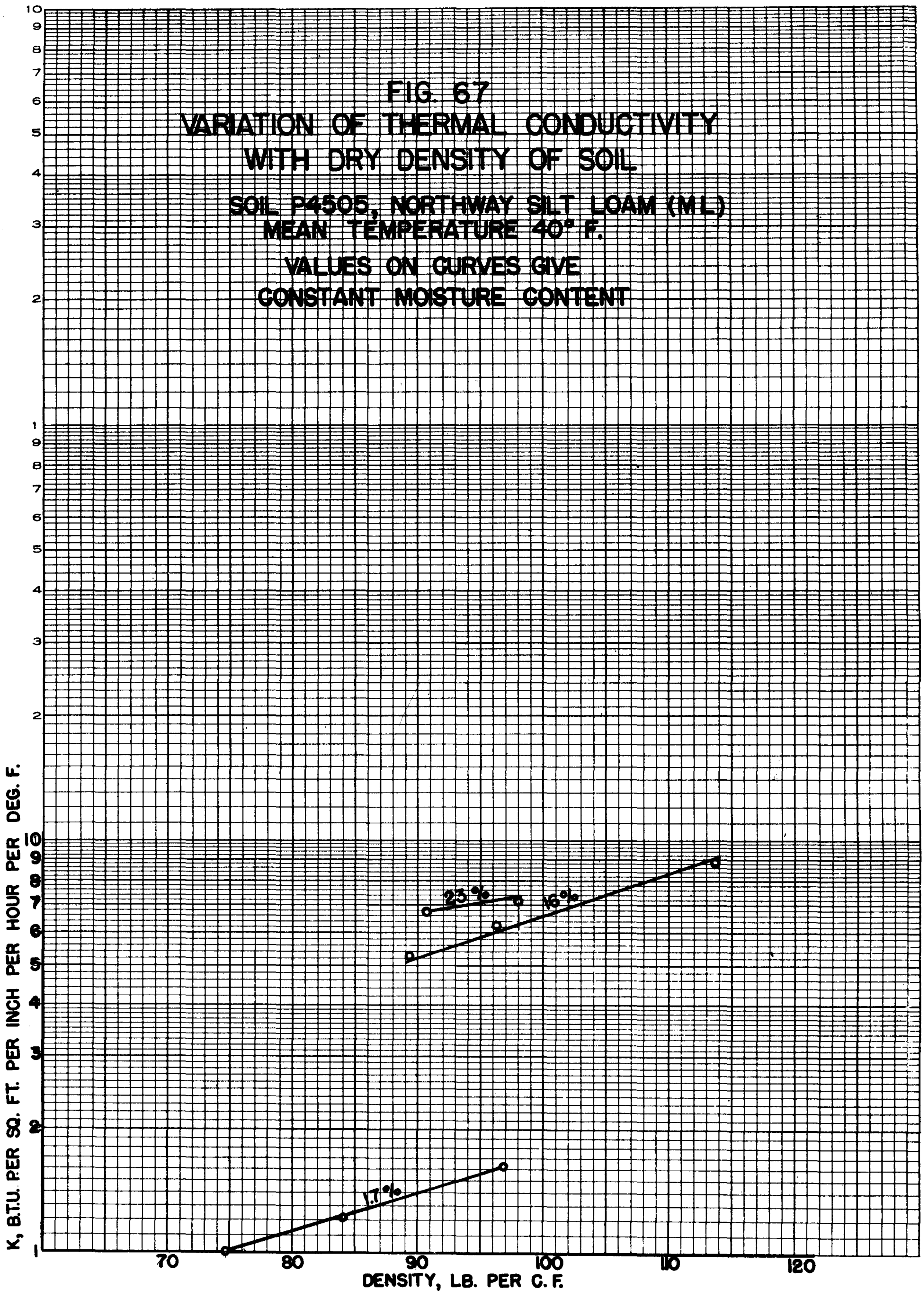


FIG. 67
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
23%
16%
1.7%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
70
80
90
100
110
120

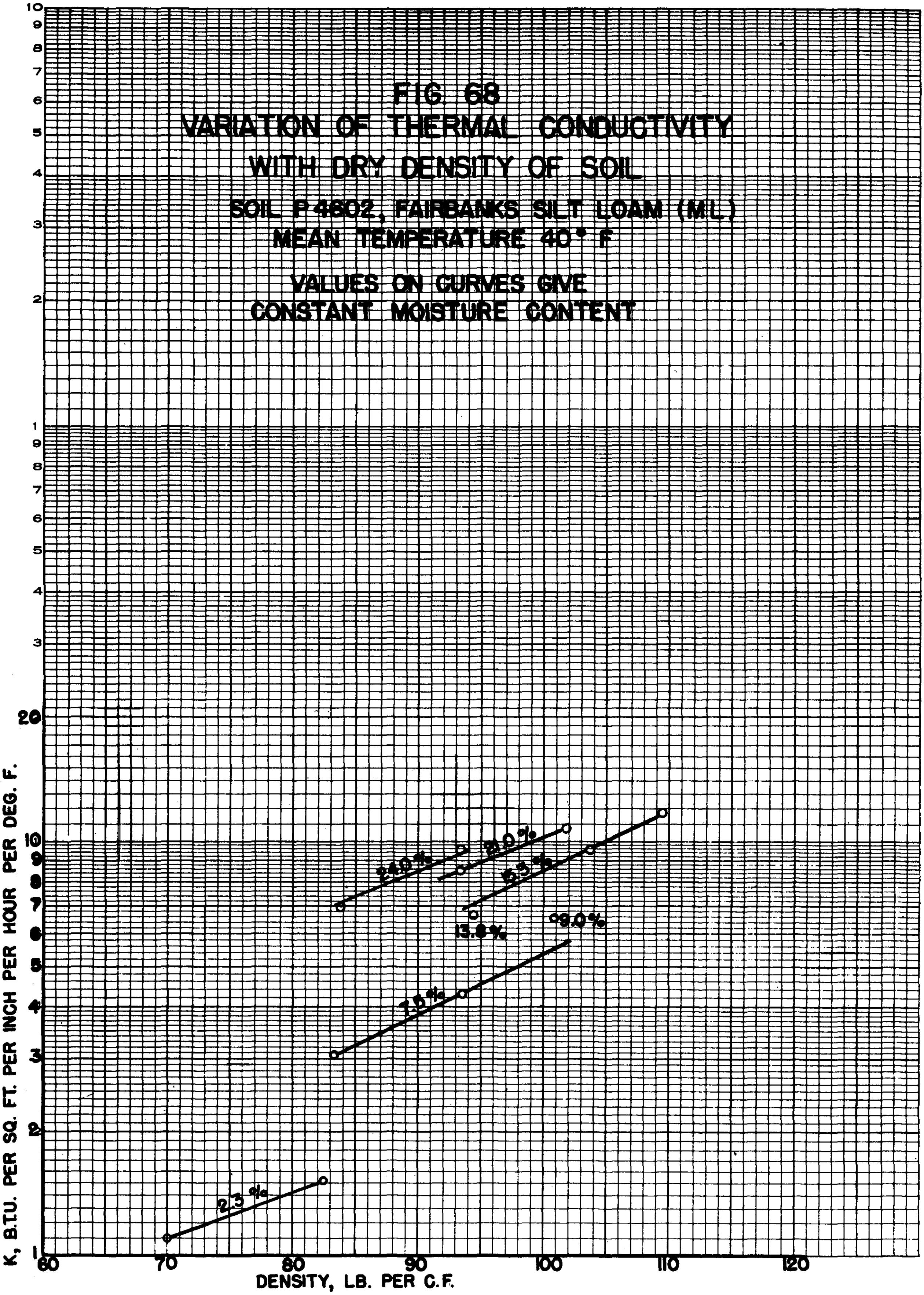


FIG. 68
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
24.0 %
21.0 %
15.5 %
13.8 %
9.0 %
7.5 %
2.3 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
60
70
80
90
100
110
120

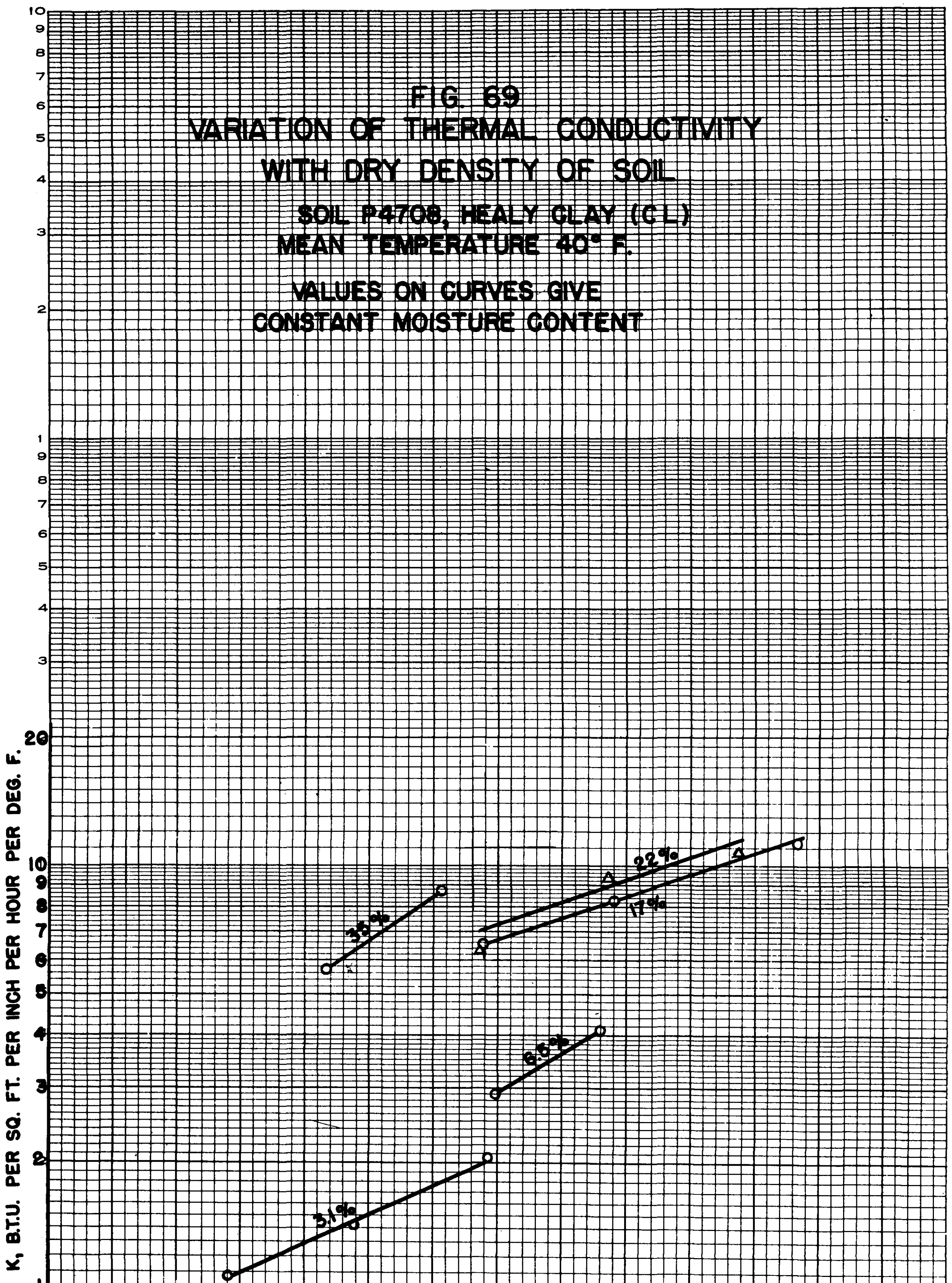


FIG. 69
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
35%
22%
17%
6.5%
3.1%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
60
70
80
90
100
110

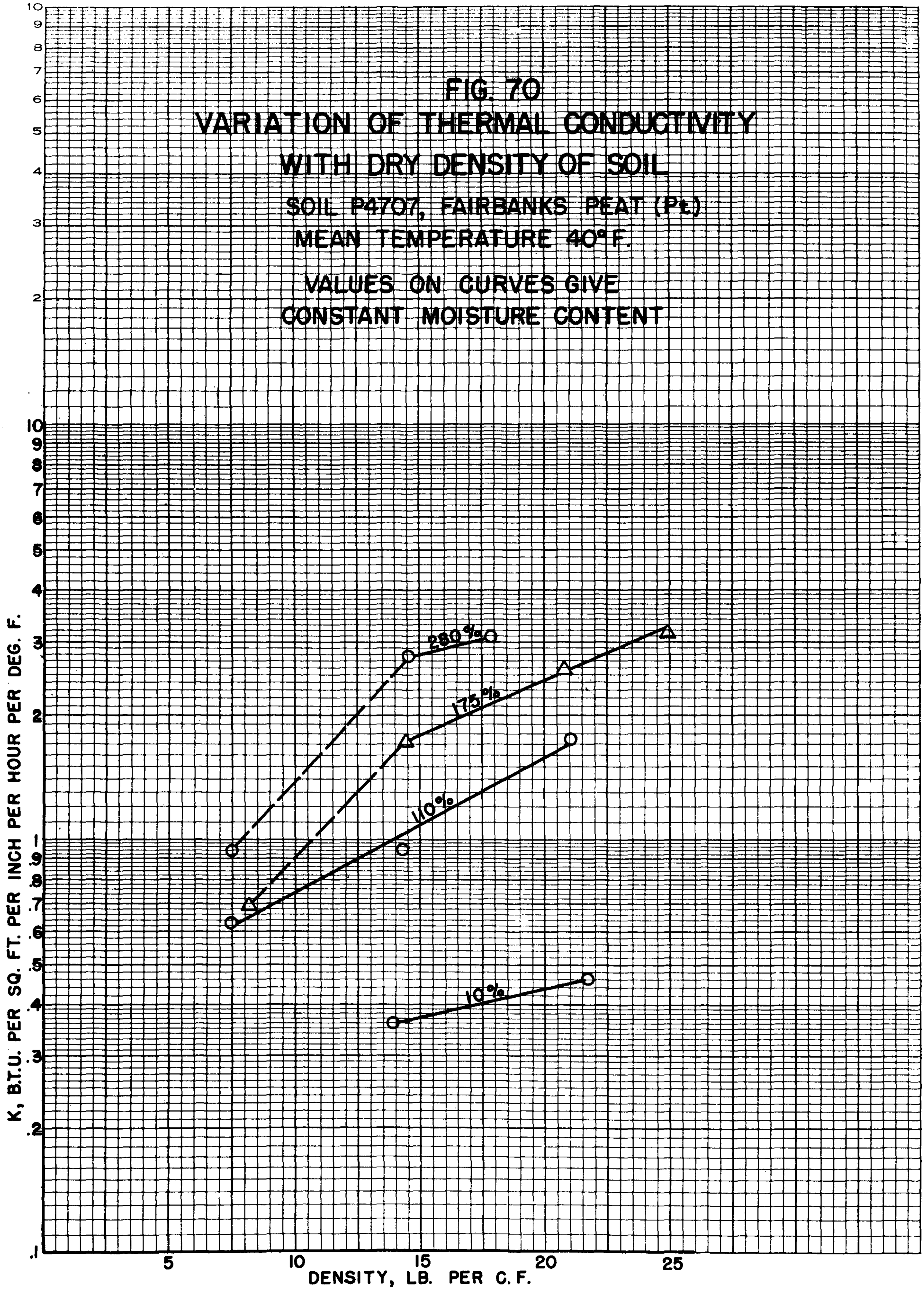


FIG. 70
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4707, FAIRBANKS PEAT (Pt)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
280%
175%
110%
10%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
5
10
15
20
25

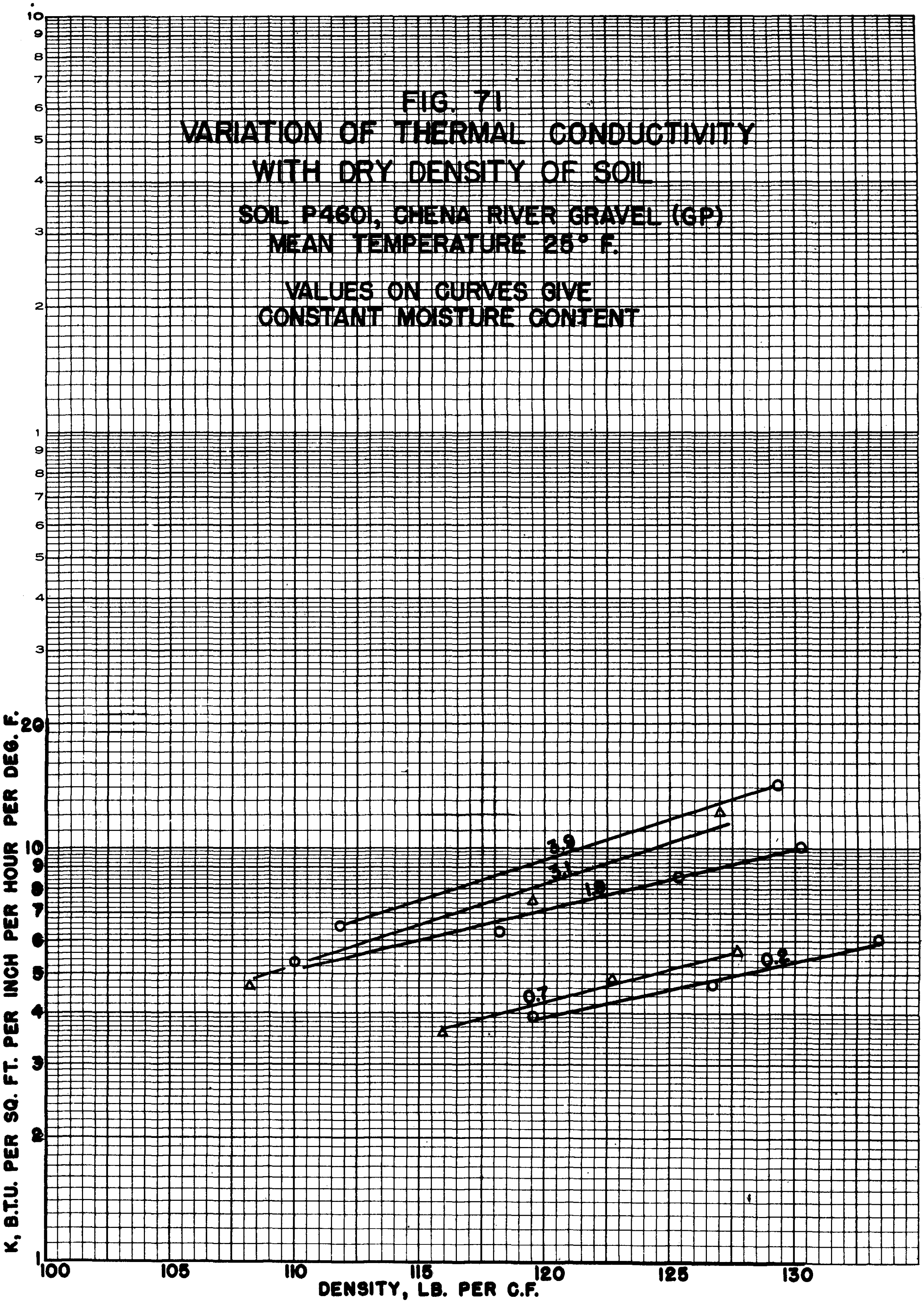


FIG. 71
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4601, CHENA RIVER GRAVEL (GP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
3.9
3.1
1.9
0.7
0.2
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120
125
130

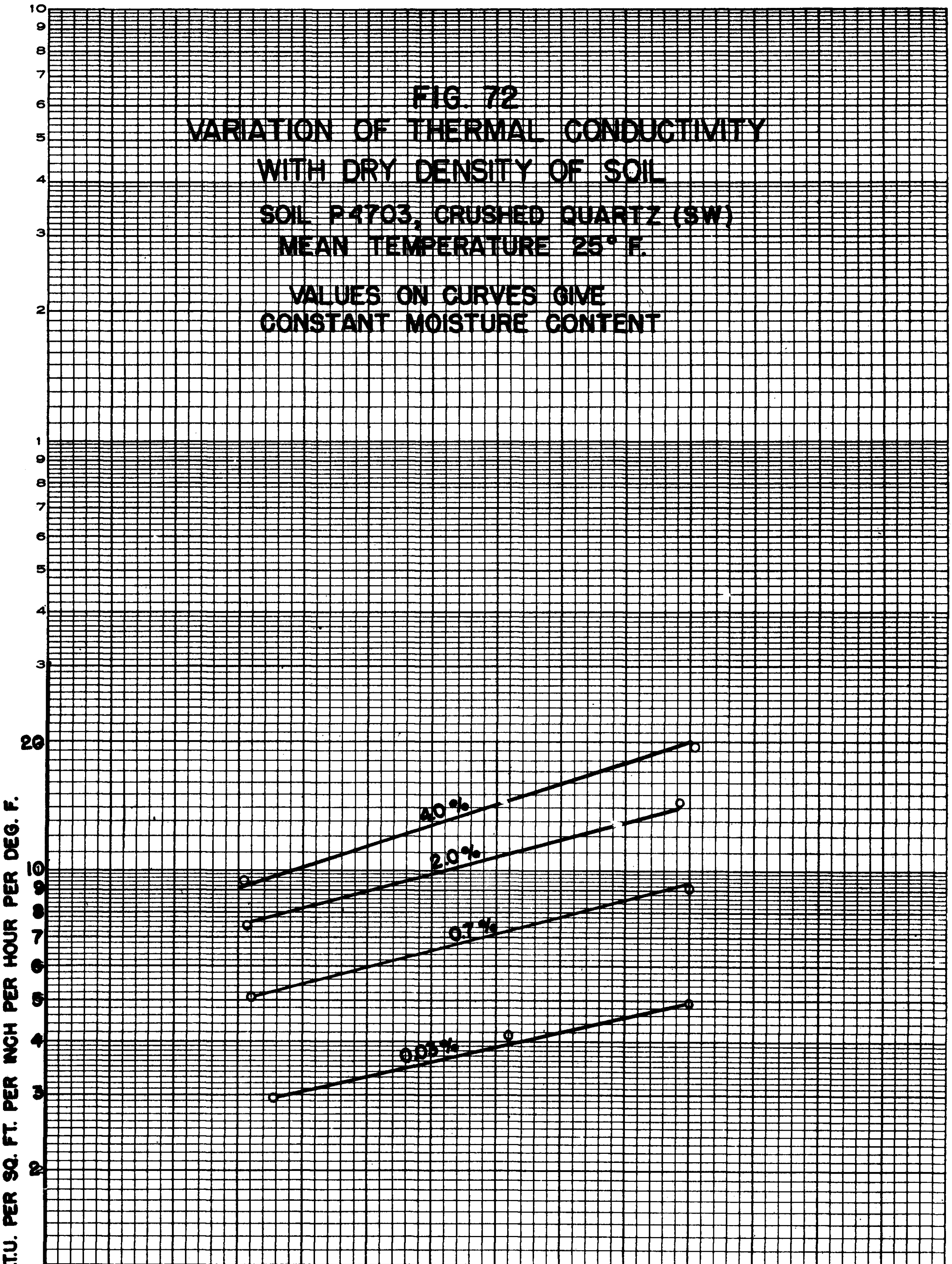


FIG. 72
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4703, CRUSHED QUARTZ (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
40%
20%
0.7%
0.03%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120
1
2
3
4
5
6
7
8
9
10
20

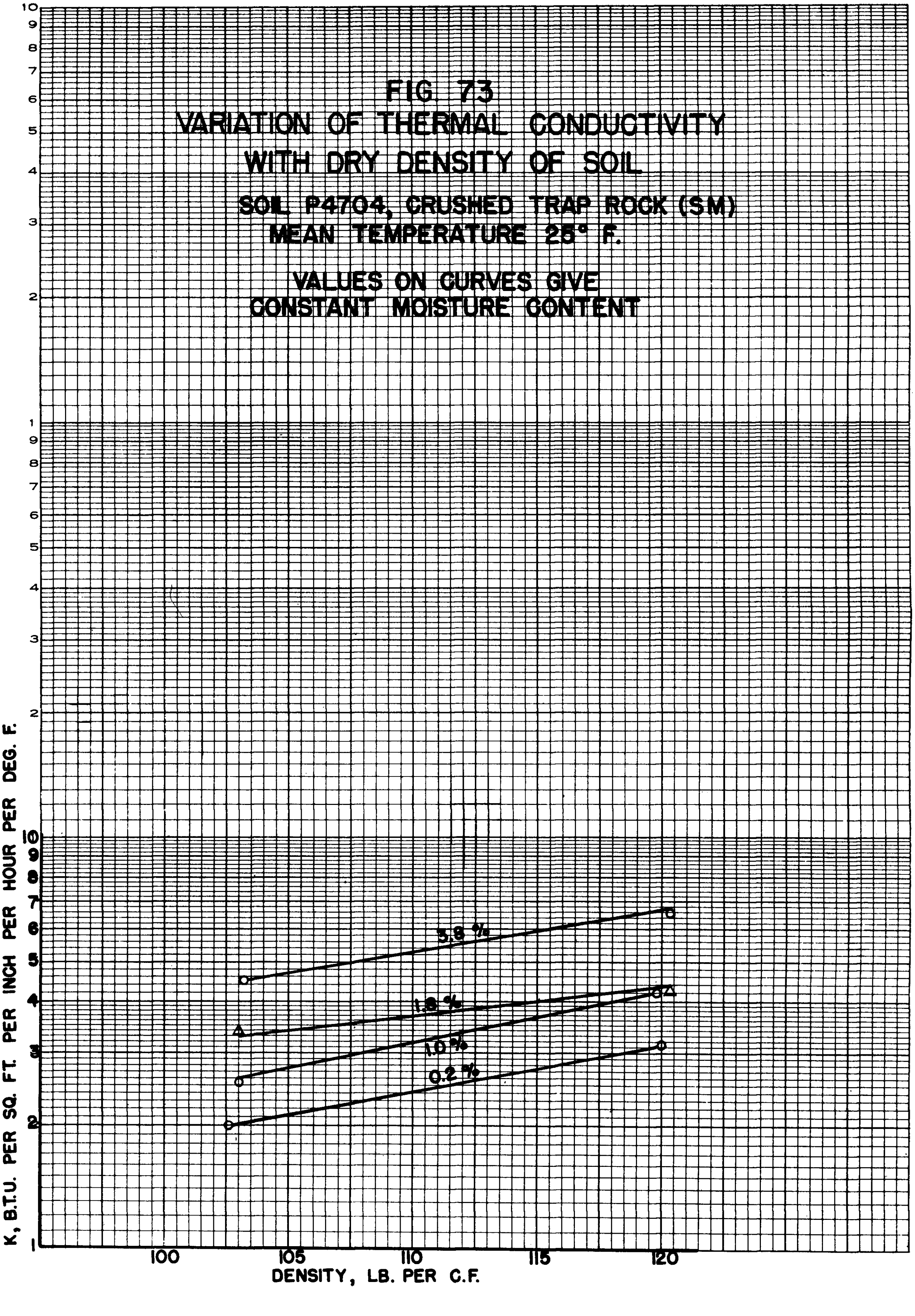


FIG. 73
VARIATION OF THERMAL CONDUCTIVITY WITH DRY DENSITY OF SOIL
SOIL P4704, CRUSHED TRAP ROCK (SM)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE CONSTANT MOISTURE CONTENT
3.8 %
1.8 %
1.0 %
0.2 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

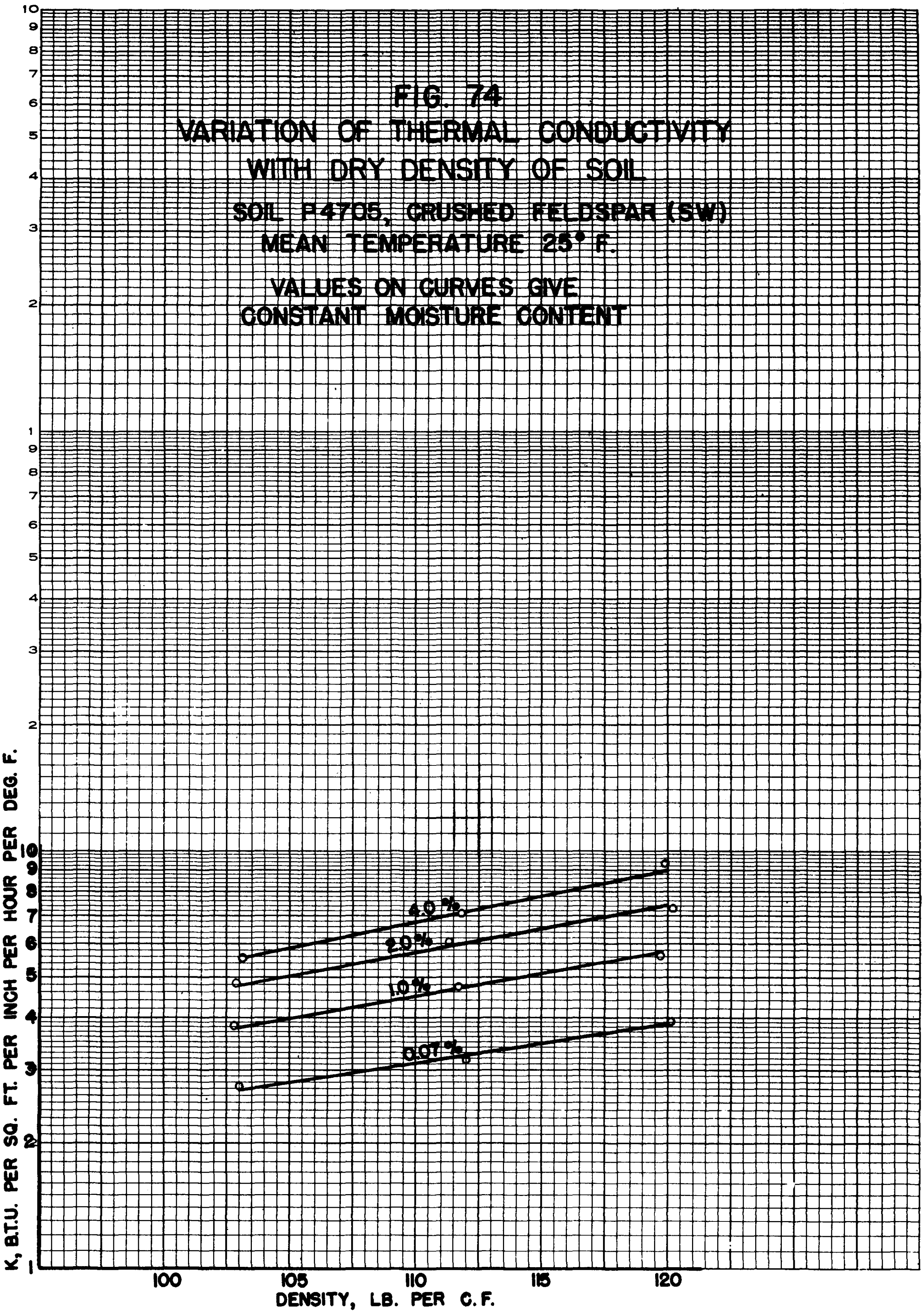


FIG. 74
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4705, CRUSHED FELDSPAR (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
4.0%
2.0%
1.0%
0.07%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
100
105
110
115
120
DENSITY, LB. PER C.F.

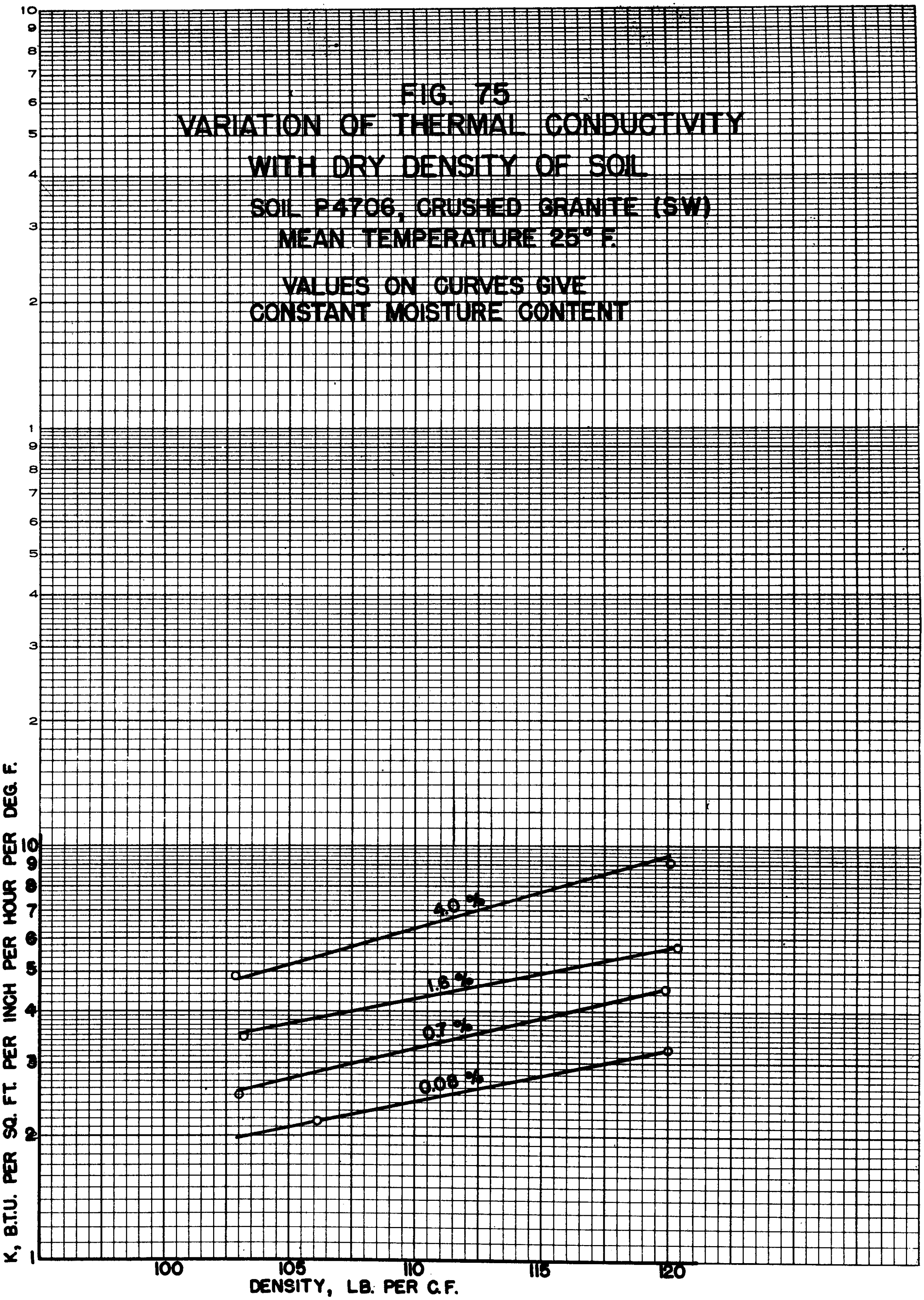


FIG. 75
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4706, CRUSHED GRANITE (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
4.0 %
1.6 %
0.7 %
0.08 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120

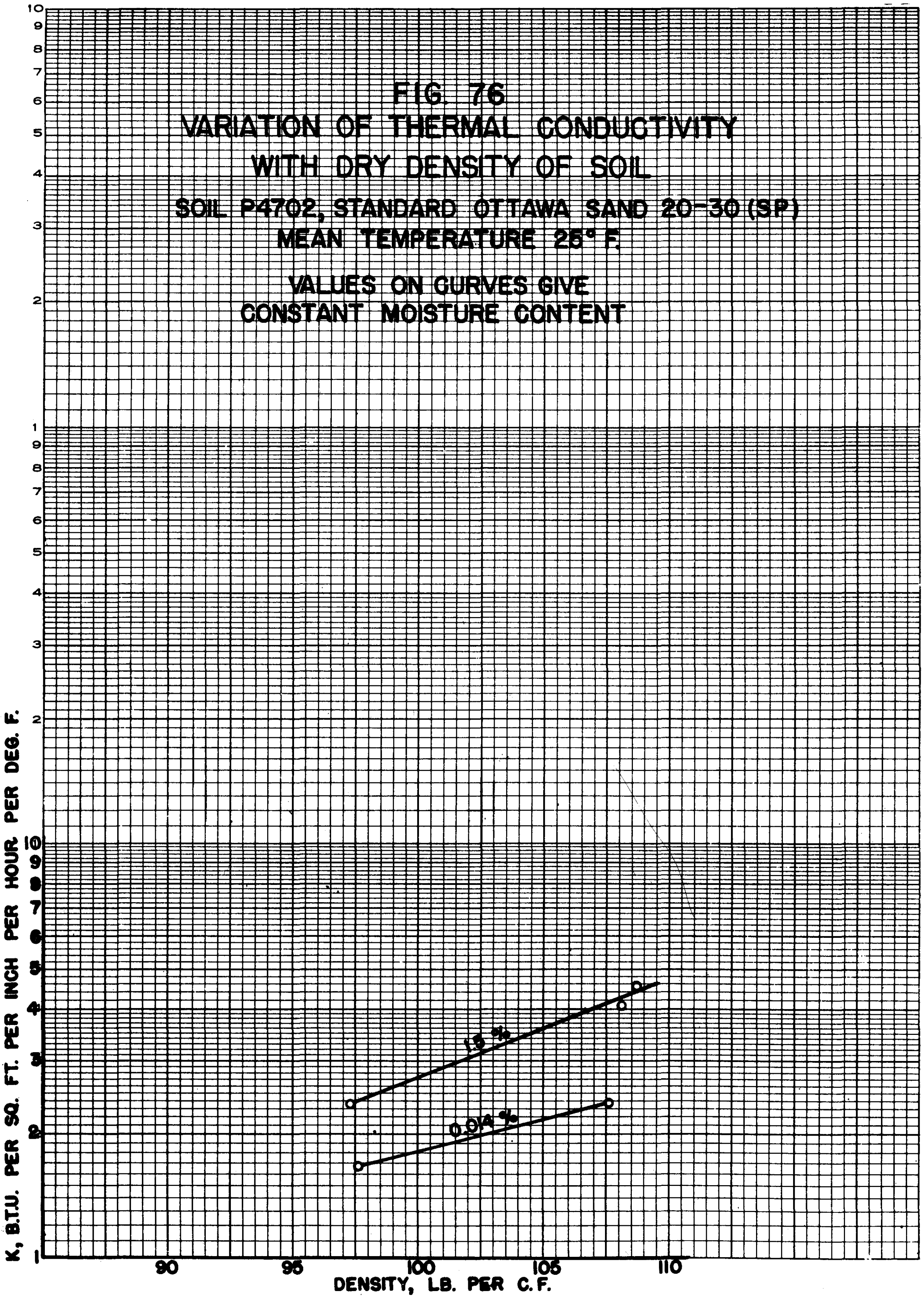


FIG. 76
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4702, STANDARD OTTAWA SAND 20-30 (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
15 %
0.014 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110

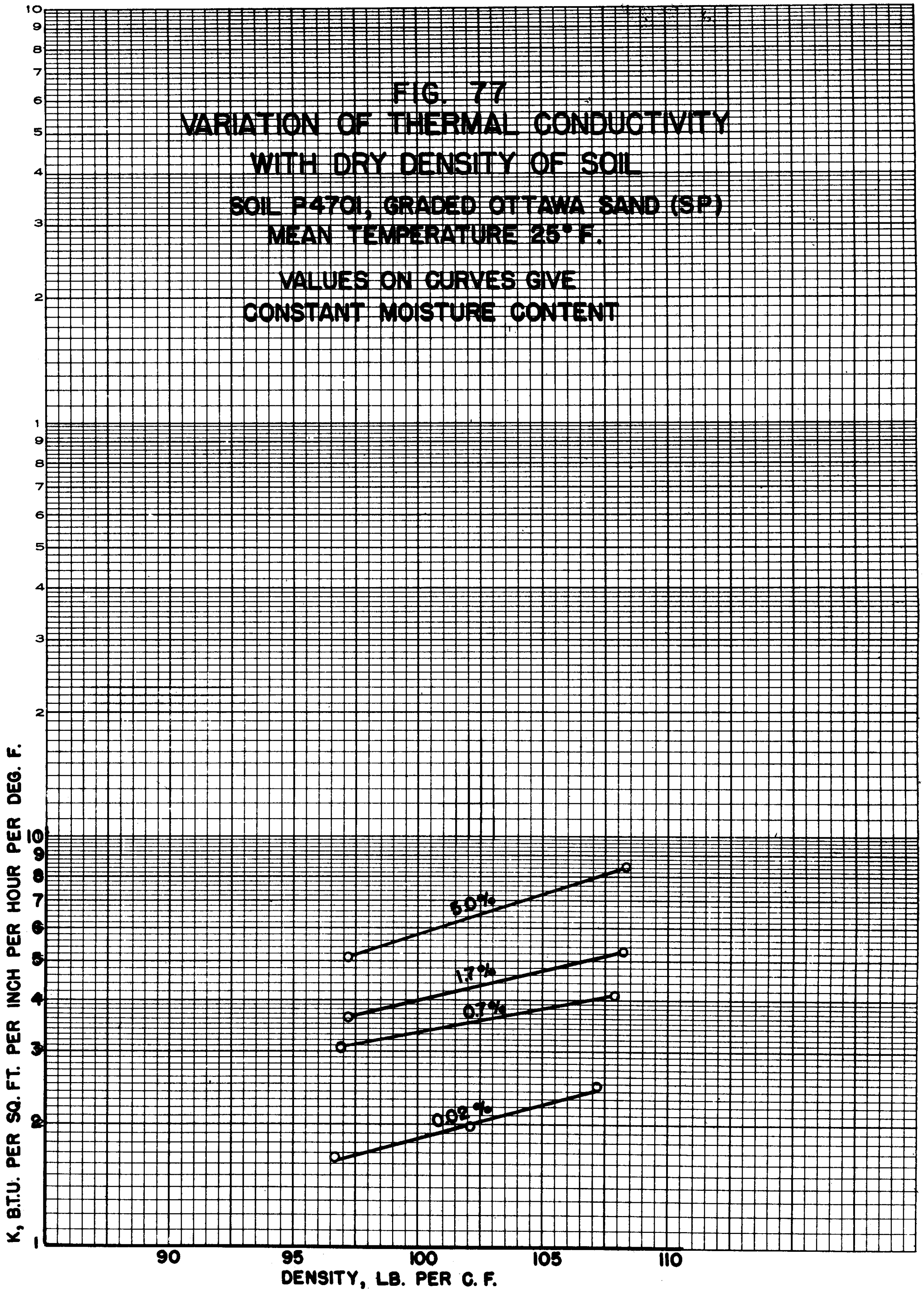


FIG. 77
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4701, GRADED OTTAWA SAND (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
5.0%
1.7%
0.7%
0.02%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C. F.
90
95
100
105
110

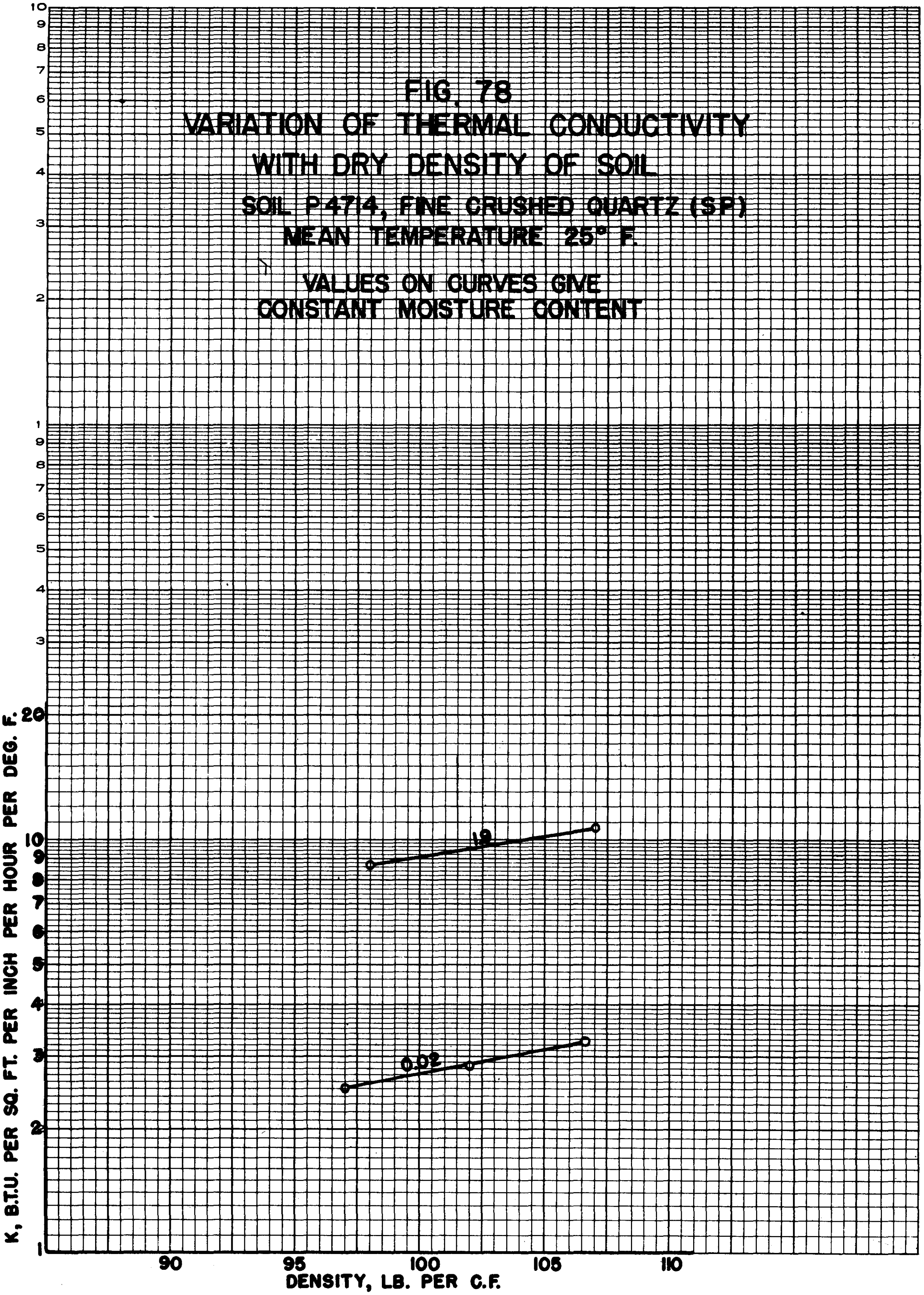


FIG. 78
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4714, FINE CRUSHED QUARTZ (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
19
0.02
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110

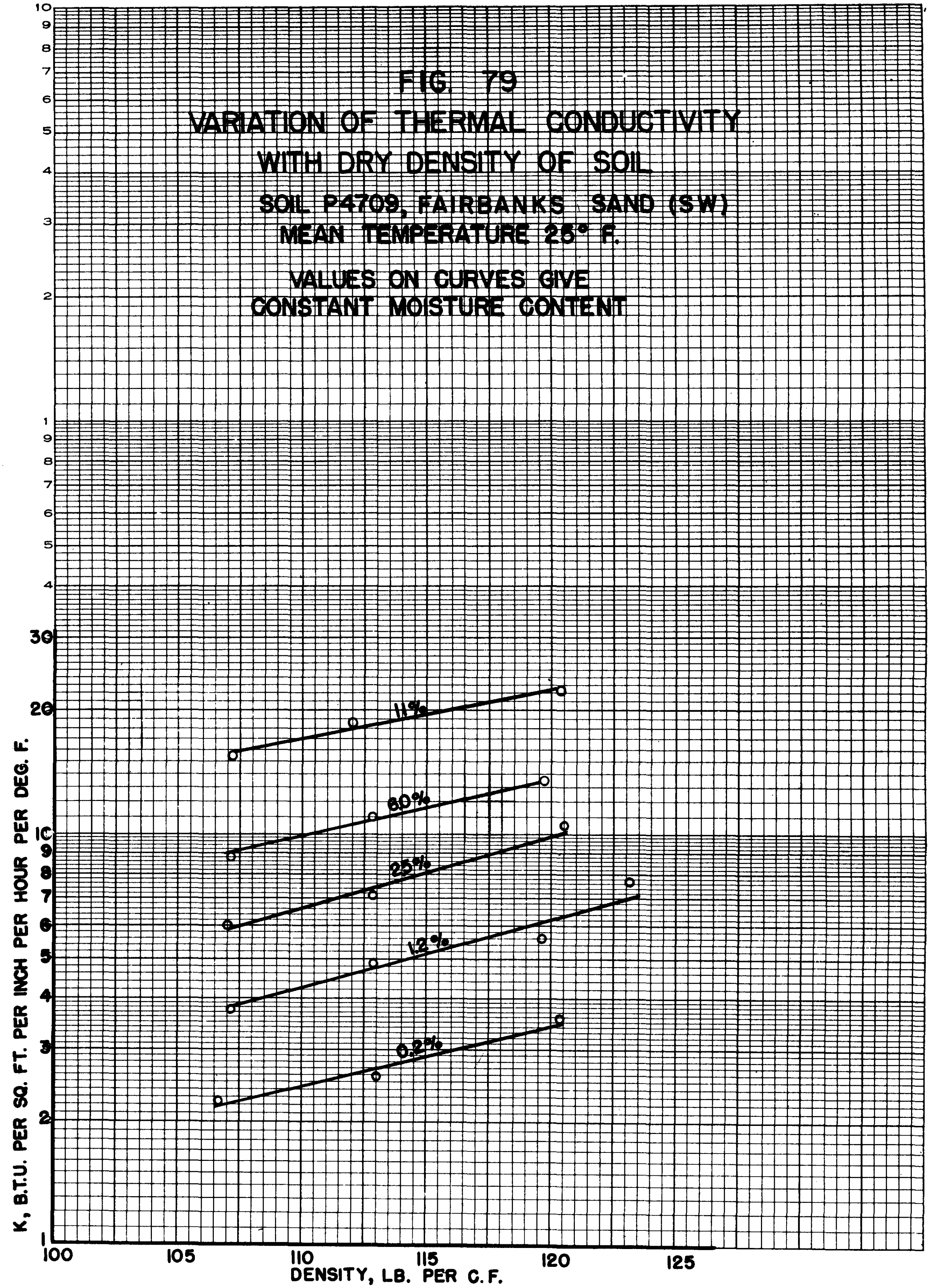


FIG. 79
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4709, FAIRBANKS SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
11%
60%
25%
1.2%
0.2%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
100
105
110
115
120
125
30
20
10
9
8
7
6
5
4
3
2
1

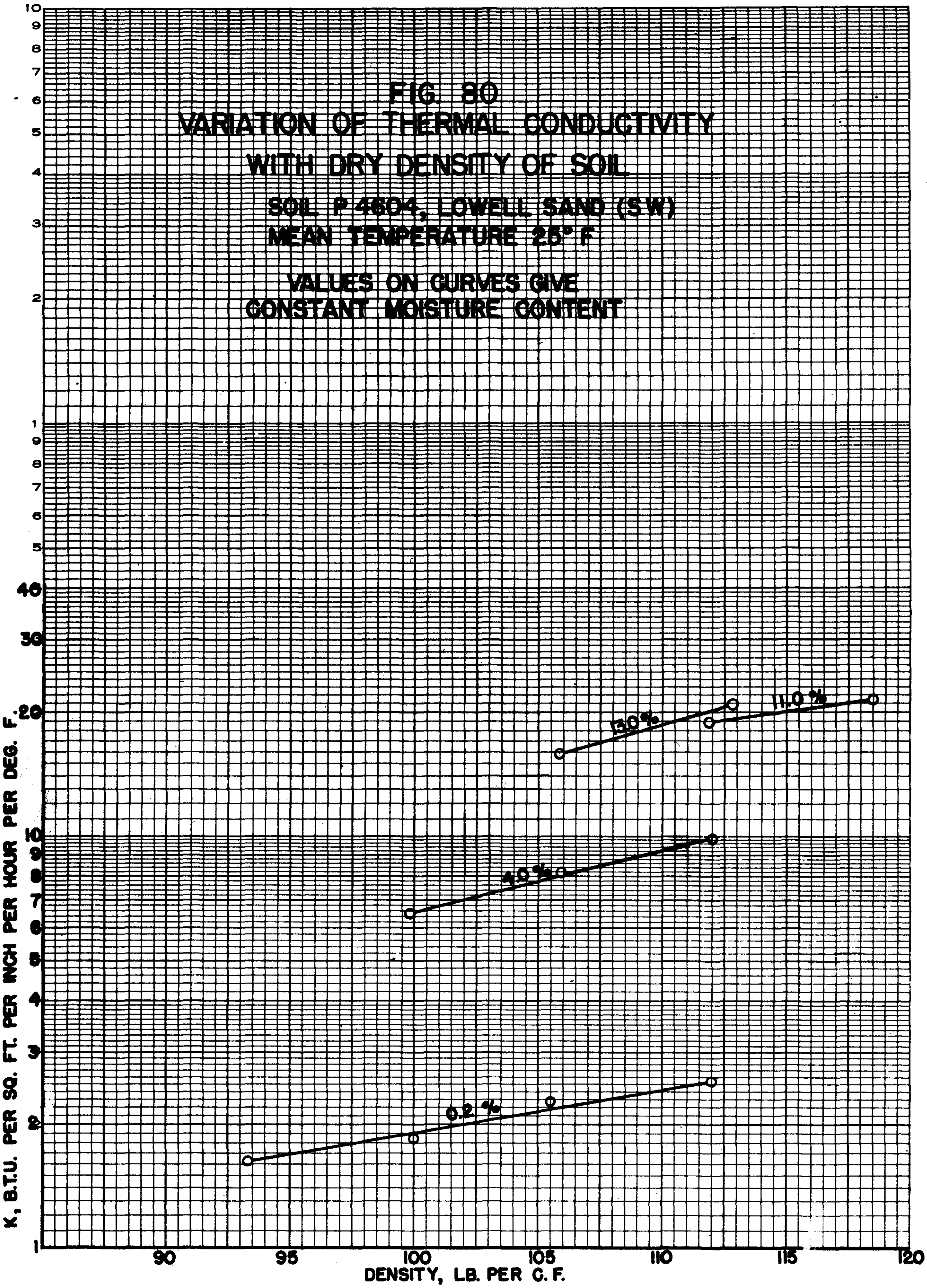


FIG. 80
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4604, LOWELL SAND (SW)
MEAN TEMPERATURE 25° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
15.0%
11.0%
4.0%
0.2%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C. F.
90
95
100
105
110
115
120

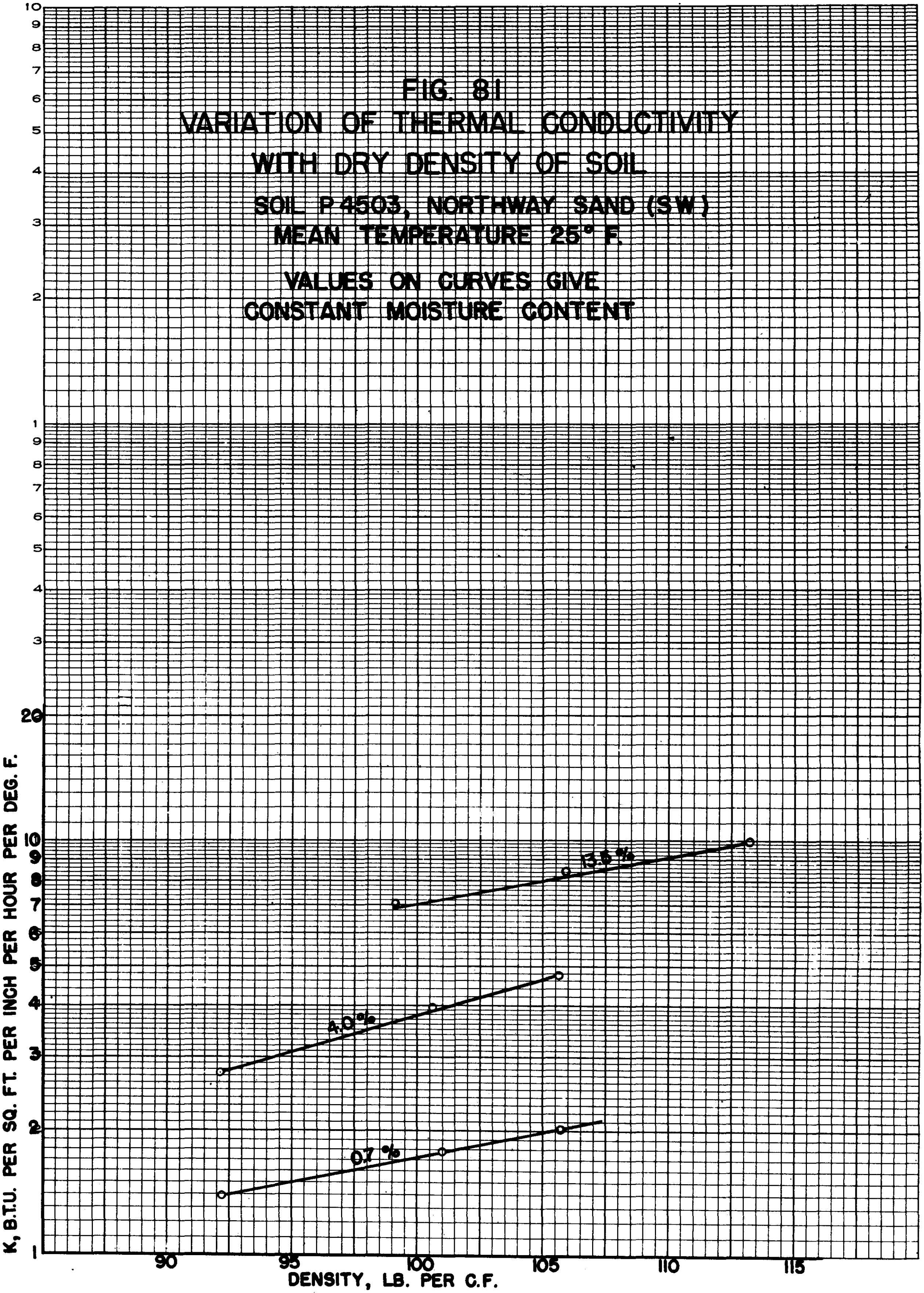


FIG. 81
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
13.6 %
4.0 %
0.7 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
90
95
100
105
110
115

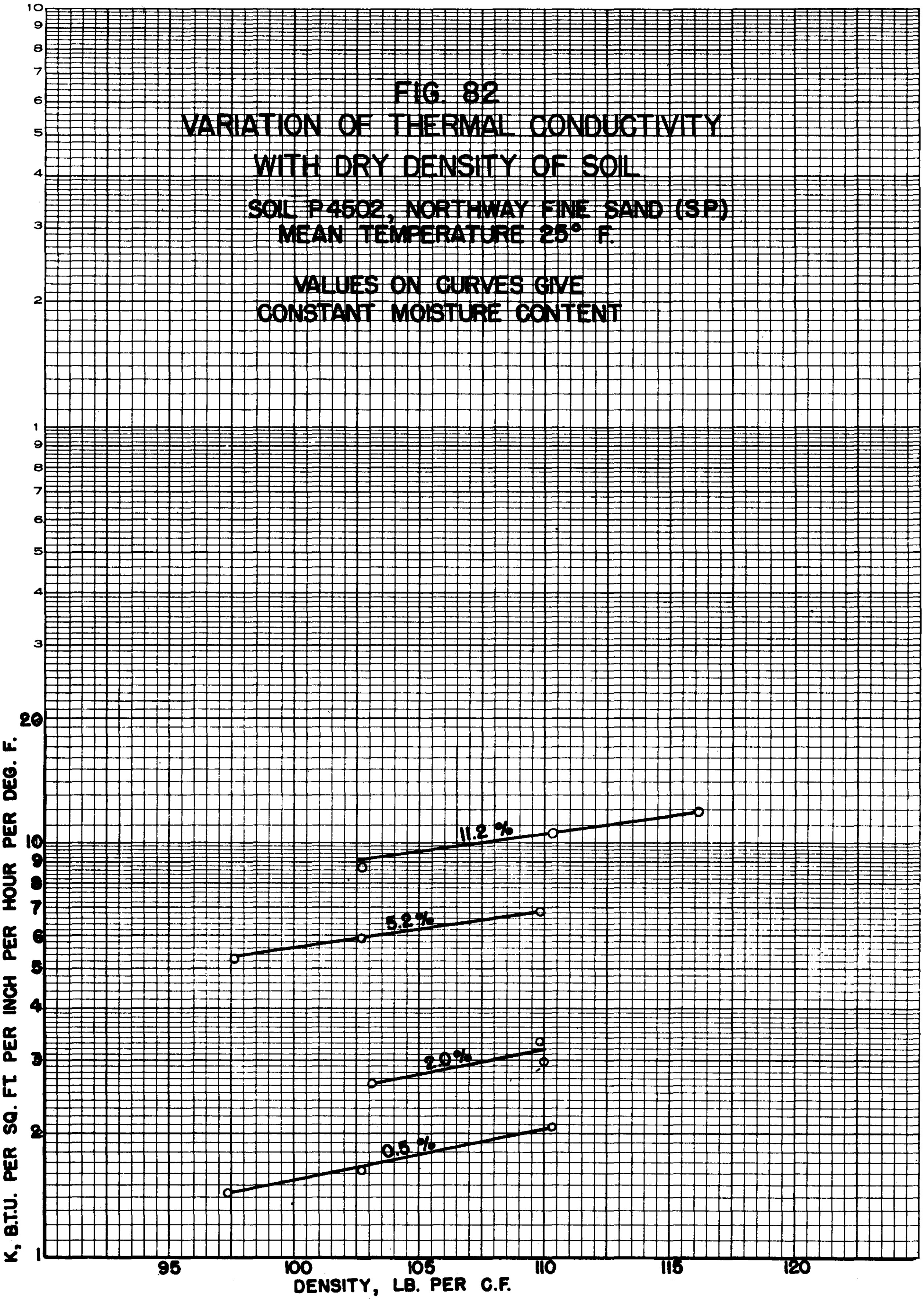


FIG. 82
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
11.2 %
5.2 %
2.0 %
0.5 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
95
100
105
110
115
120

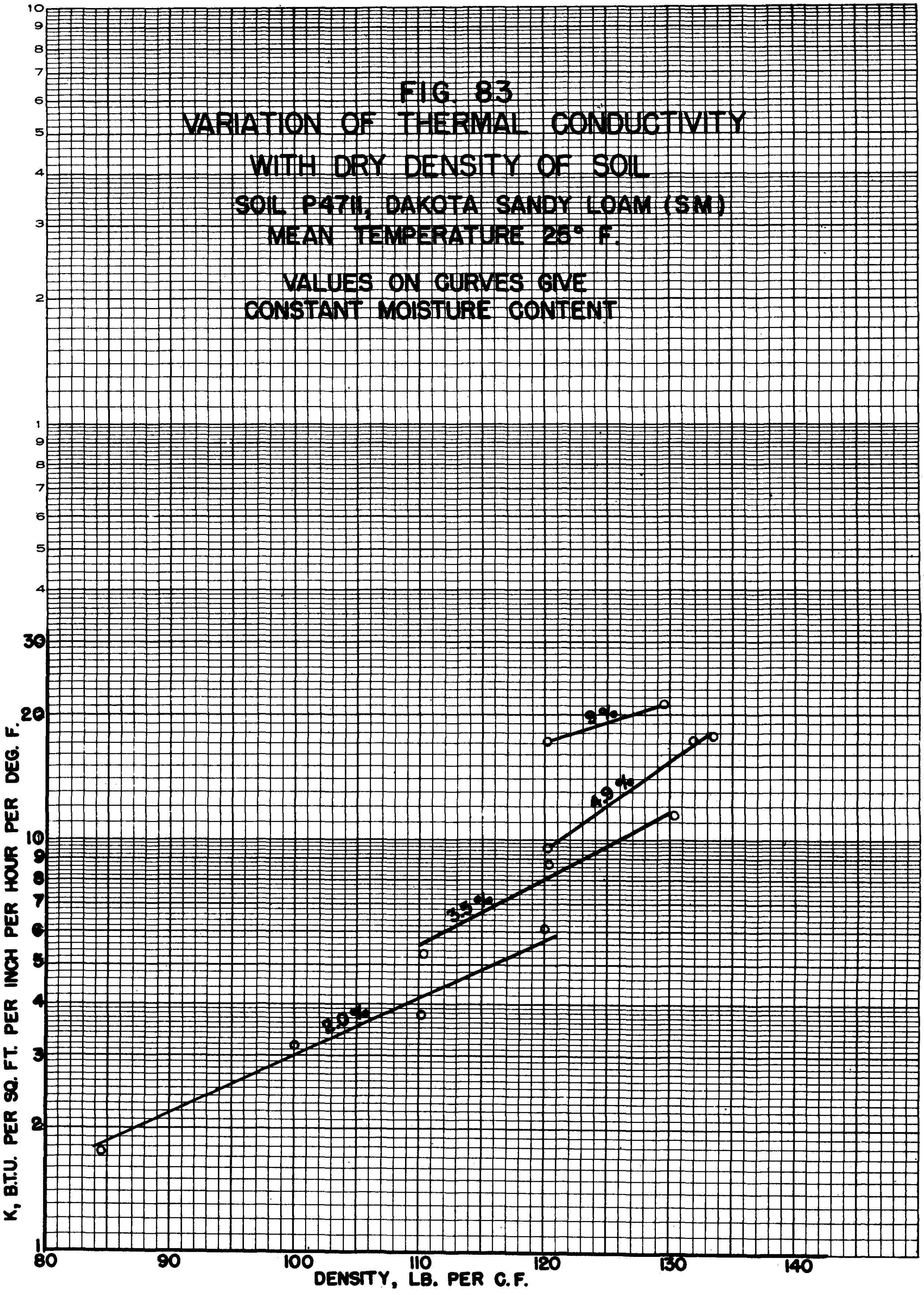


FIG. 83
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
9%
4.9%
3.5%
2.0%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
80
90
100
110
120
130
140
1
2
3
4
5
6
7
8
9
10
20
30

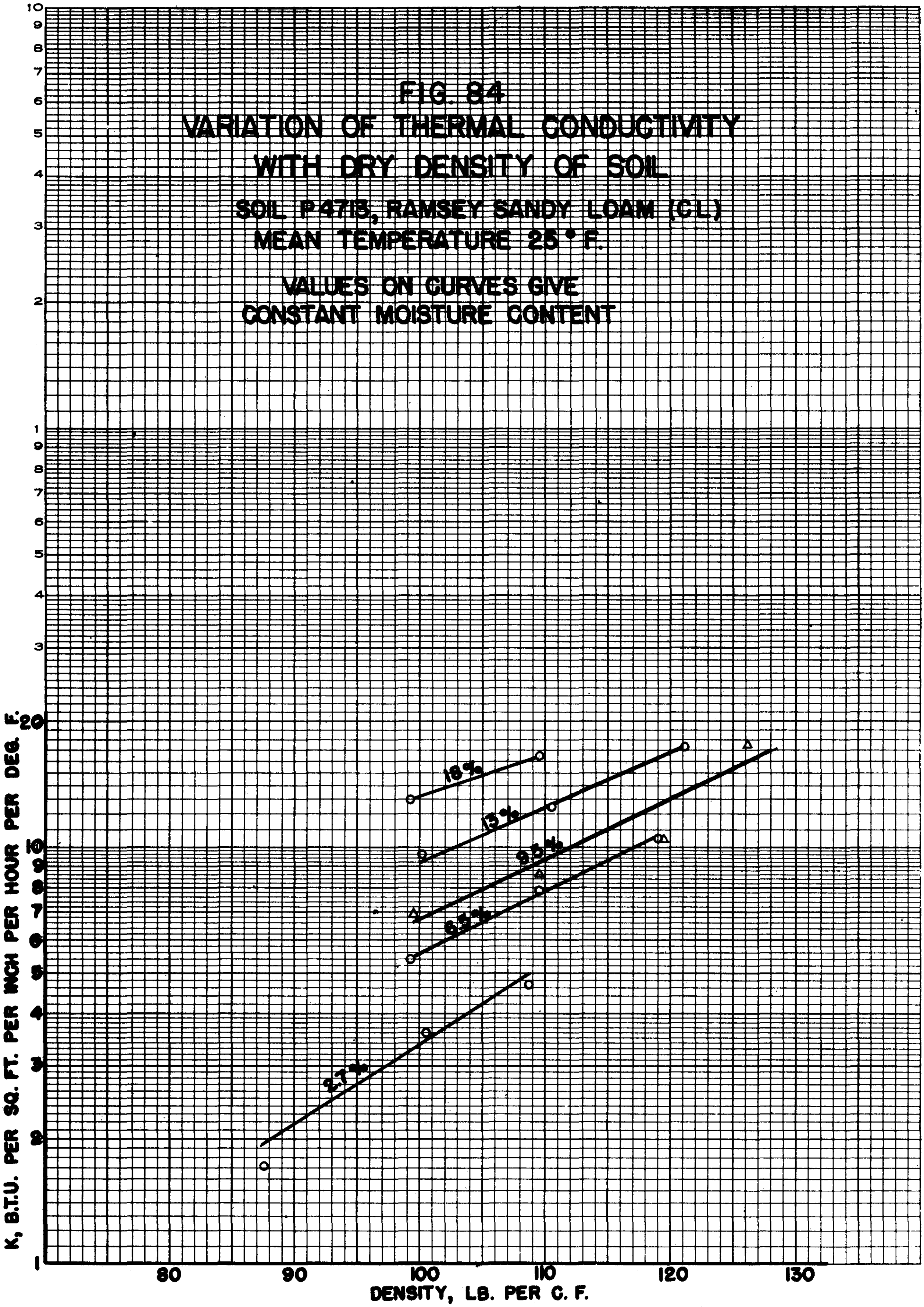


FIG. 84
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
18%
13%
9.5%
6.5%
2.7%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C. F.
80
90
100
110
120
130

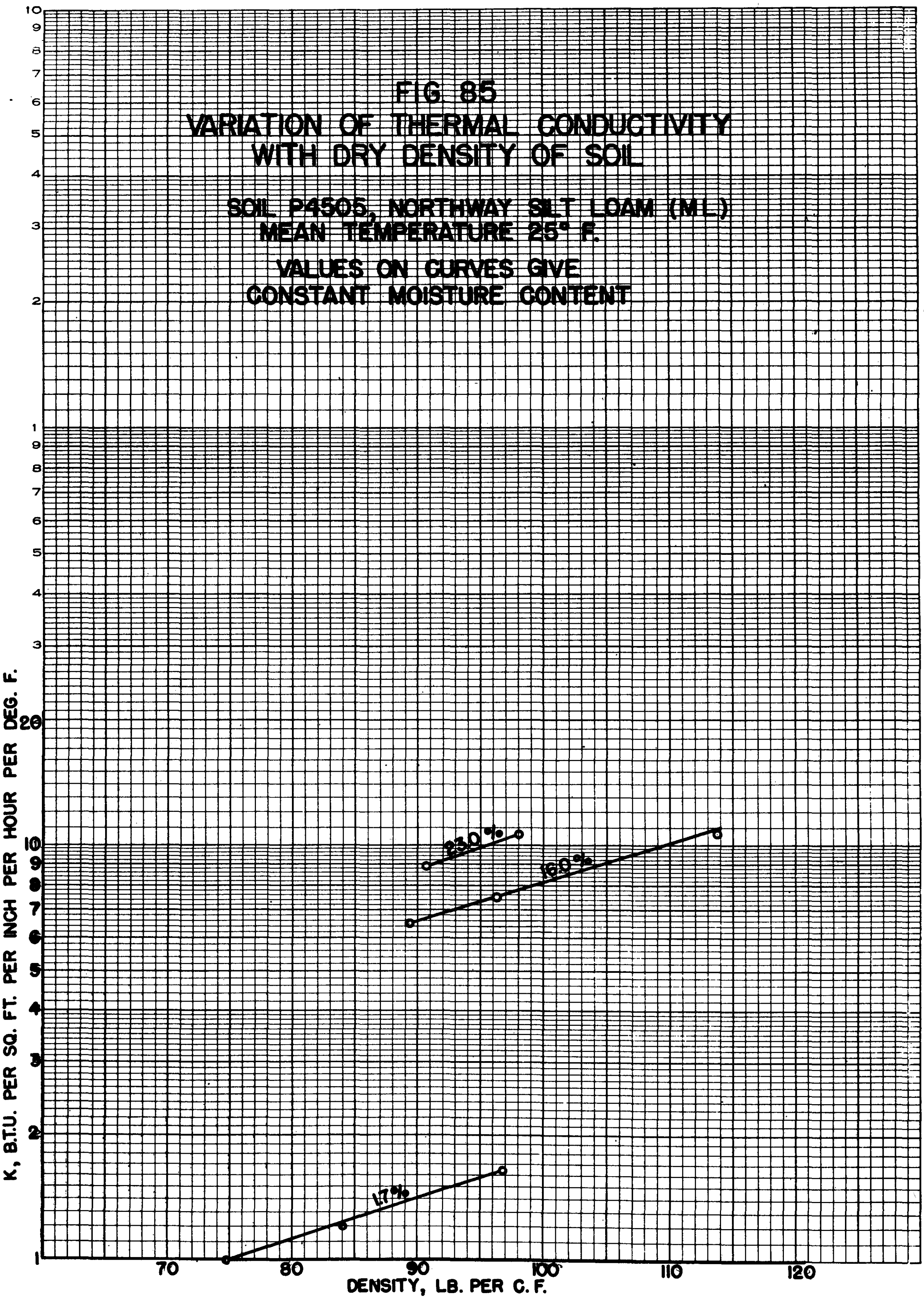


FIG. 85
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
23.0%
16.0%
1.7%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
70
80
90
100
110
120

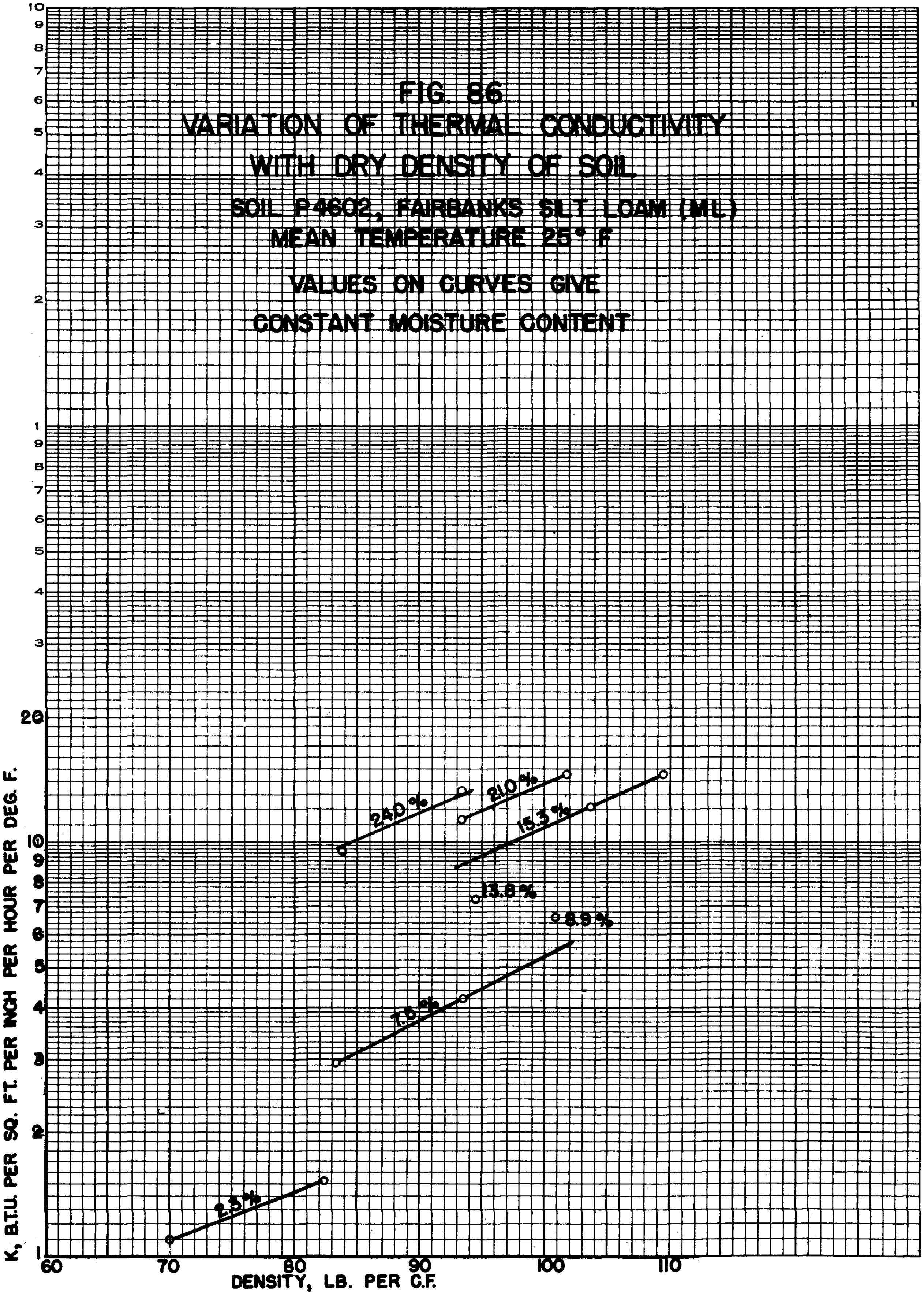


FIG. 86
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 25° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
24.0 %
21.0 %
15.3 %
13.8 %
8.9 %
7.5 %
2.3 %
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
60
70
80
90
100
110
1
2
3
4
5
6
7
8
9
10
20

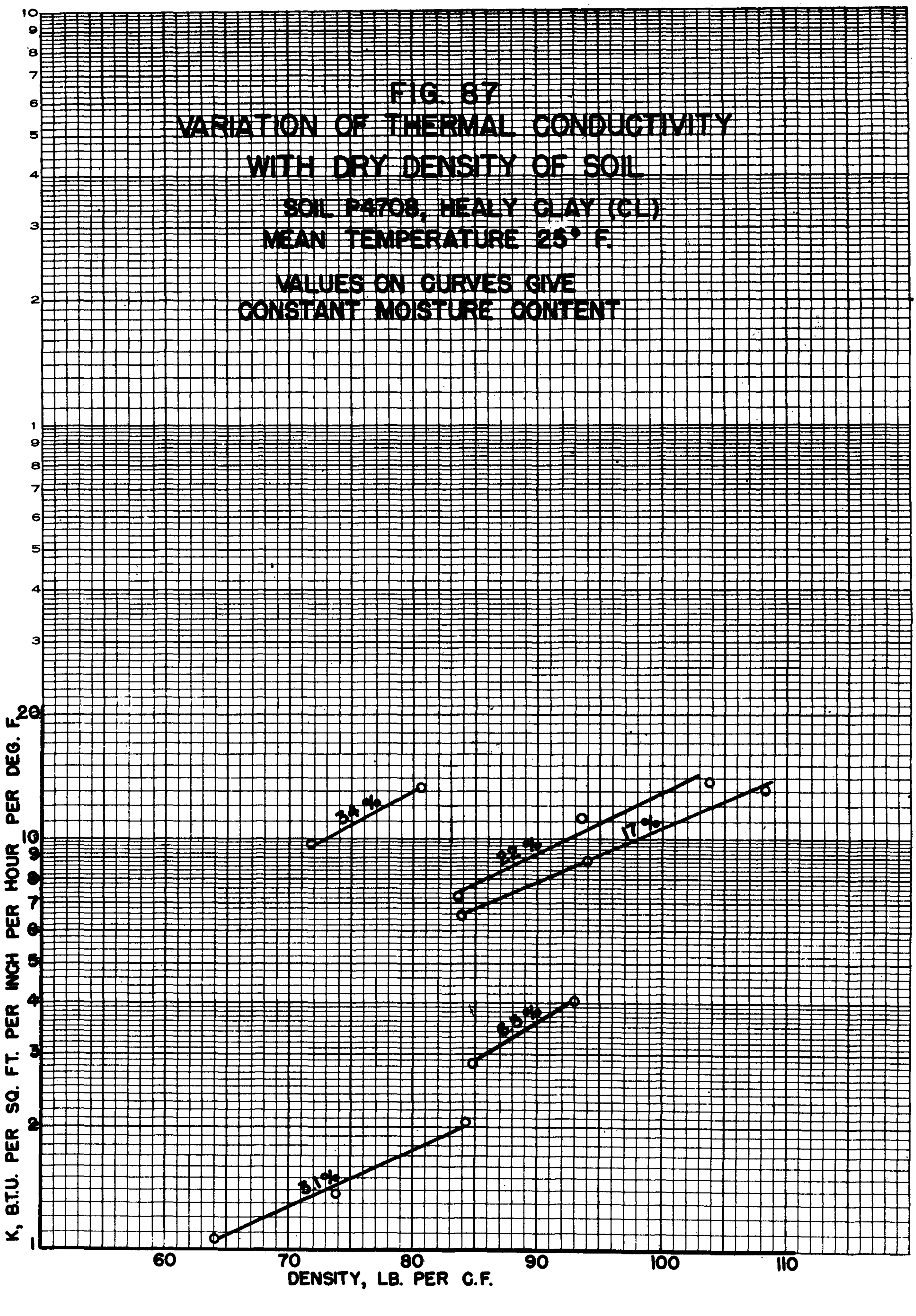


FIG. 87
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
34%
22%
17%
8.5%
3.1%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
60
70
80
90
100
110
1
2
3
4
5
6
7
8
9
10
20

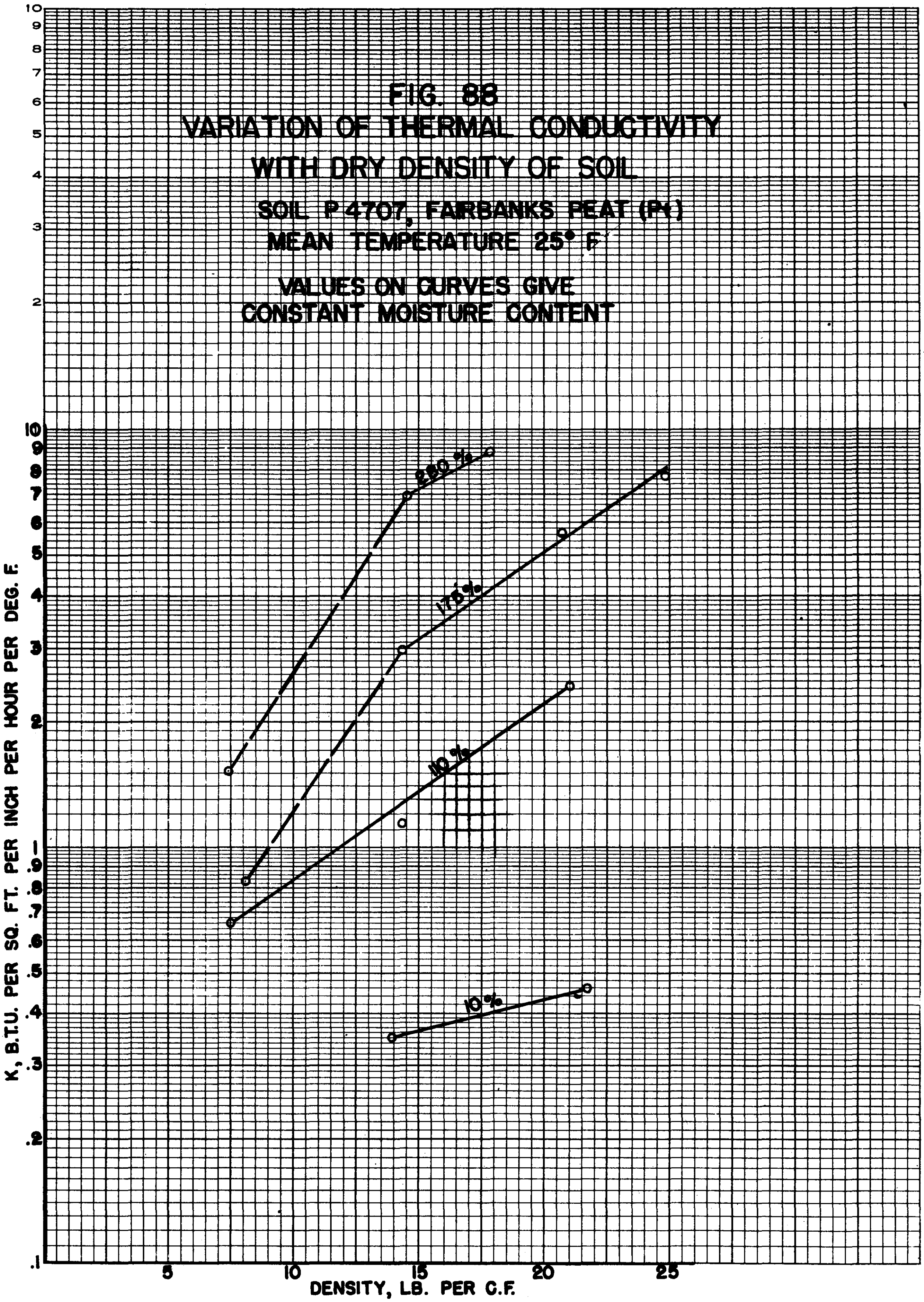


FIG. 88
VARIATION OF THERMAL CONDUCTIVITY
WITH DRY DENSITY OF SOIL
SOIL P 4707, FAIRBANKS PEAT (Pt)
MEAN TEMPERATURE 25° F
VALUES ON CURVES GIVE
CONSTANT MOISTURE CONTENT
250%
175%
110%
10%
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
DENSITY, LB. PER C.F.
5
10
15
20
25

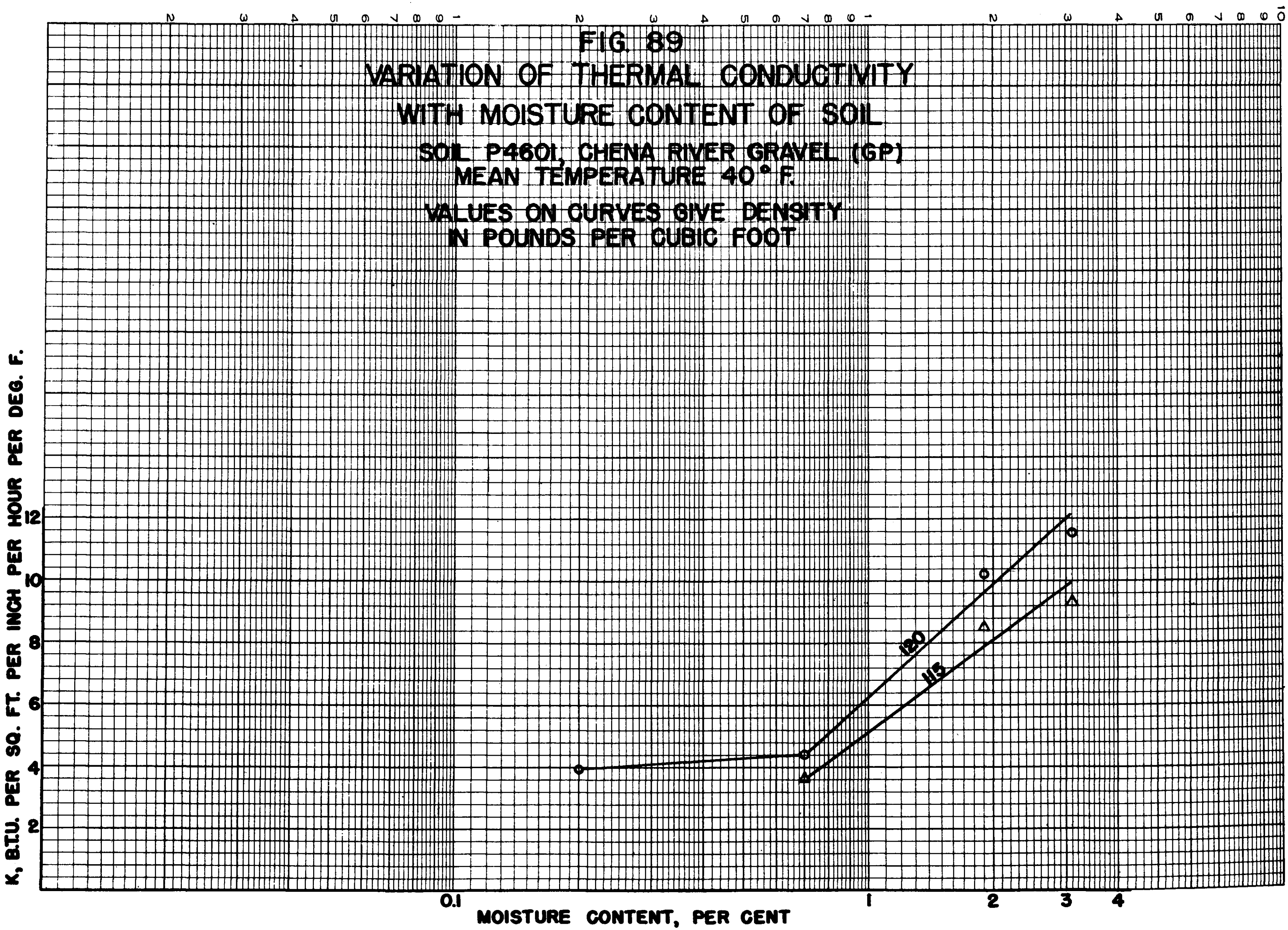


FIG. 89
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4601, CHENA RIVER GRAVEL (GP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
115
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT
0.1
1
2
3
4

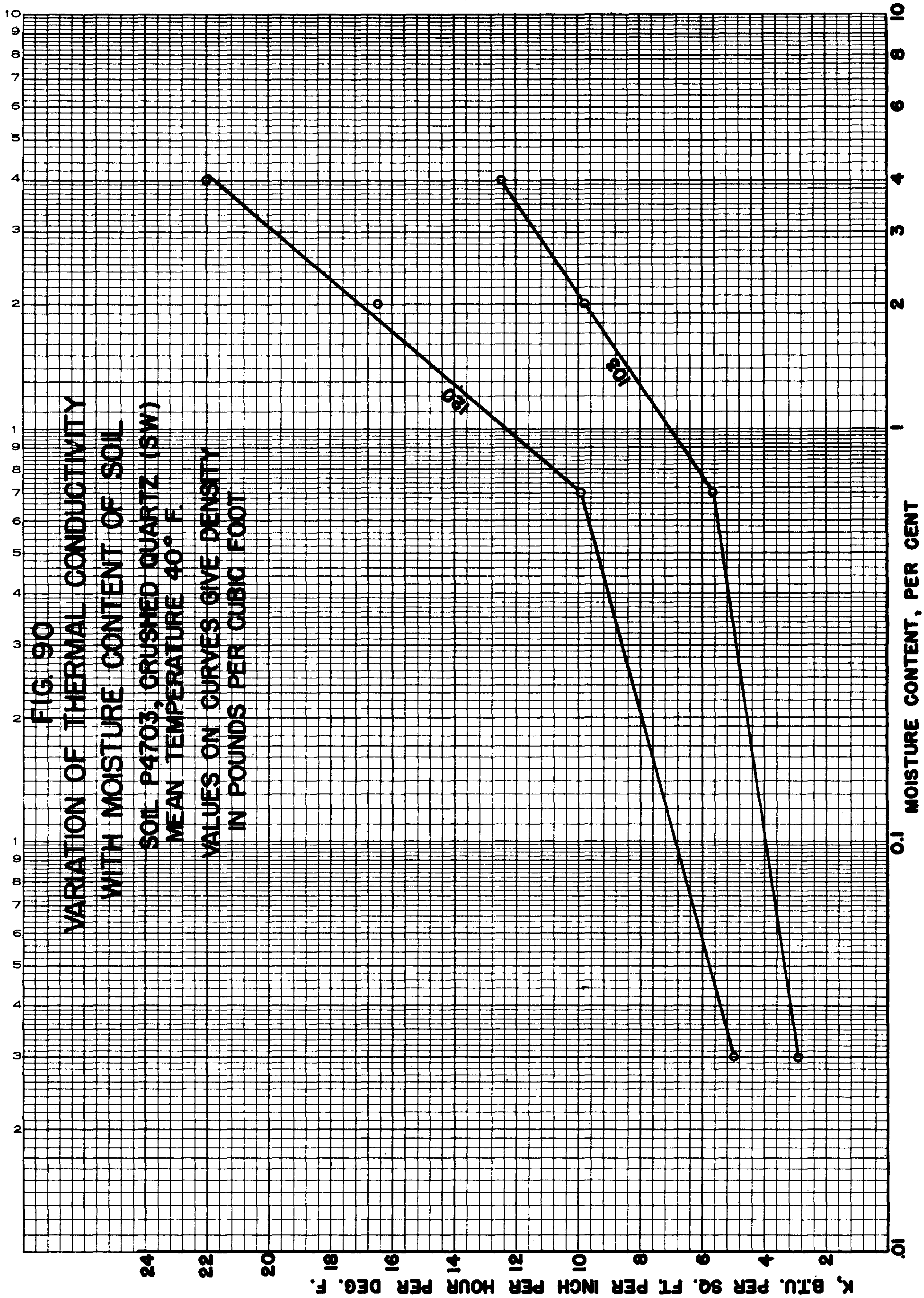


FIG. 90
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4703, CRUSHED QUARTZ (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
108
MOISTURE CONTENT, PER CENT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
.01
0.1
1
10
2
4
6
8
10
12
14
16
18
20
22
24

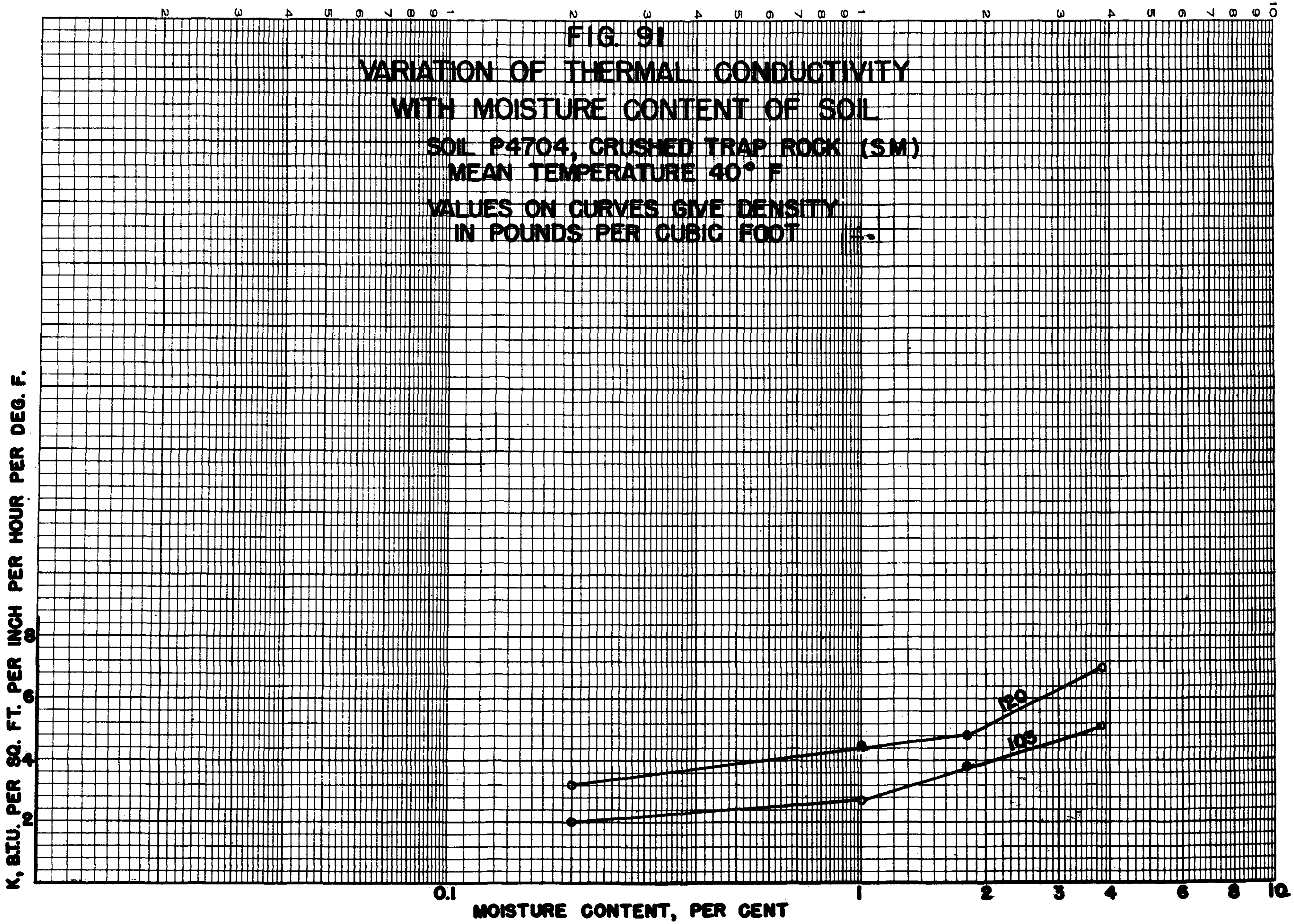


FIG. 91
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4704, CRUSHED TRAP ROCK (SM)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

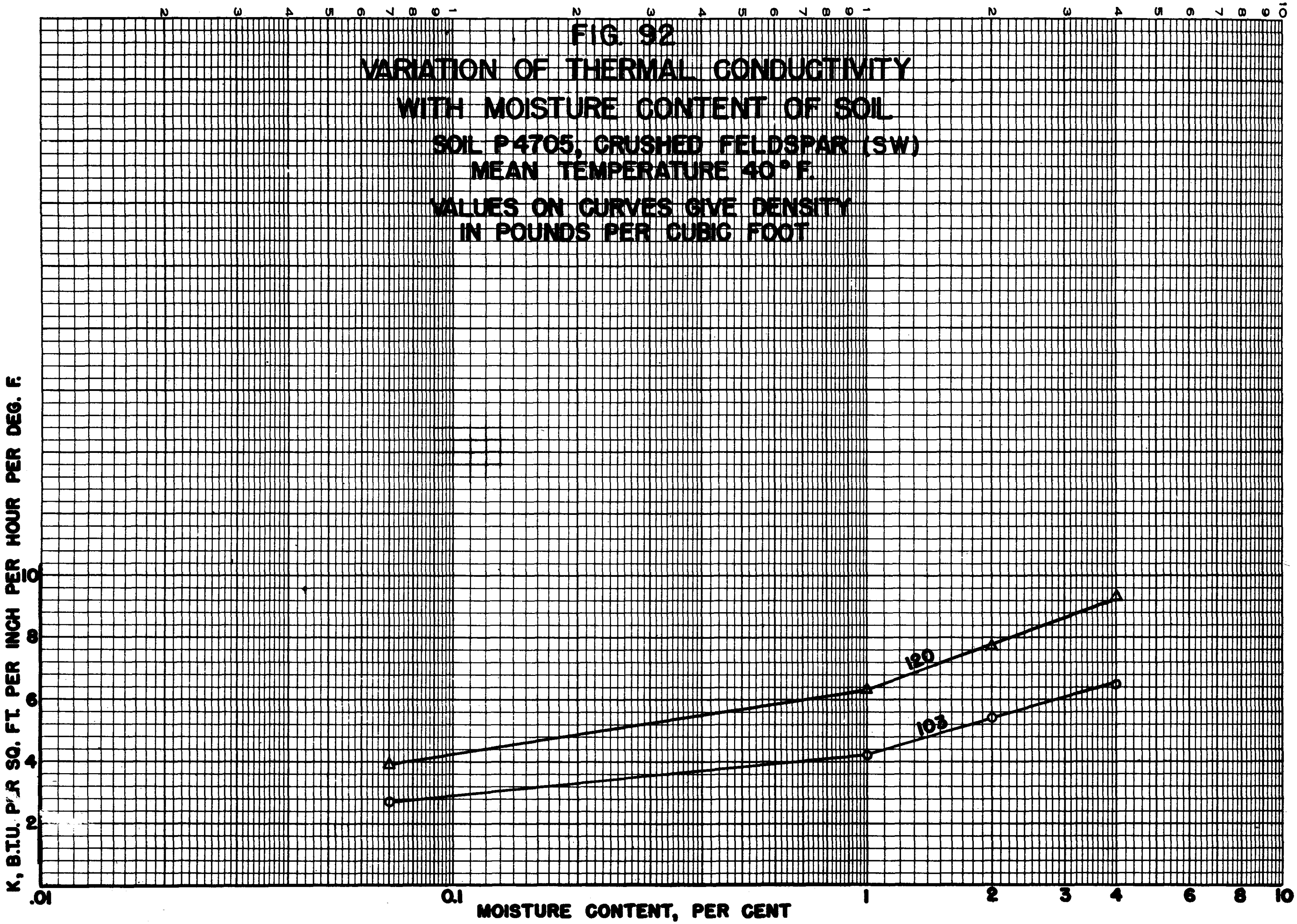


FIG. 92
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4705, CRUSHED FELDSPAR (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
120
103
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT
.01
0.1
1
2
3
4
6
8
10

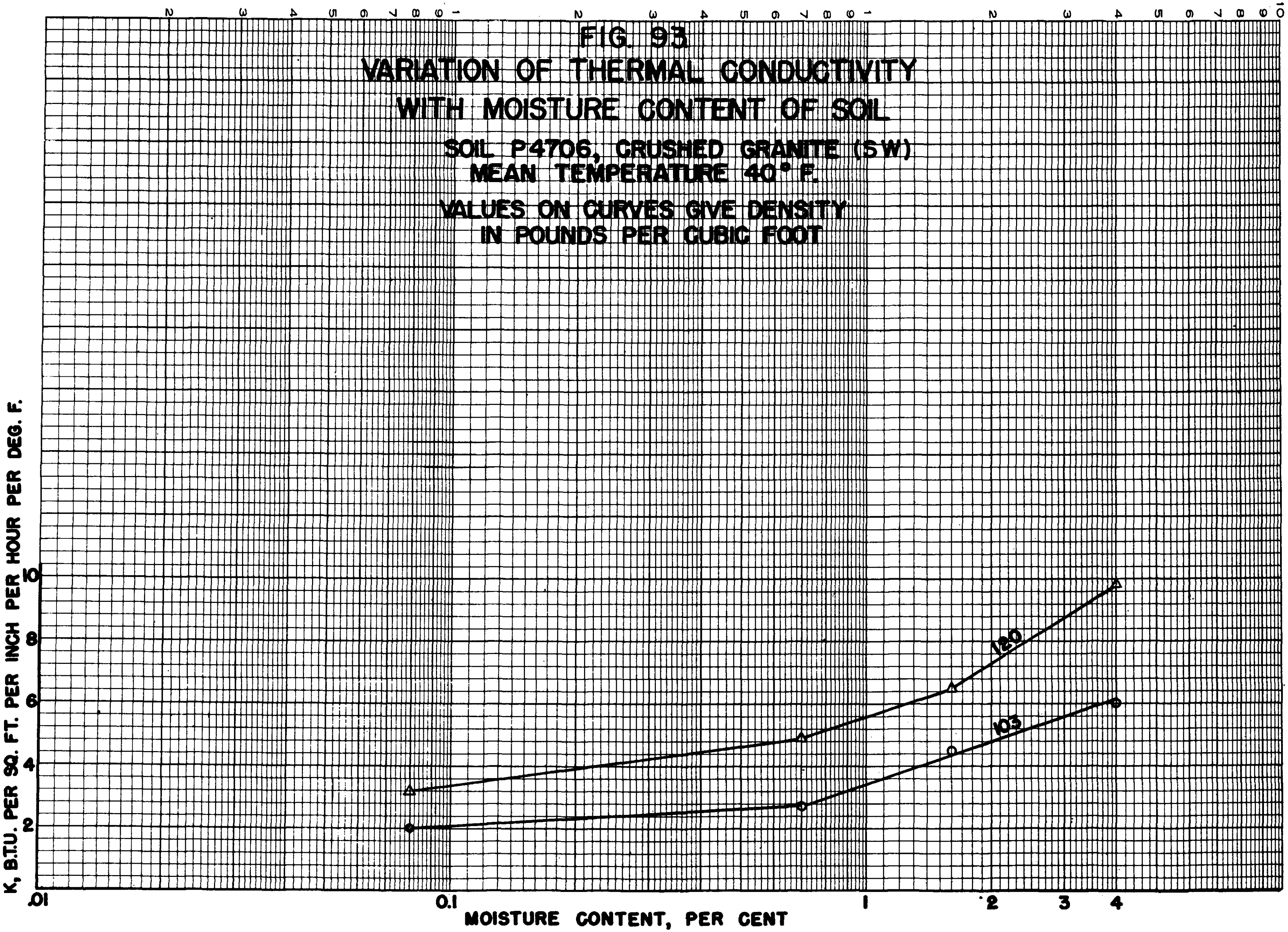


FIG. 93
VARIATION OF THERMAL CONDUCTIVITY WITH MOISTURE CONTENT OF SOIL
SOIL P4706, CRUSHED GRANITE (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY IN POUNDS PER CUBIC FOOT

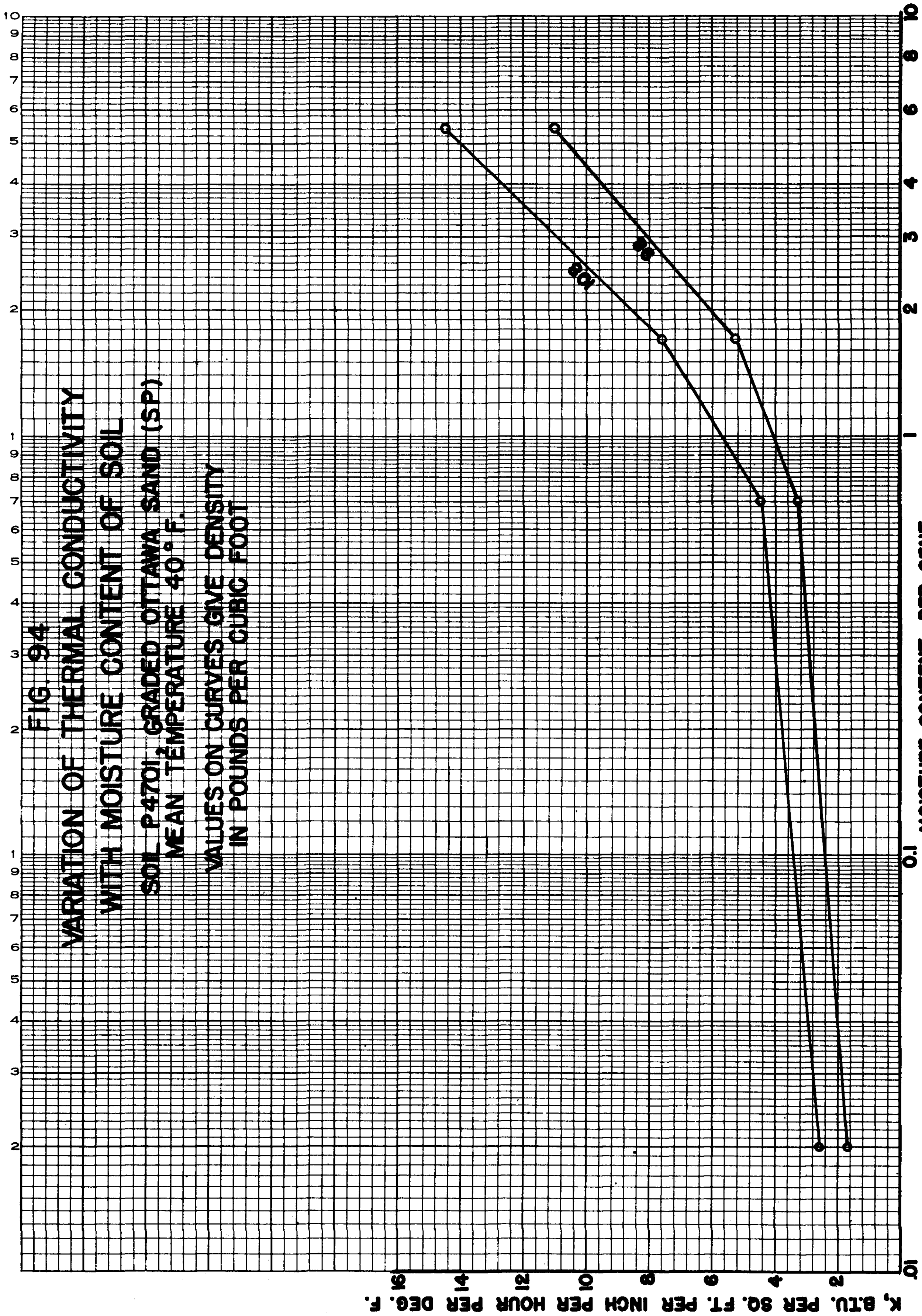


FIG. 94
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4701, GRADED OTTAWA SAND (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
108
98
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
16
14
12
10
8
6
4
2
MOISTURE CONTENT, PER CENT
.01
0.1
1
2
3
4
6
8
10

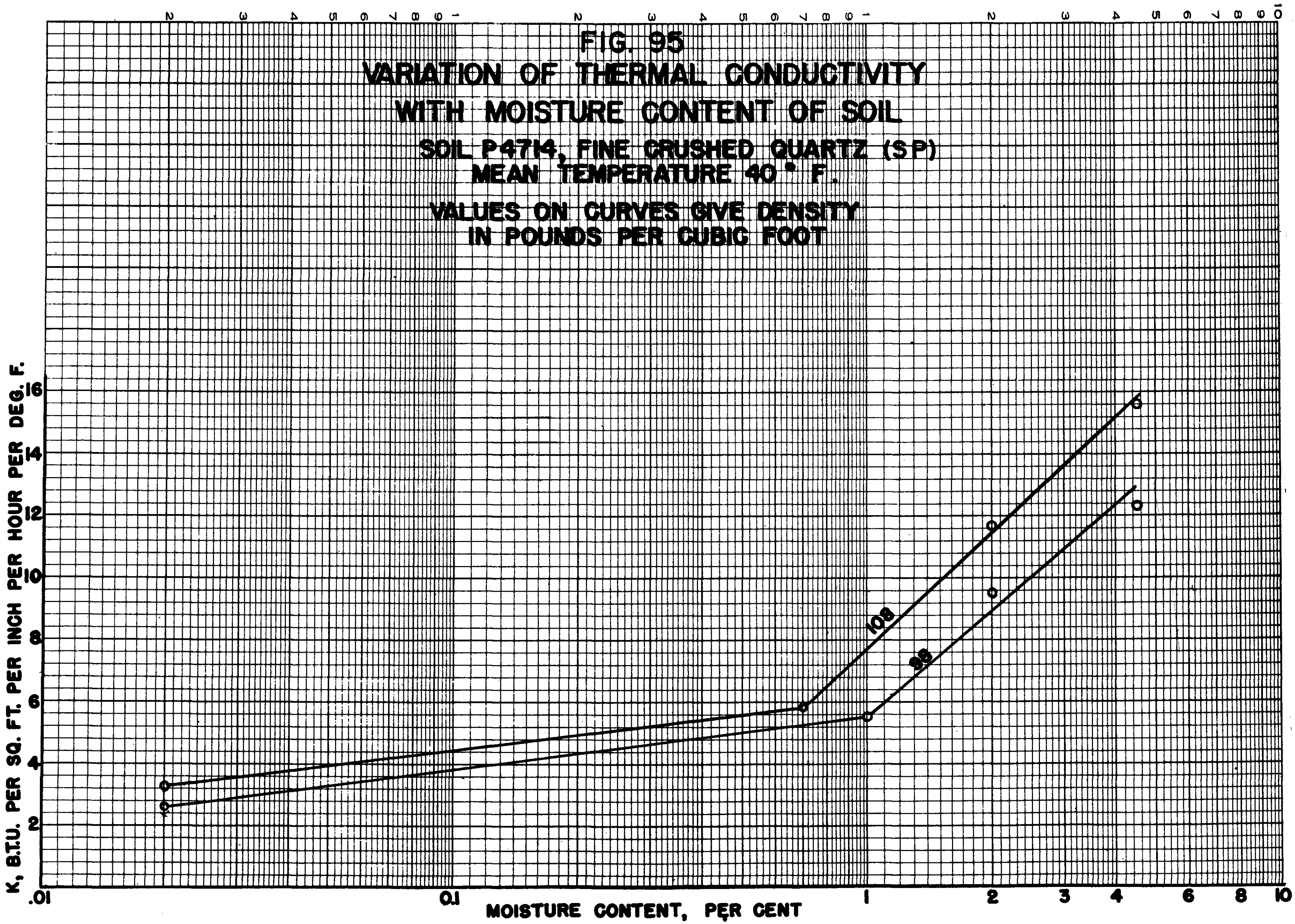


FIG. 95
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4714, FINE CRUSHED QUARTZ (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
108
98
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
16
14
12
10
8
6
4
2
.01
0.1
1
2
3
4
6
8
10
MOISTURE CONTENT, PER CENT

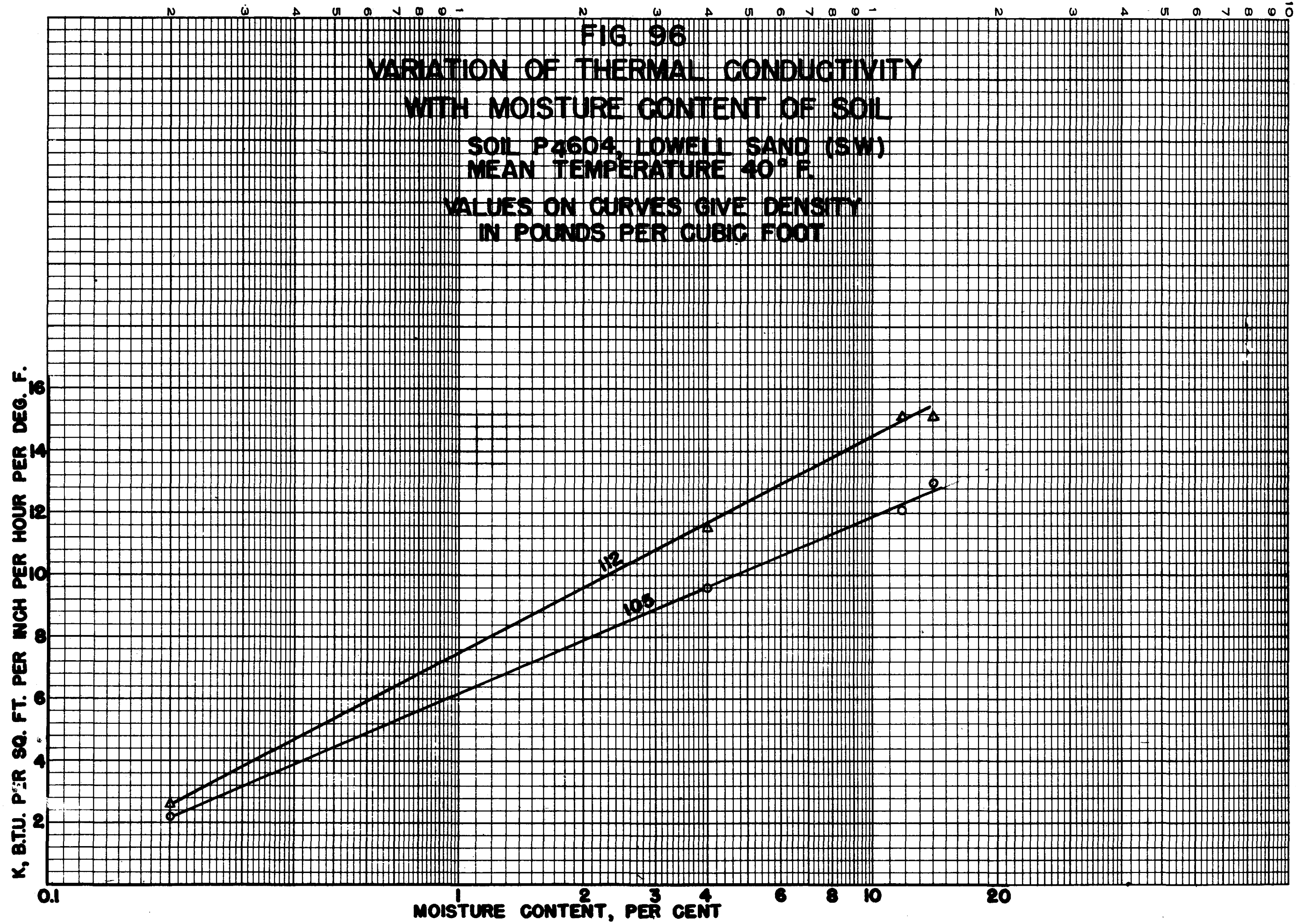


FIG. 96
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4604, LOWELL SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
112
105
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT
0.1
1
2
3
4
6
8
10
20
2
4
6
8
10
12
14
16

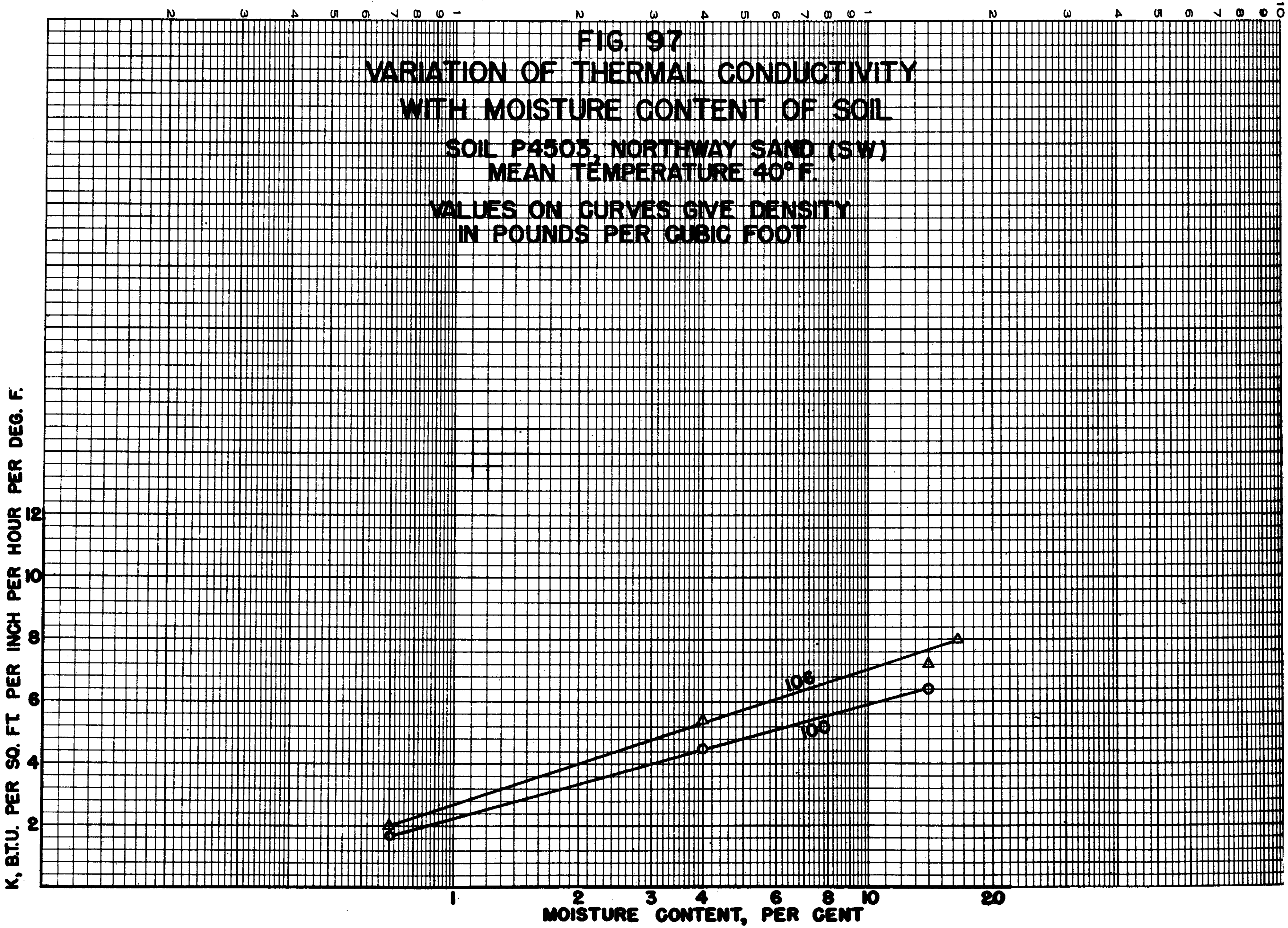


FIG. 97
VARIATION OF THERMAL CONDUCTIVITY WITH MOISTURE CONTENT OF SOIL
SOIL P4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY IN POUNDS PER CUBIC FOOT

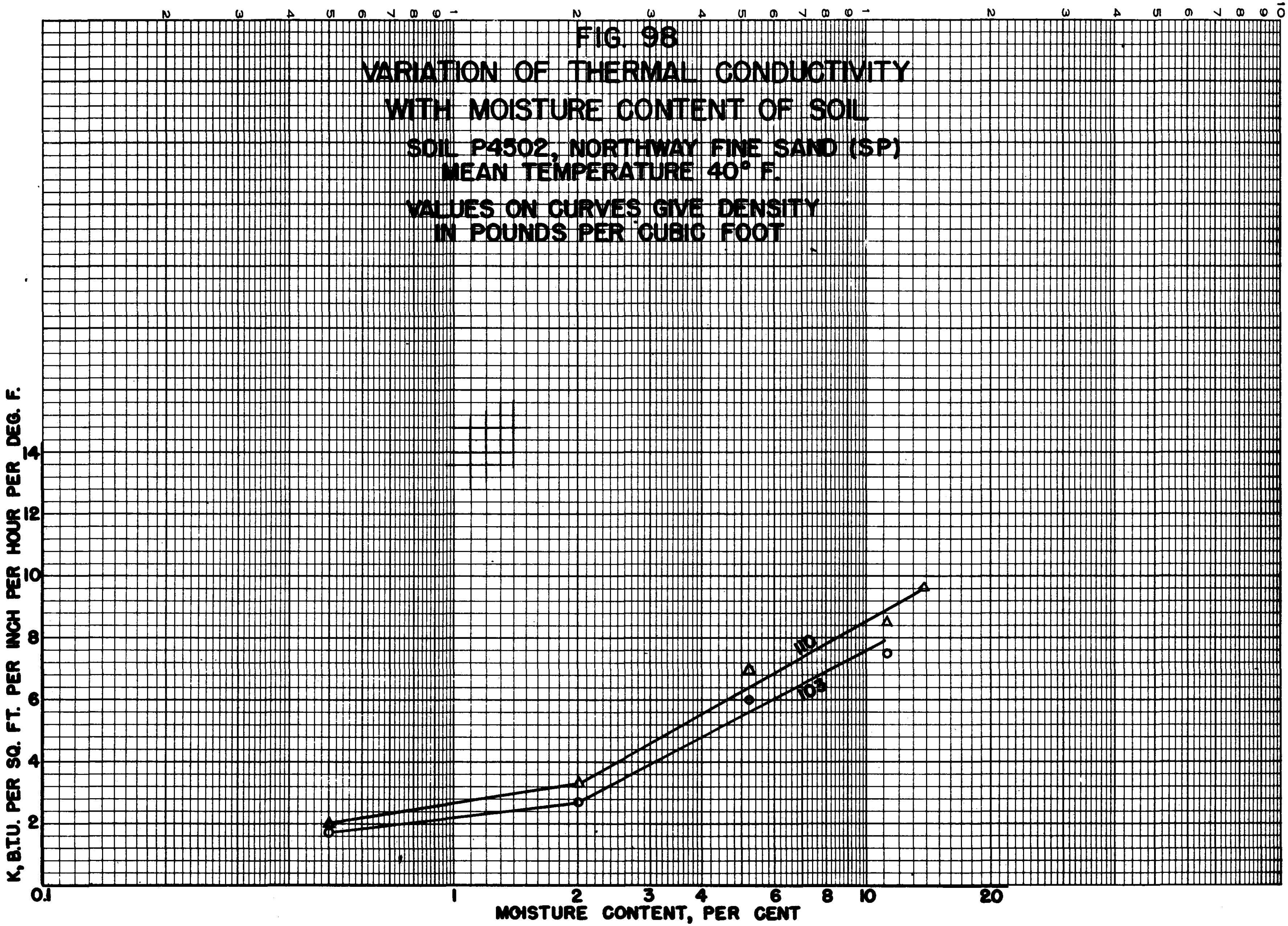


FIG. 98
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

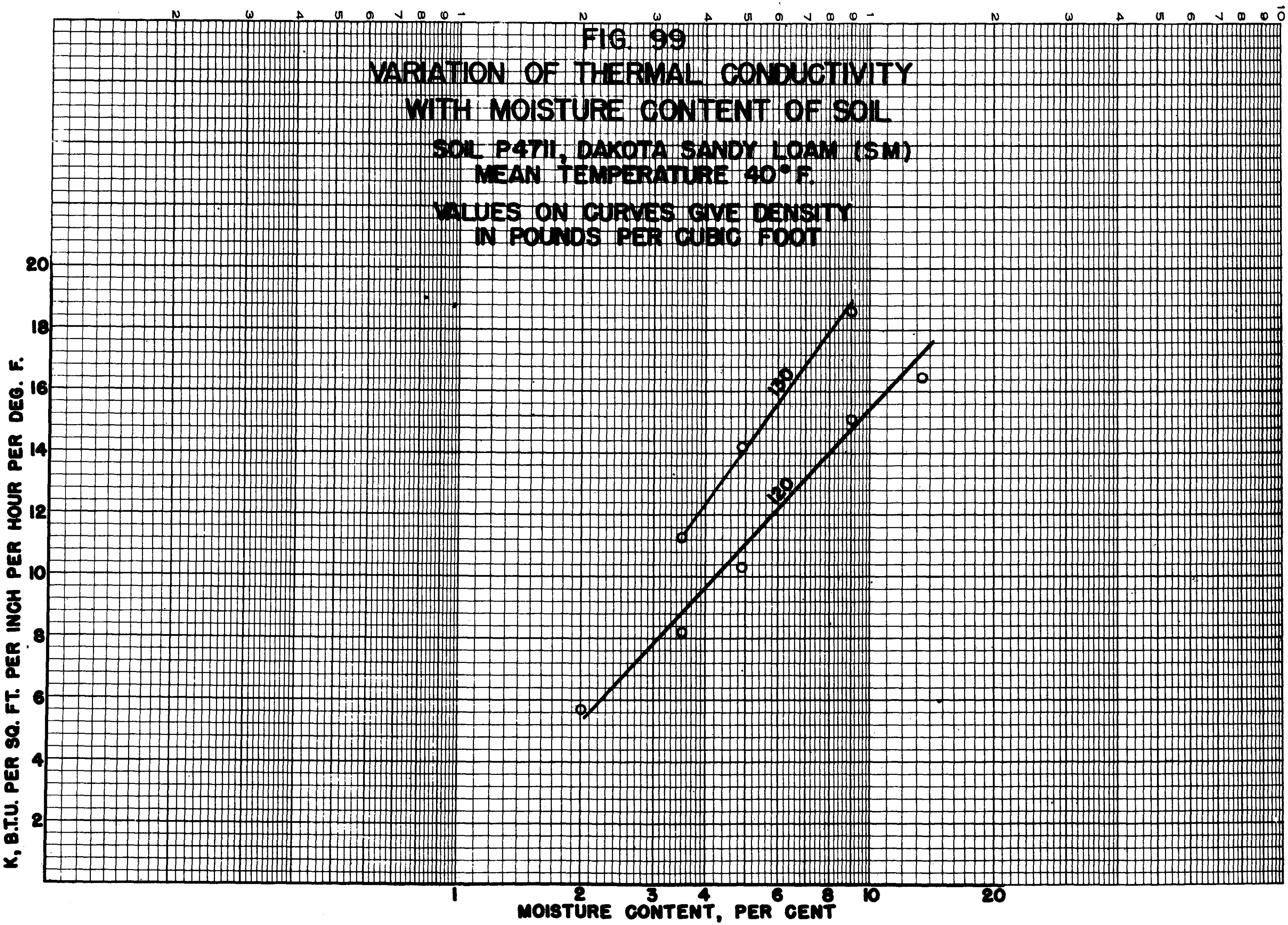


FIG. 99
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
130
120
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT

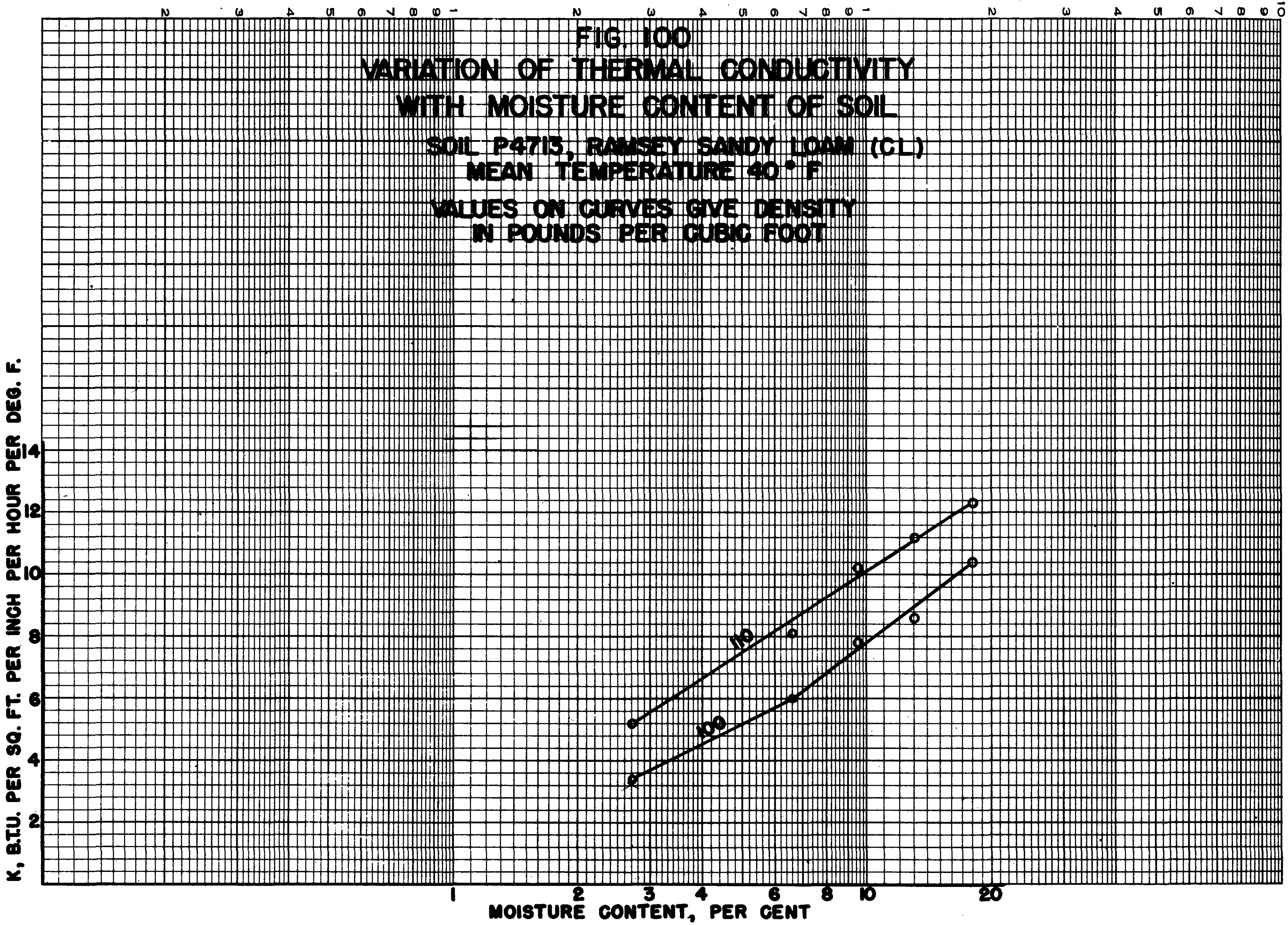


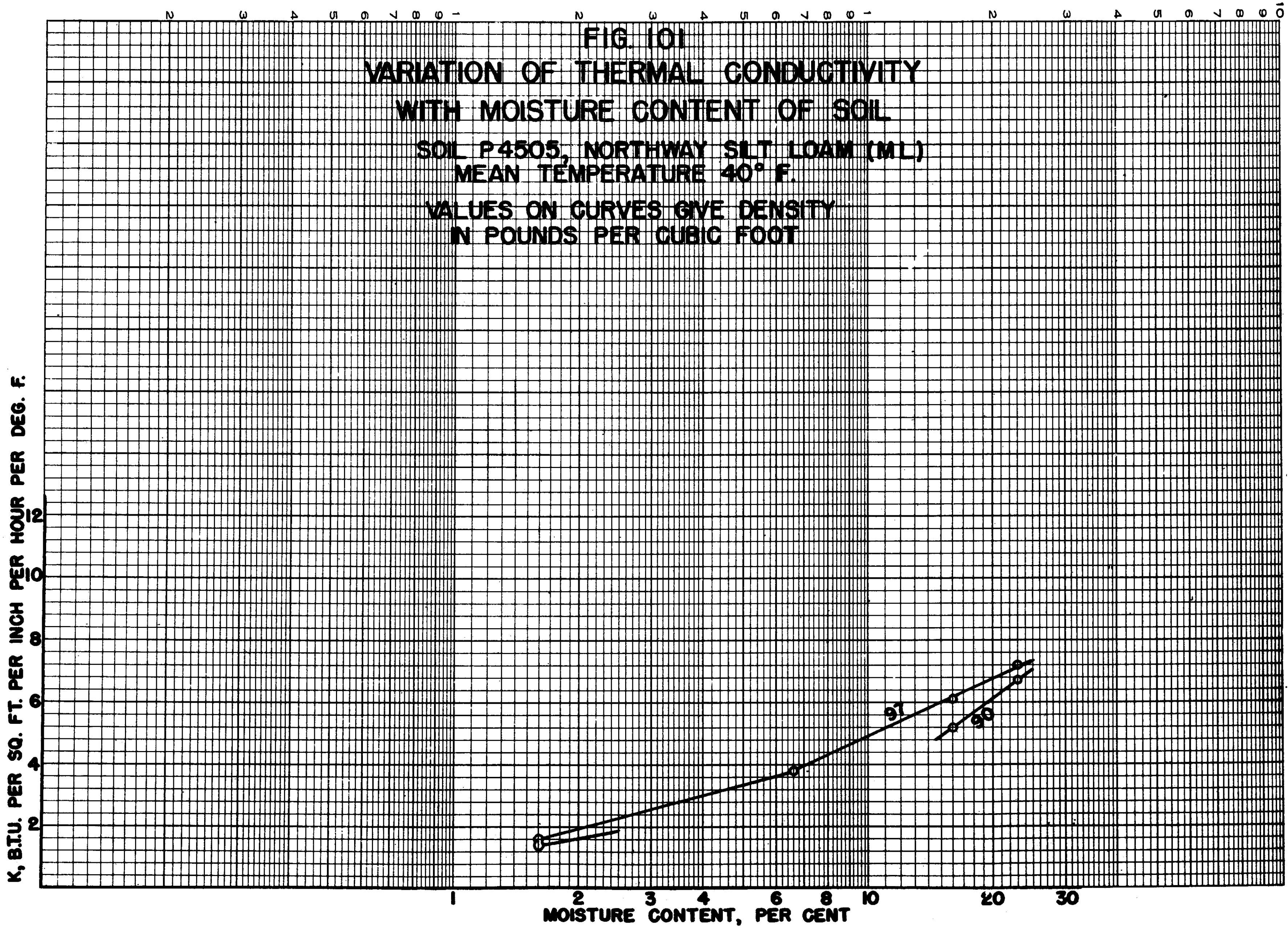
FIG. 100
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
110
100
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
MOISTURE CONTENT, PER CENT

FIG. 101

VARIATION OF THERMAL CONDUCTIVITY WITH MOISTURE CONTENT OF SOIL

SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 40° F.

VALUES ON CURVES GIVE DENSITY IN POUNDS PER CUBIC FOOT



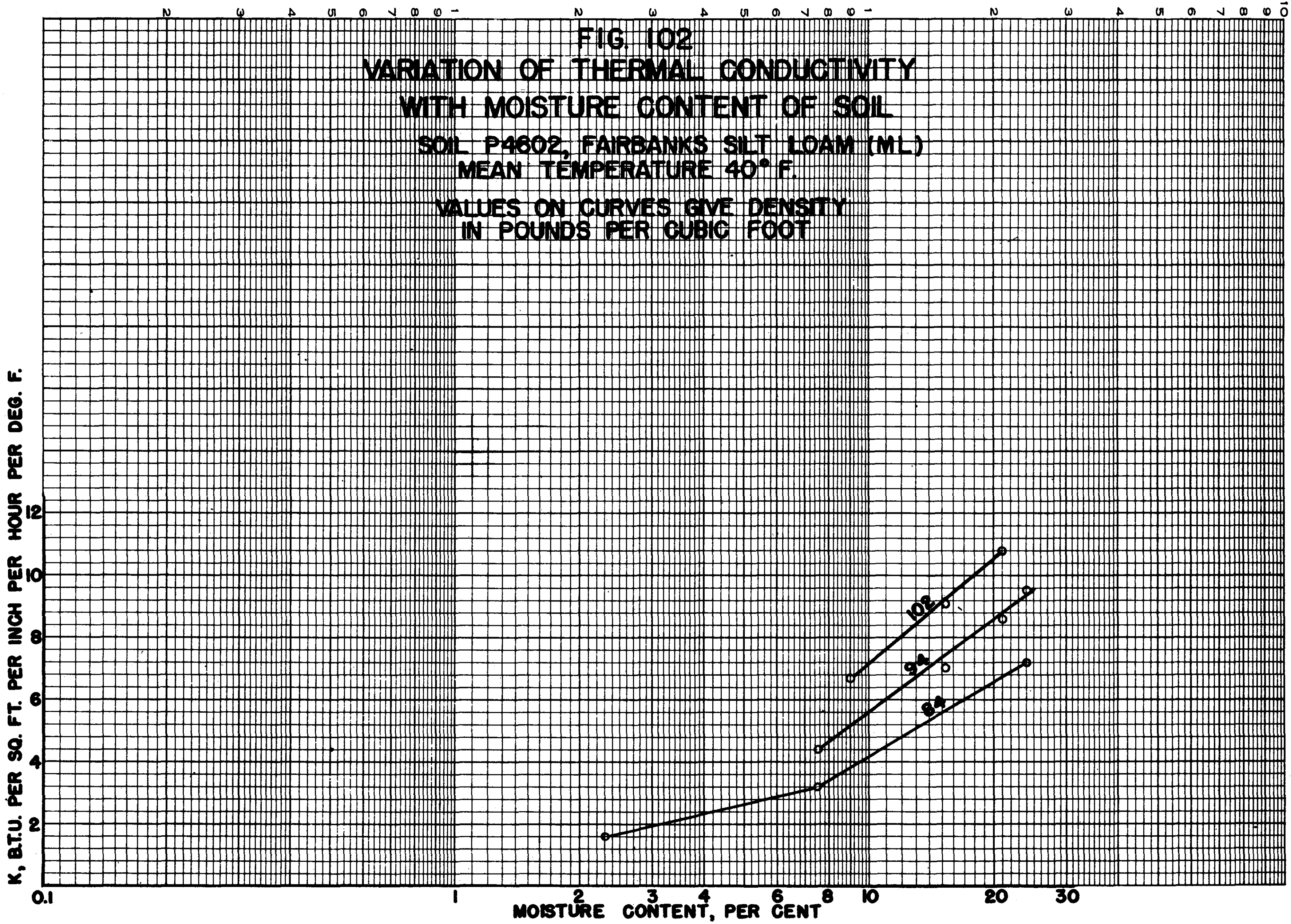


FIG. 102
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

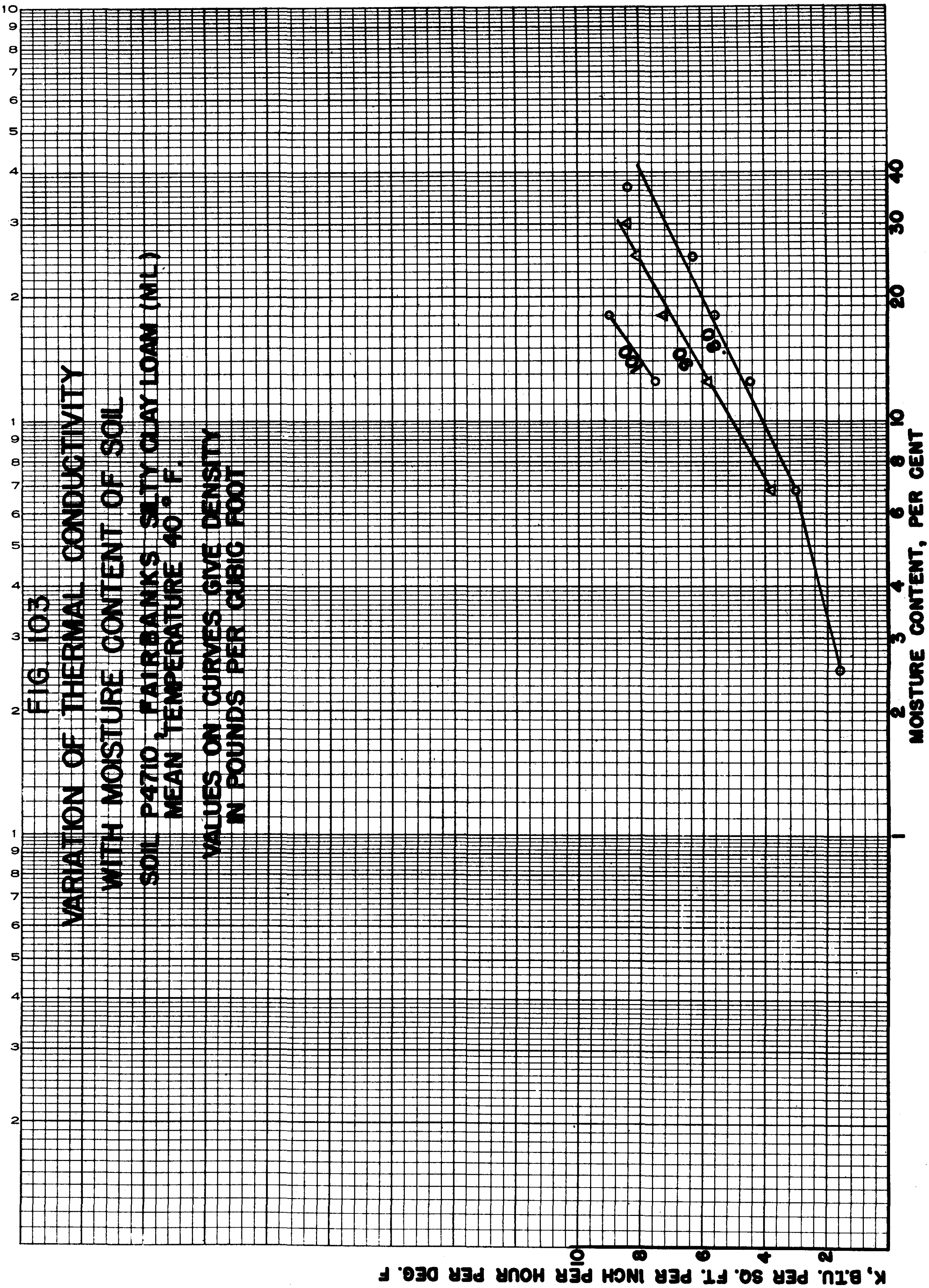


FIG. 103
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
100
90
80
MOISTURE CONTENT, PER CENT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F

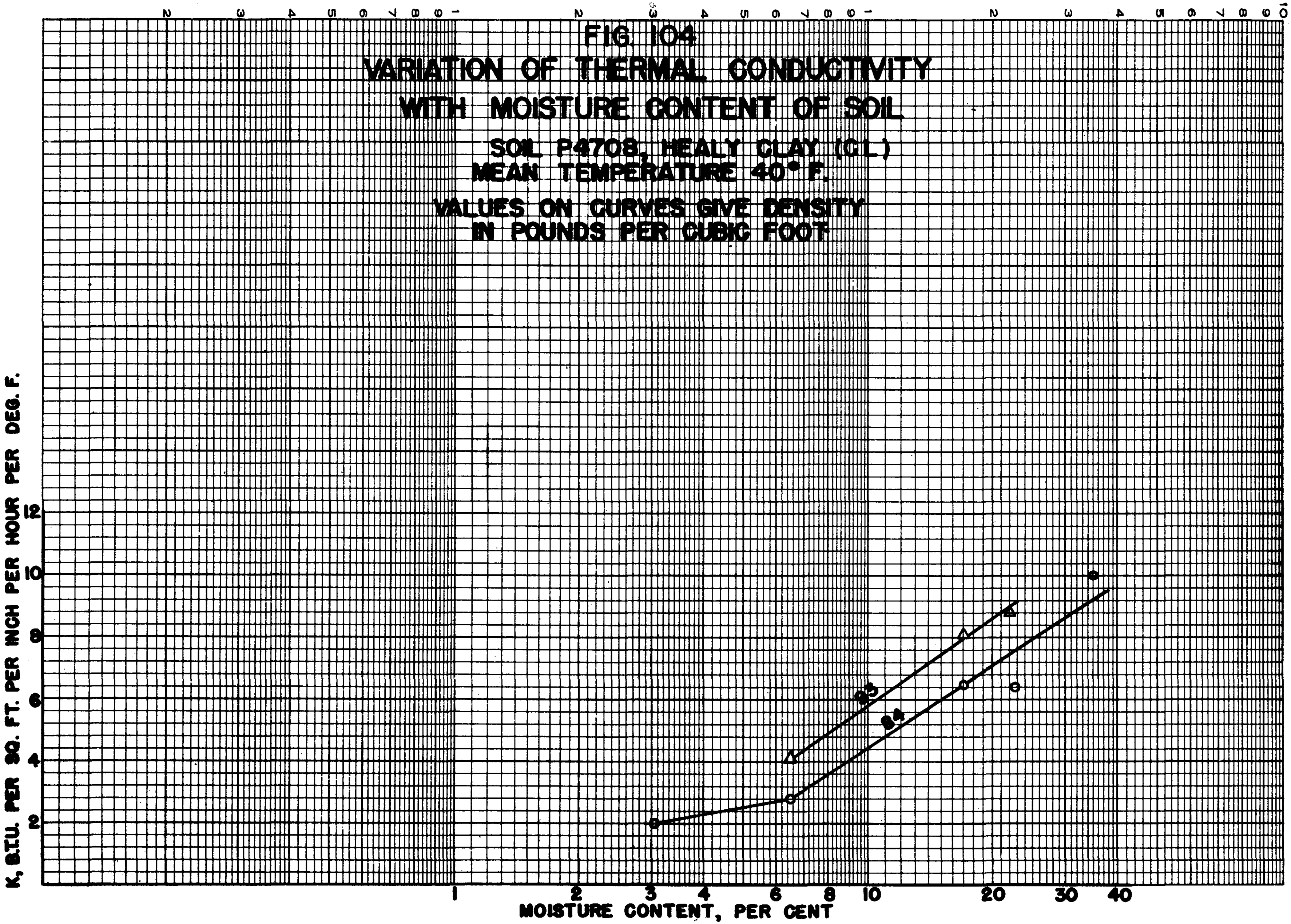


FIG. 104
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

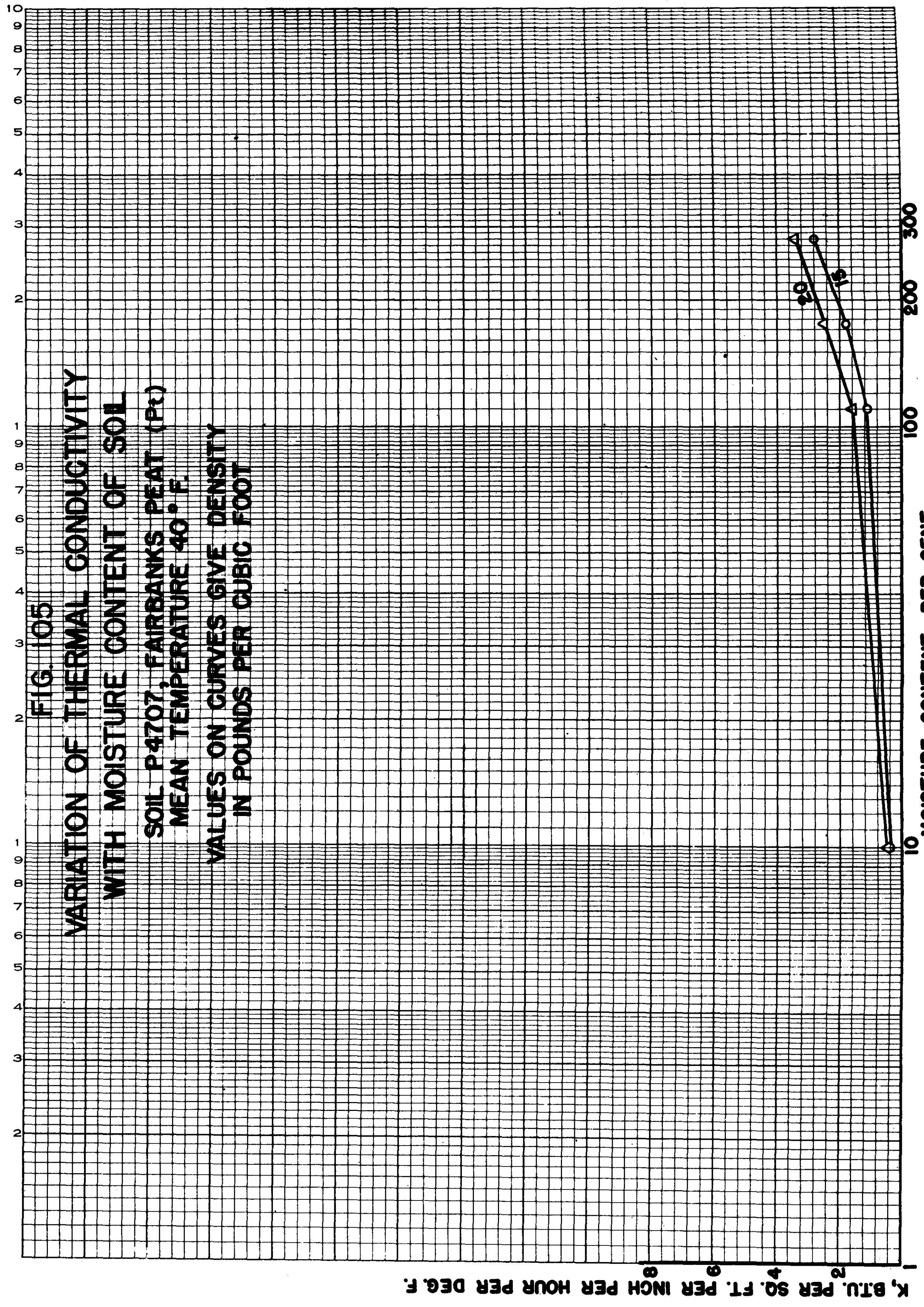


FIG. 105
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4707, FAIRBANKS PEAT (Pt)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

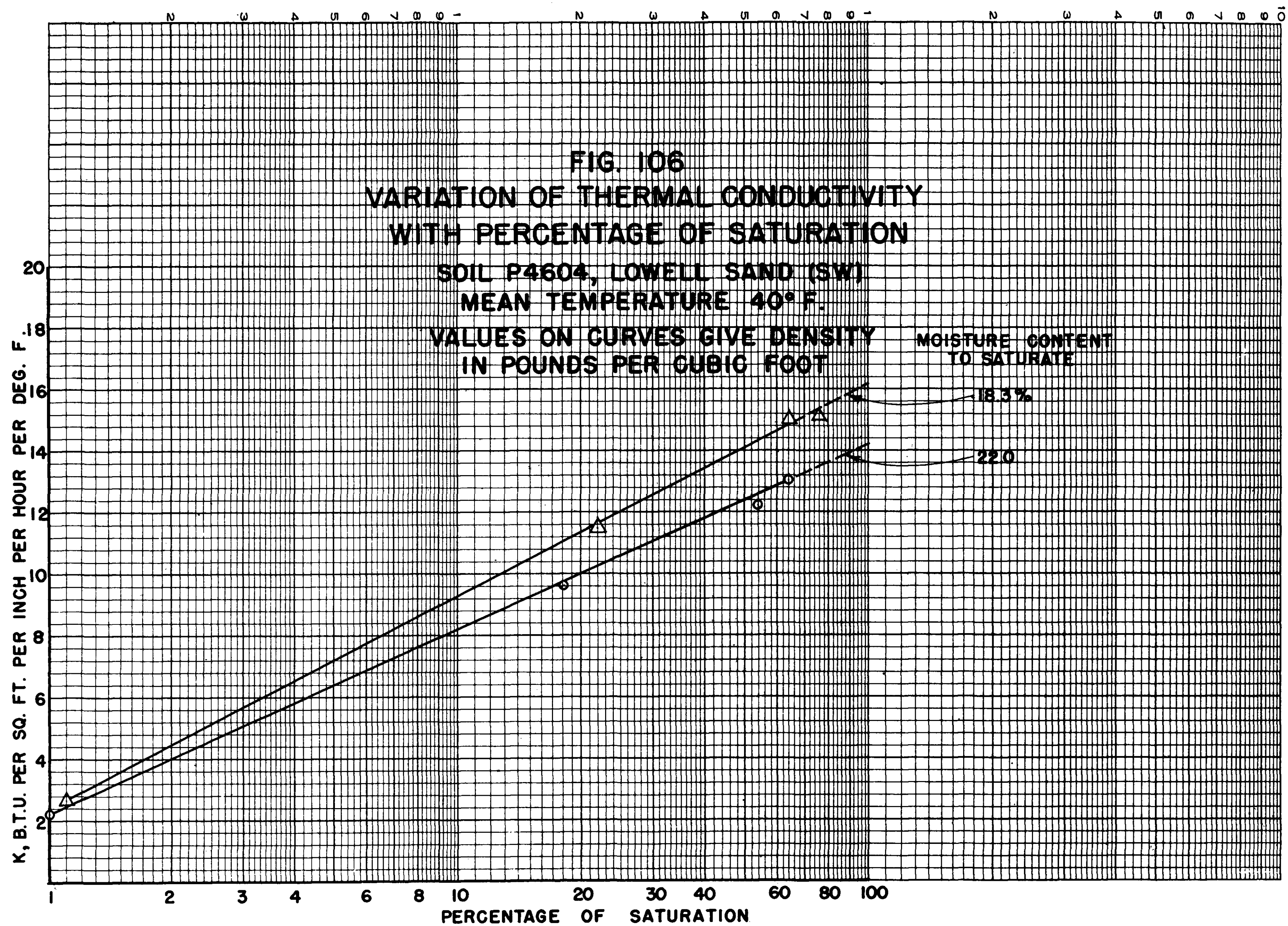


FIG. 106
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4604, LOWELL SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
18.3%
22.0
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
20
18
16
14
12
10
8
6
4
2
1
2
3
4
6
8
10
20
30
40
60
80
100
PERCENTAGE OF SATURATION

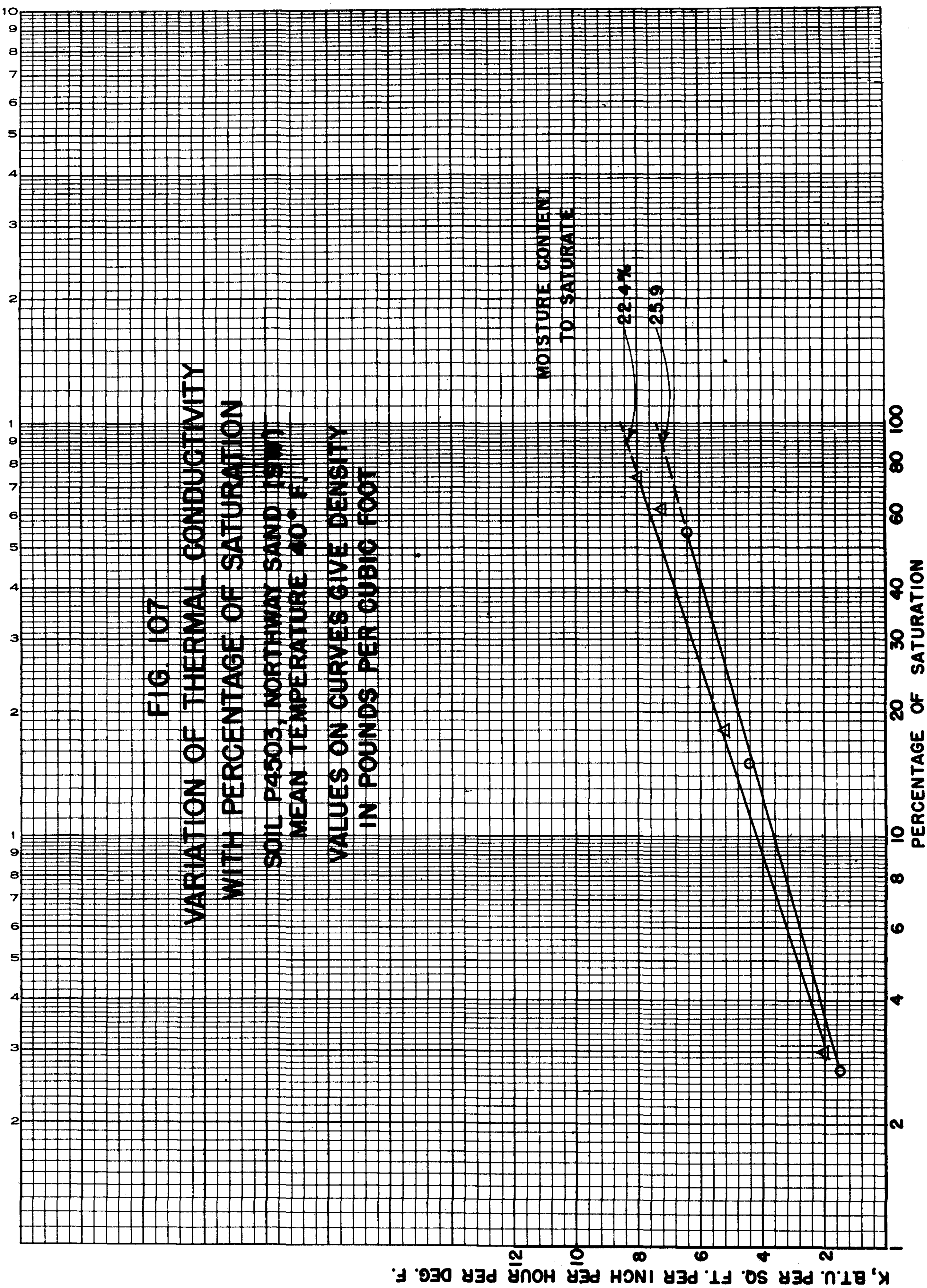


FIG. 107
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
22.4%
25.9
PERCENTAGE OF SATURATION
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.

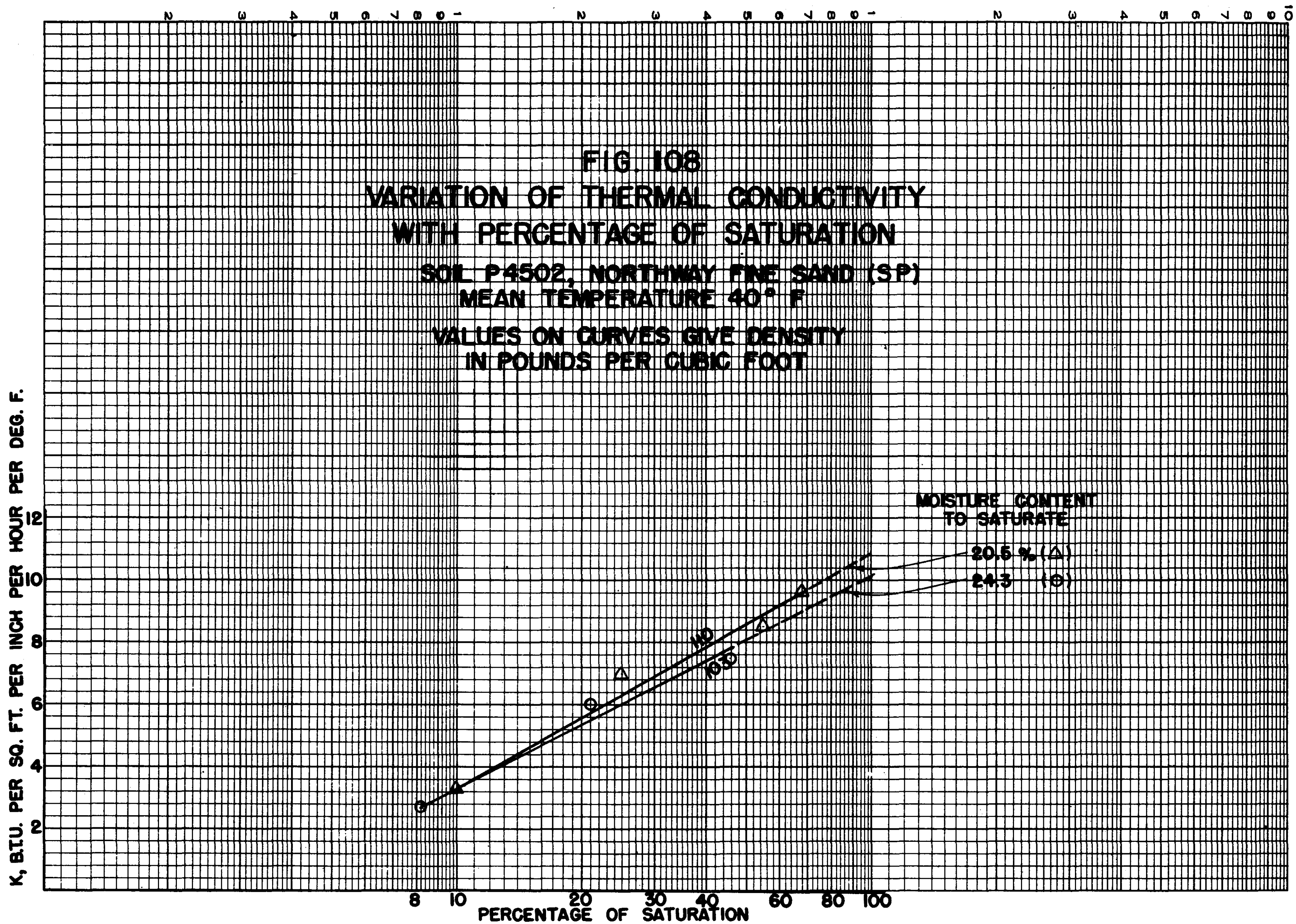


FIG. 108
VARIATION OF THERMAL CONDUCTIVITY WITH PERCENTAGE OF SATURATION
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 40° F
VALUES ON CURVES GIVE DENSITY IN POUNDS PER CUBIC FOOT

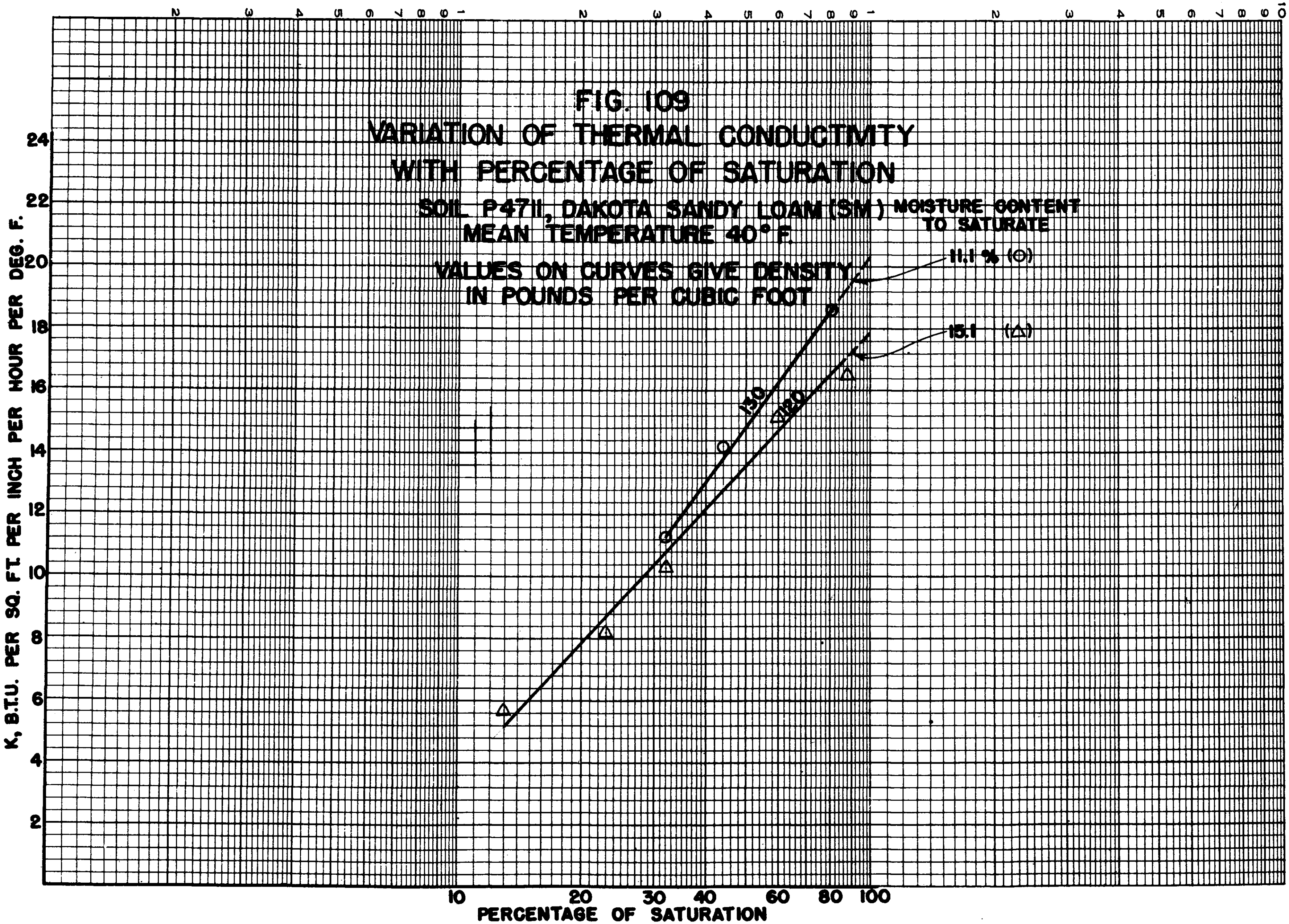


FIG. 109
VARIATION OF THERMAL CONDUCTIVITY WITH PERCENTAGE OF SATURATION
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY IN POUNDS PER CUBIC FOOT

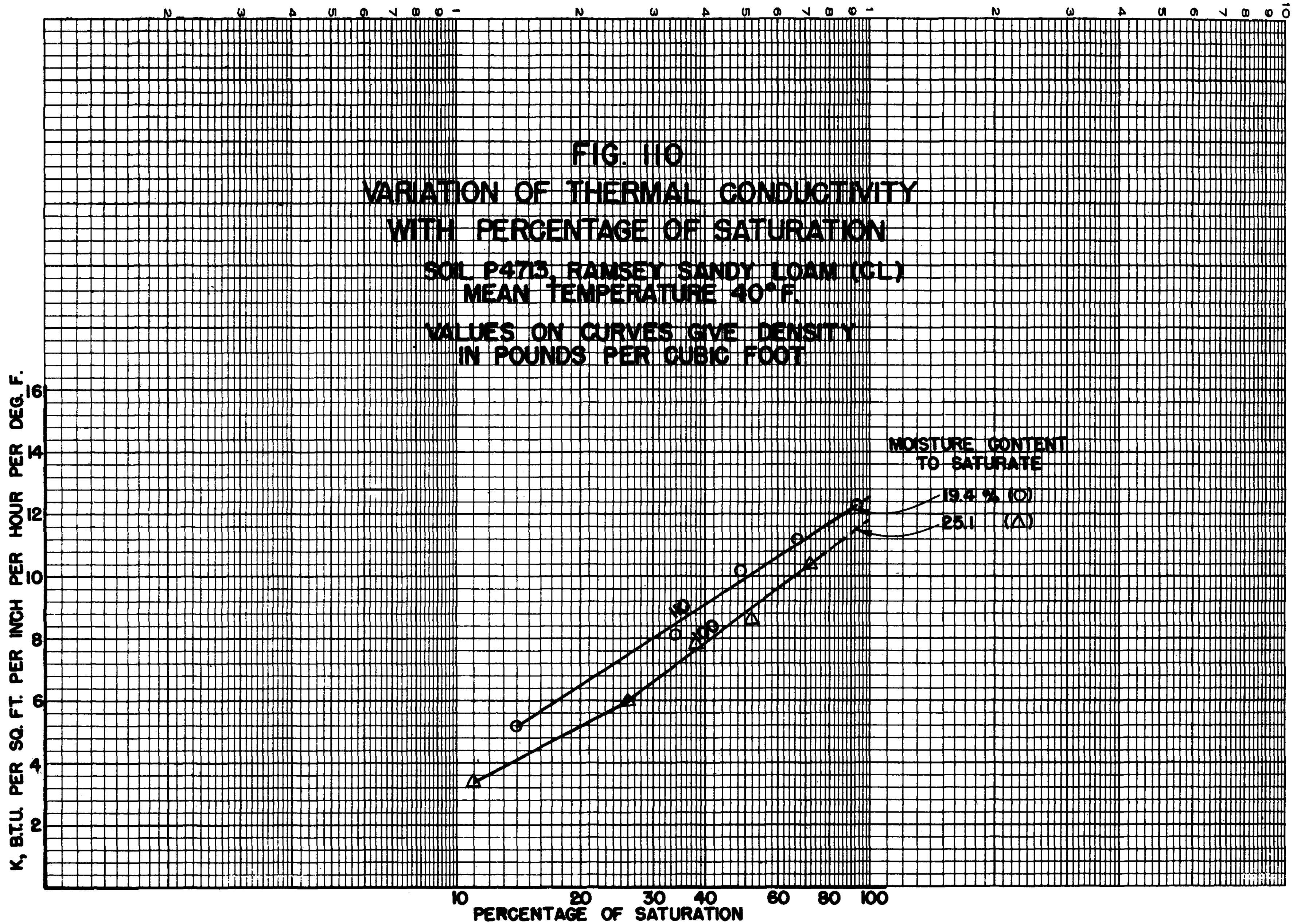


FIG. 110
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

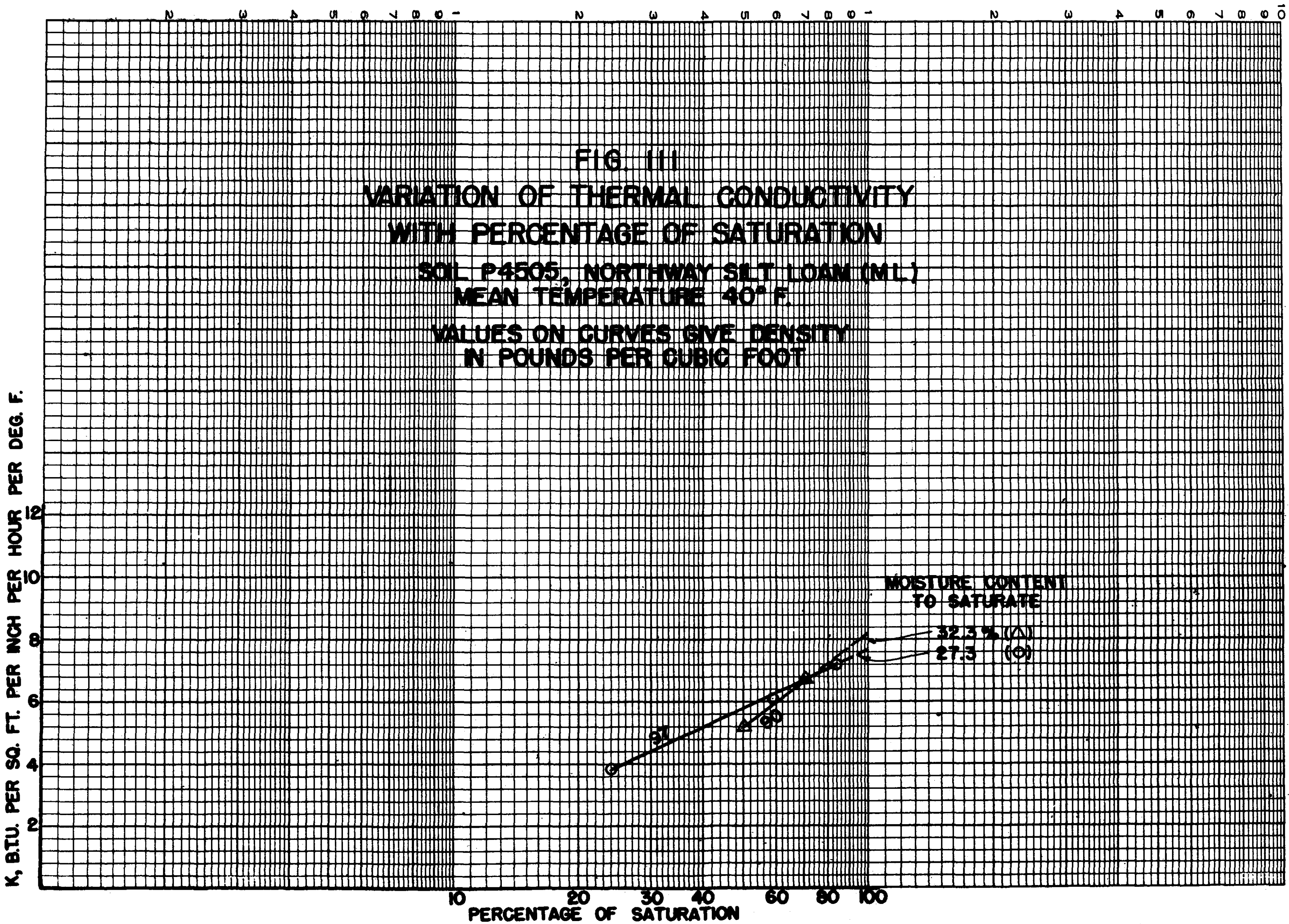


FIG. 111
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

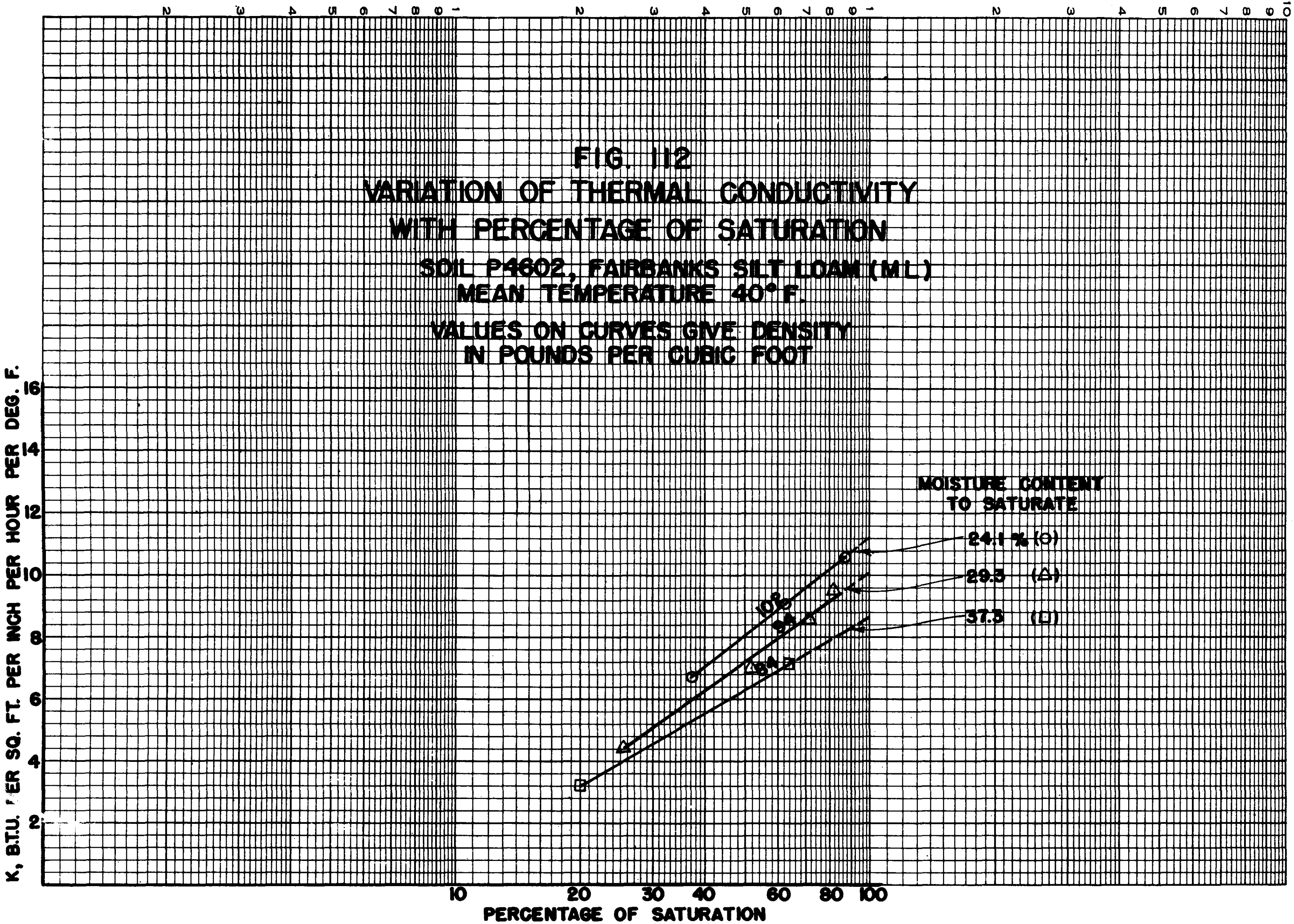


FIG. 112
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
24.1 % (○)
29.3 (△)
37.3 (□)
108
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
PERCENTAGE OF SATURATION

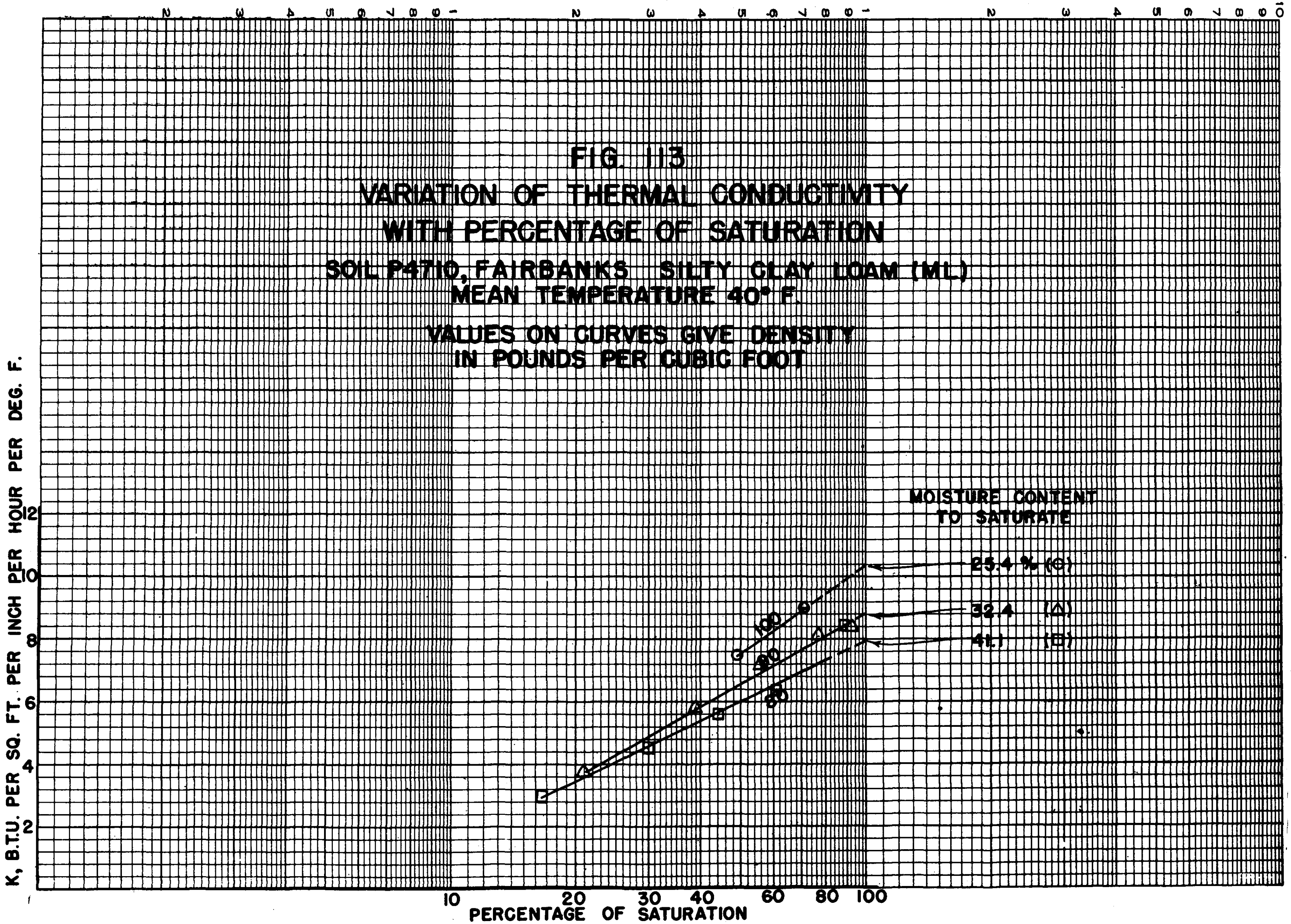


FIG. 113
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

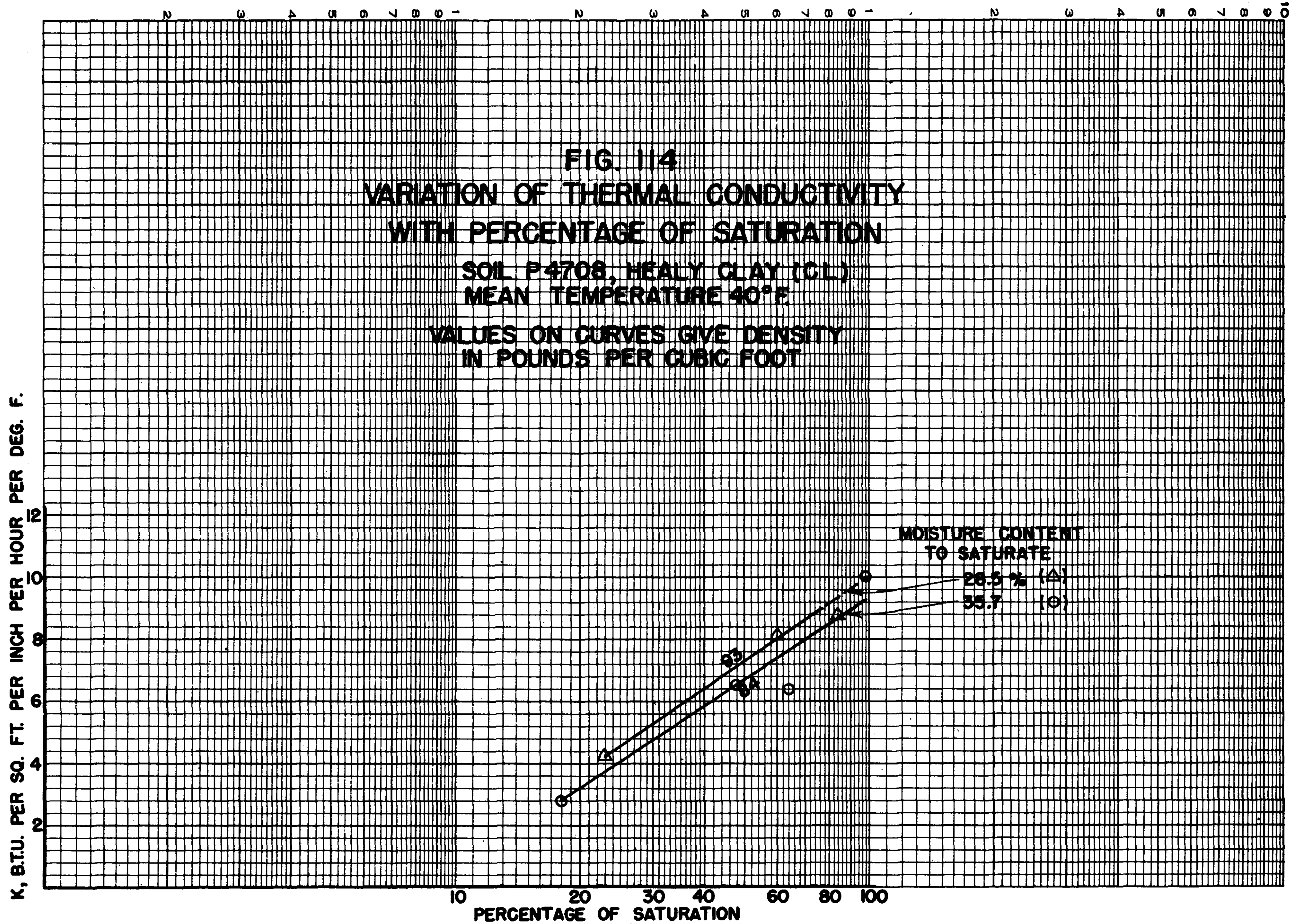


FIG. 114
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 40° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT

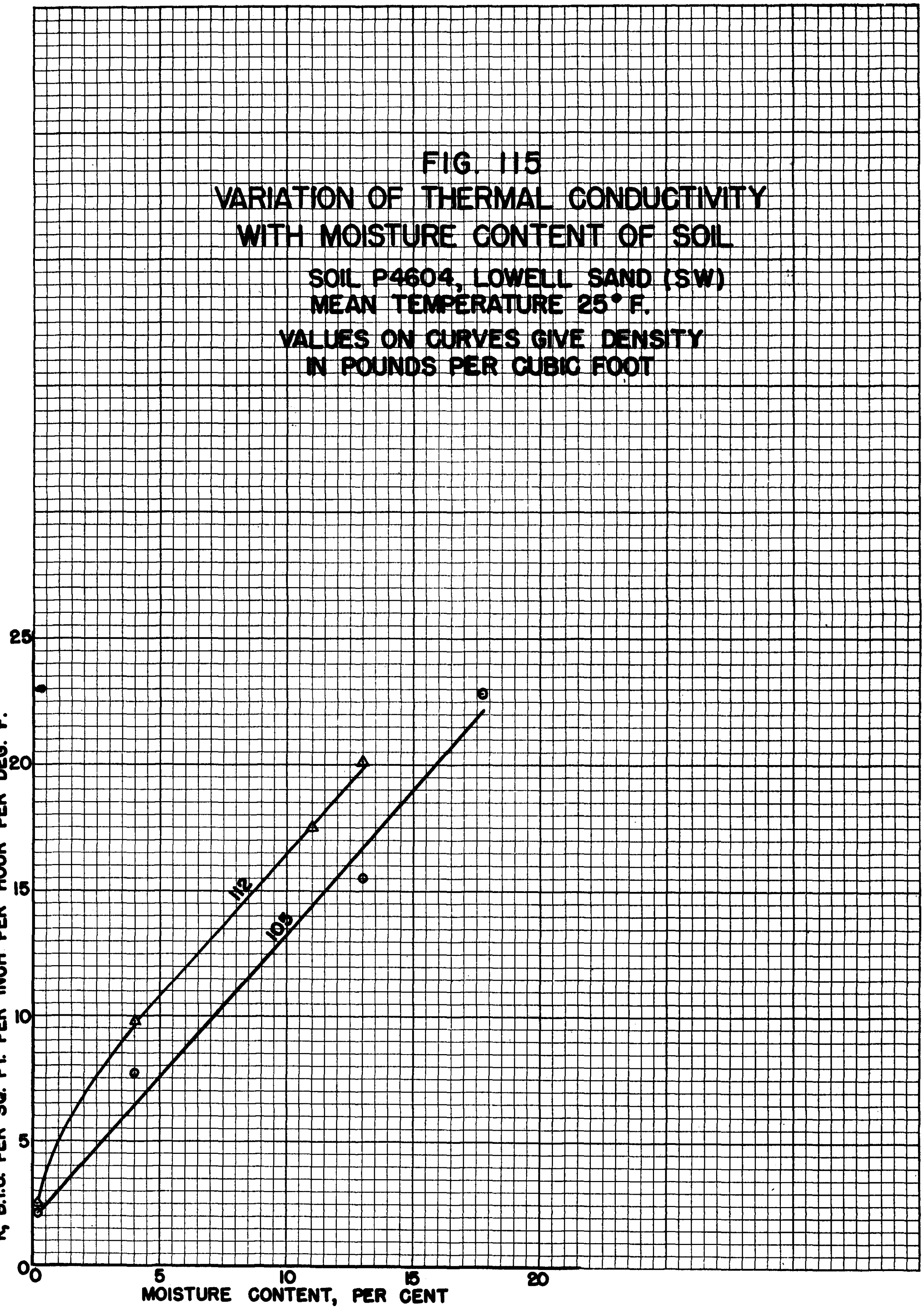


FIG. 115
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4604, LOWELL SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
112
105
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

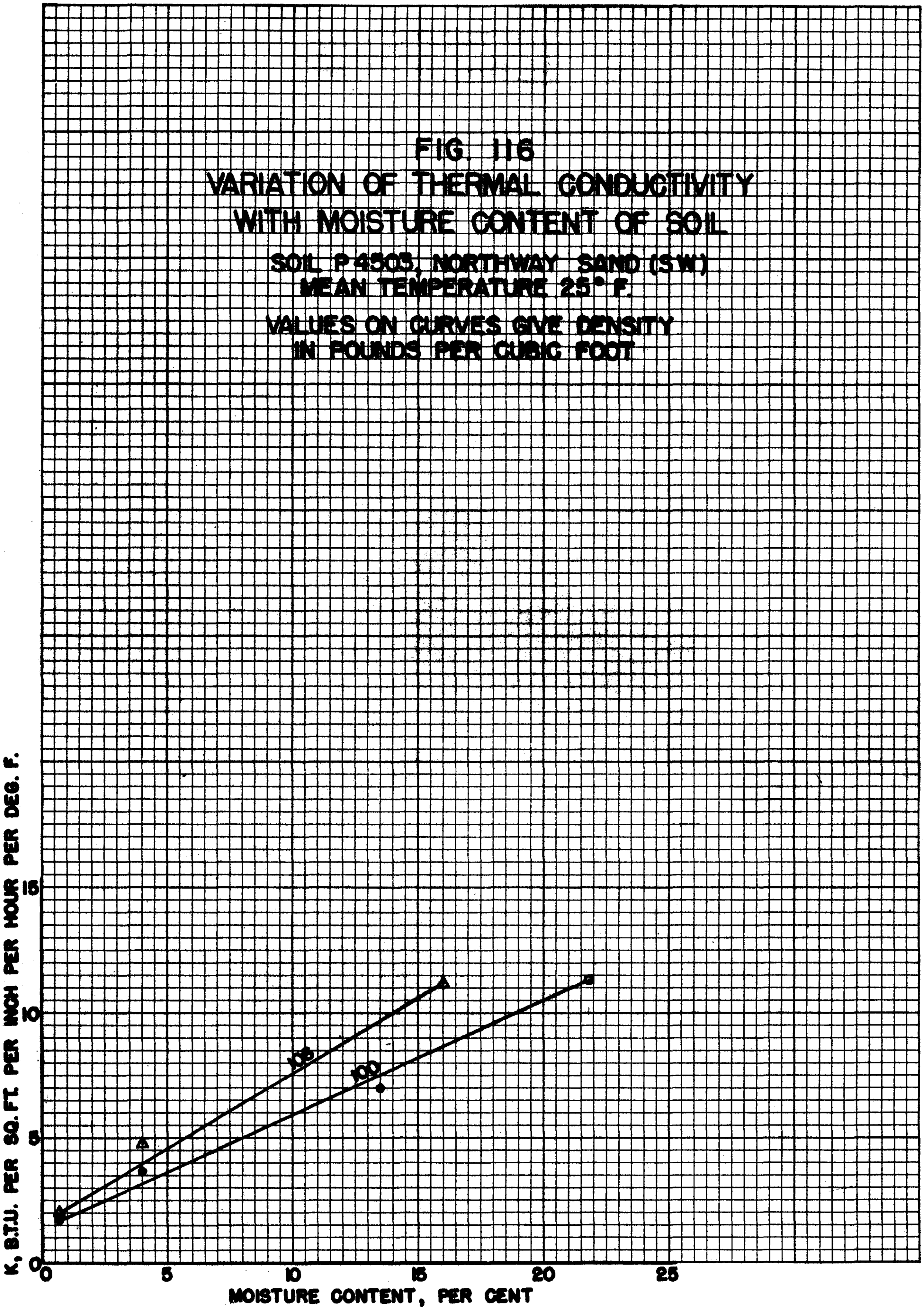


FIG. 116
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P 4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
105
100
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

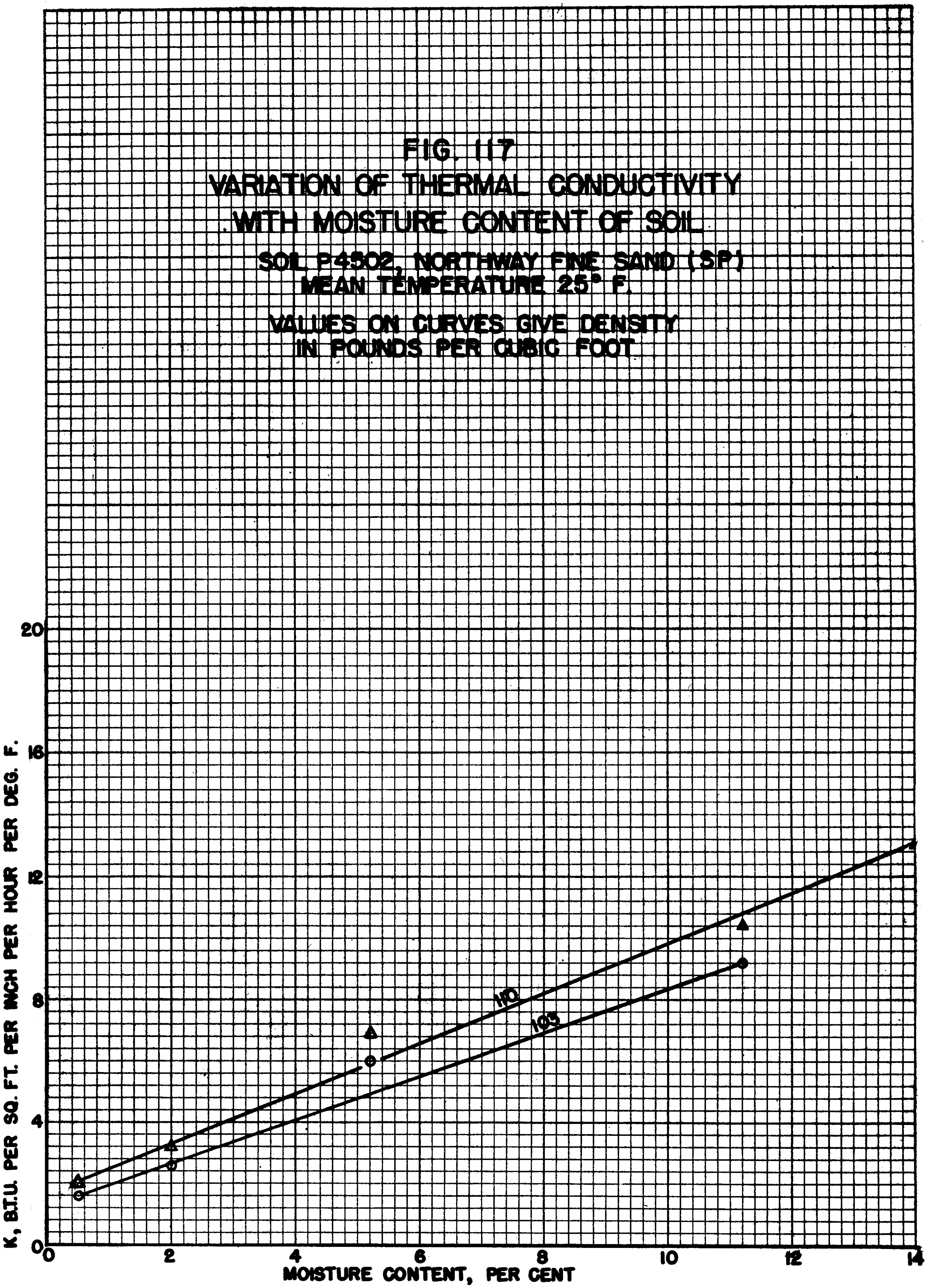


FIG. 117
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
110
103
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
0
2
4
6
8
10
12
14
MOISTURE CONTENT, PER CENT

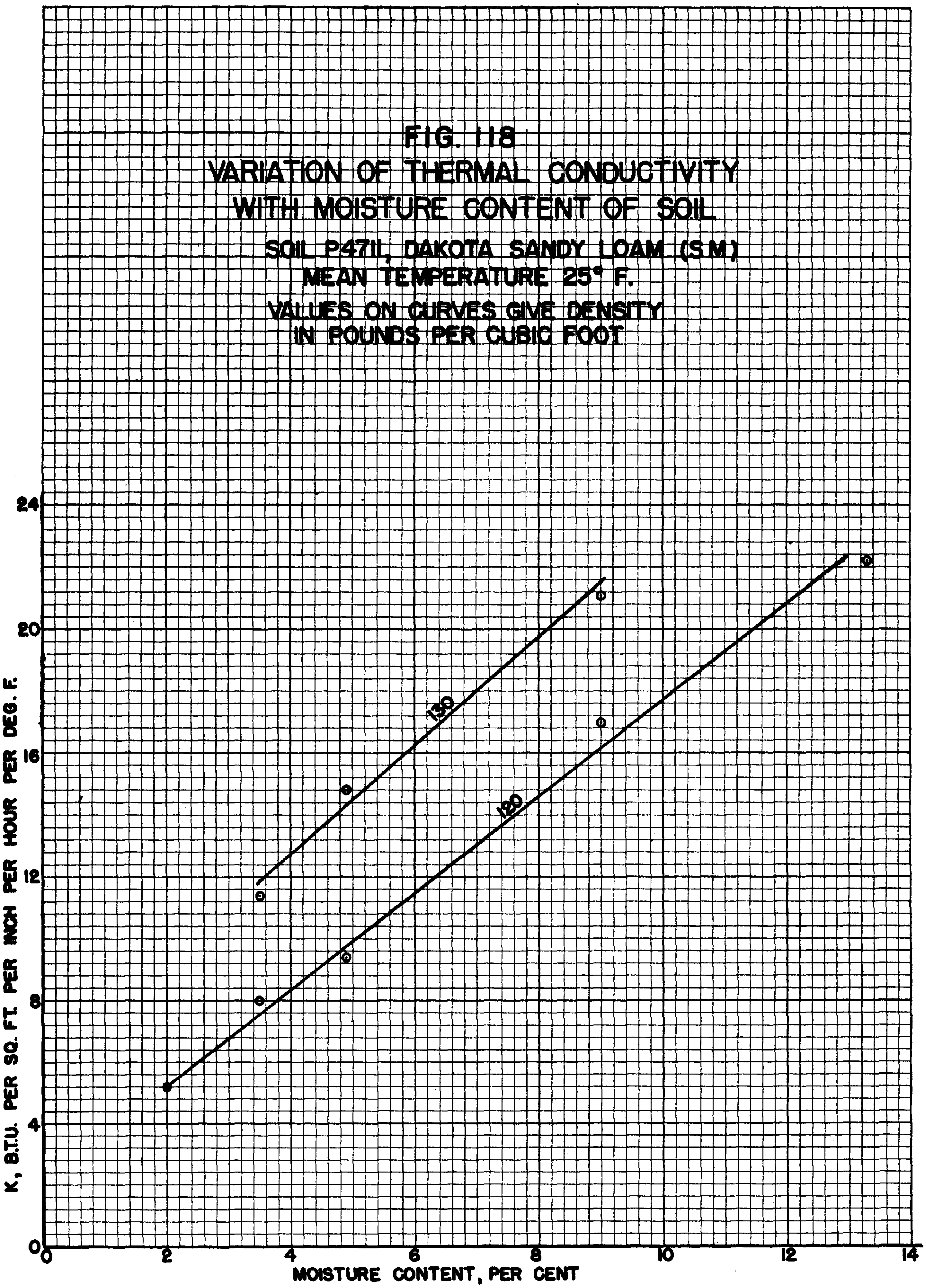


FIG. 118
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
130
120
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
24
0
2
4
6
8
10
12
14
MOISTURE CONTENT, PER CENT

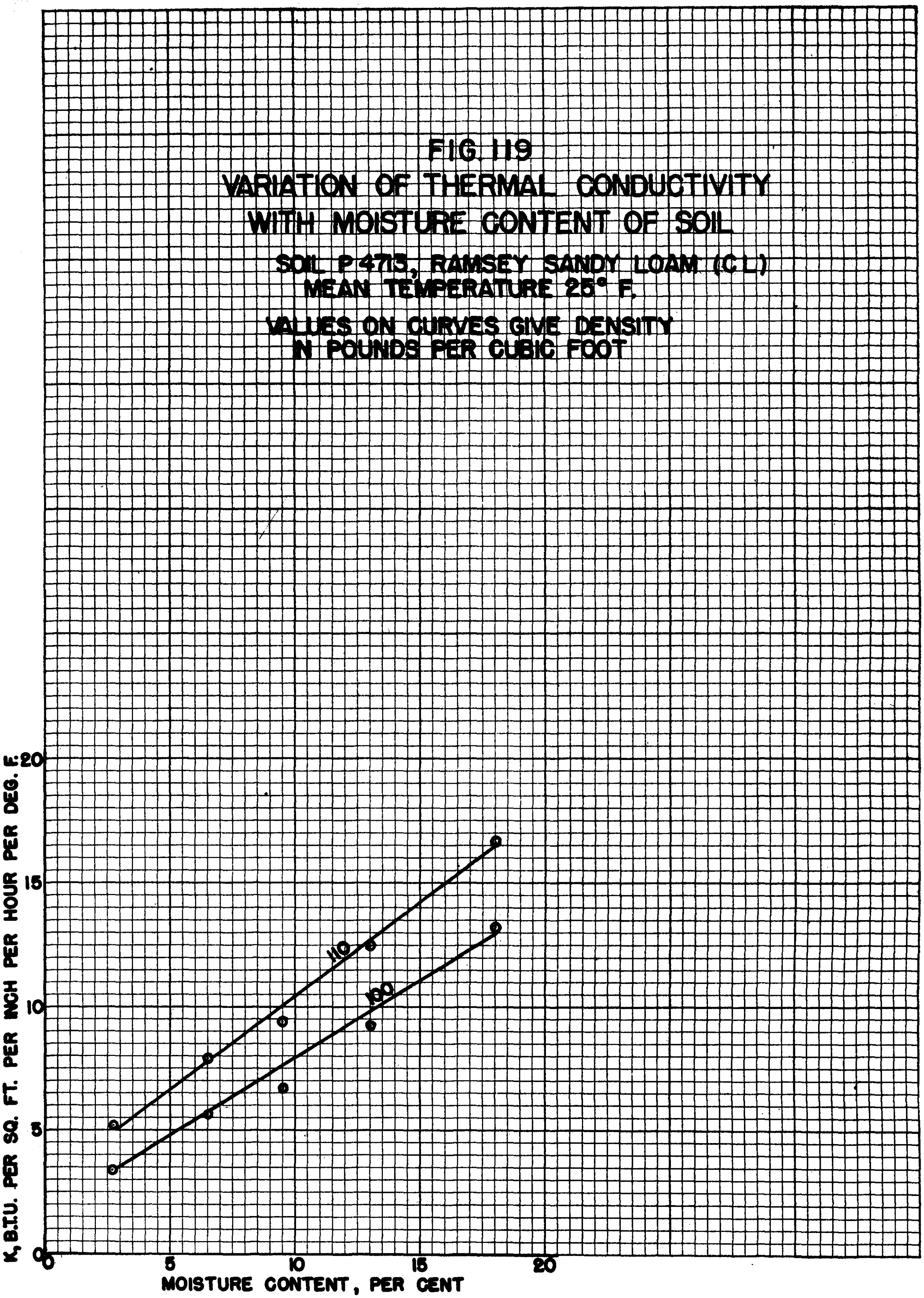


FIG. 119
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P 4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
20
MOISTURE CONTENT, PER CENT
110
100

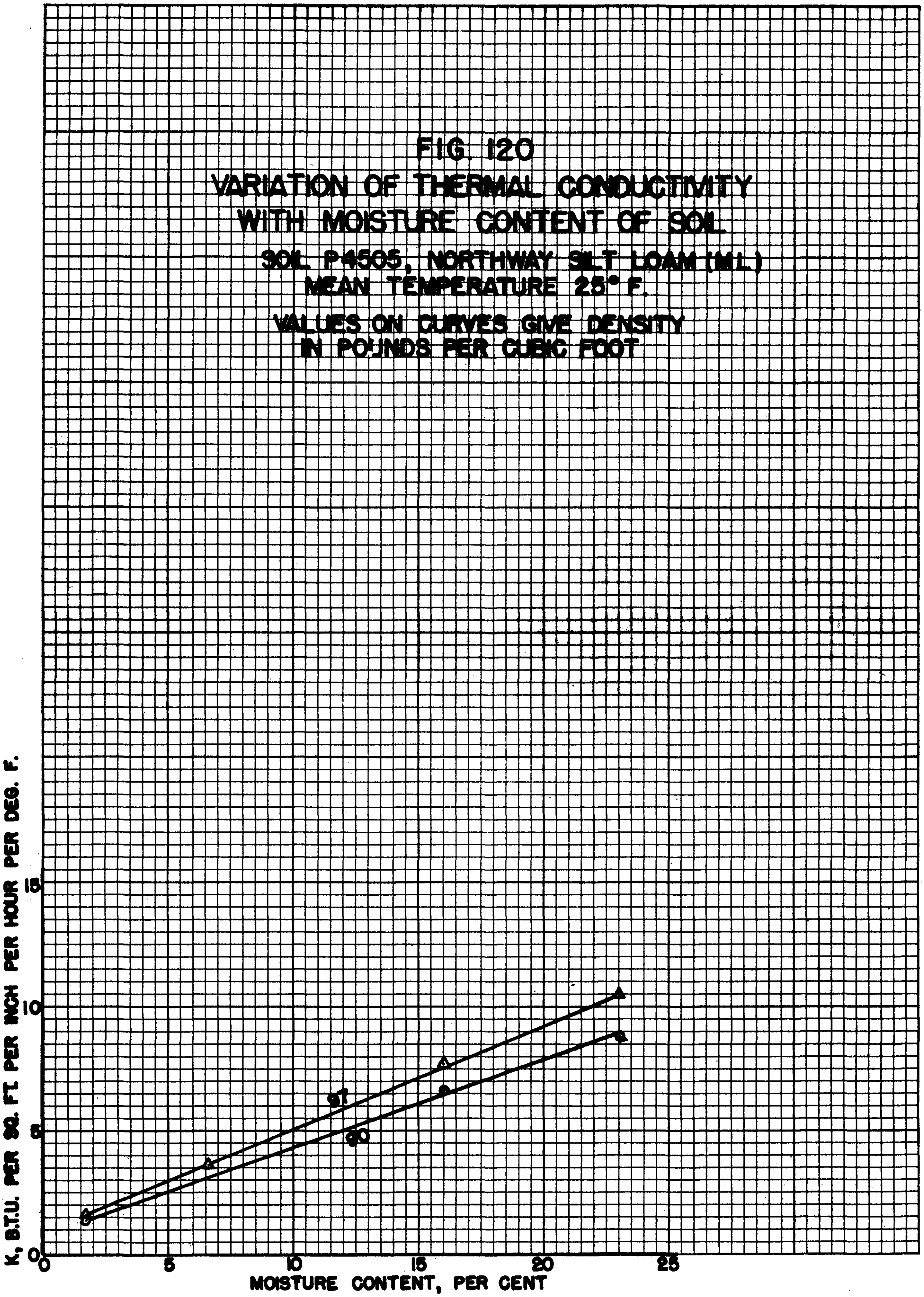


FIG. 120
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
97
90
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
0
5
10
15
20
25
MOISTURE CONTENT, PER CENT

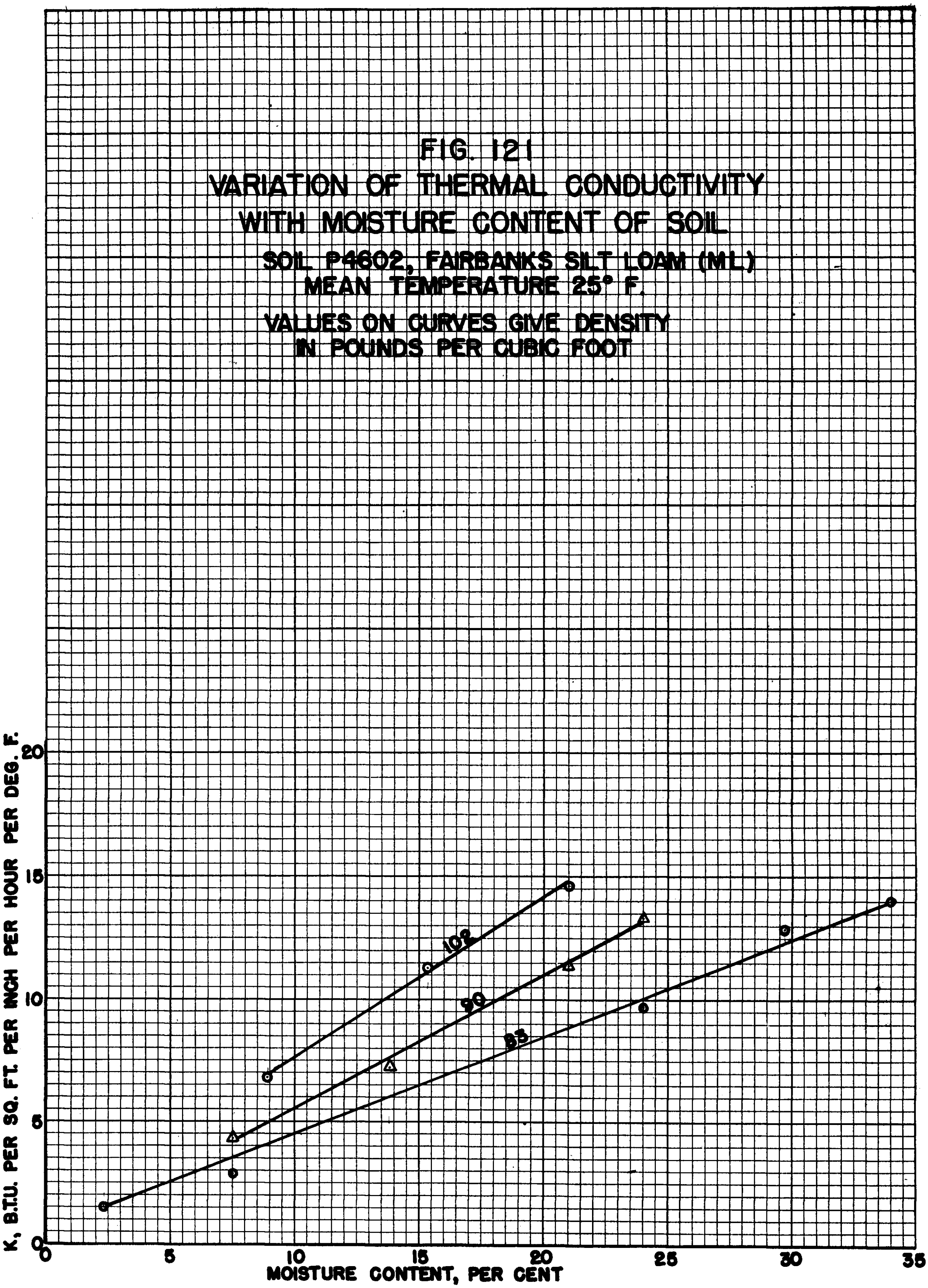


FIG. 121
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
102
90
83
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
20
25
30
35
MOISTURE CONTENT, PER CENT

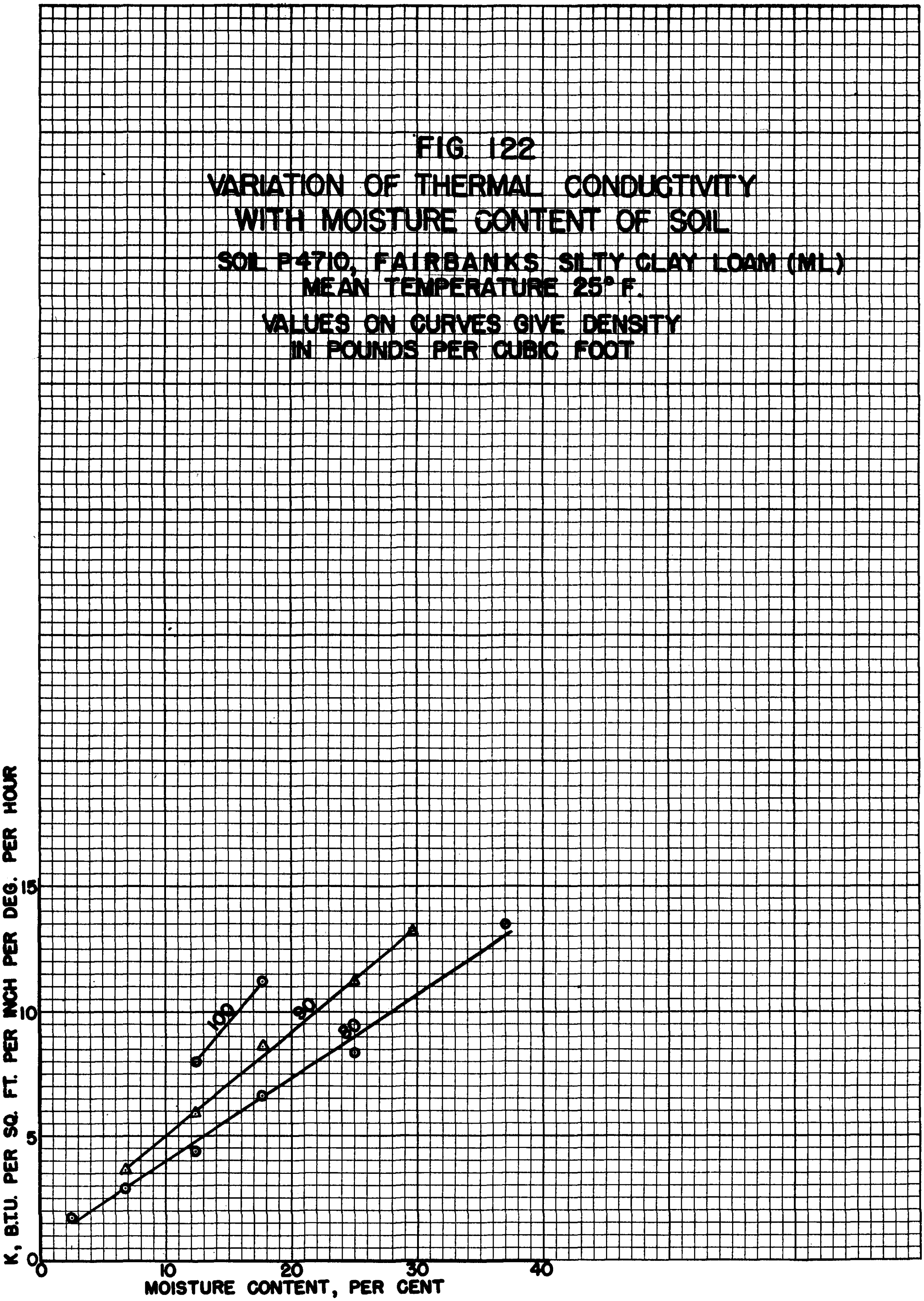


FIG. 122
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
100
90
80
K, B.T.U. PER SQ. FT. PER INCH PER DEG. PER HOUR
0
5
10
15
0
10
20
30
40
MOISTURE CONTENT, PER CENT

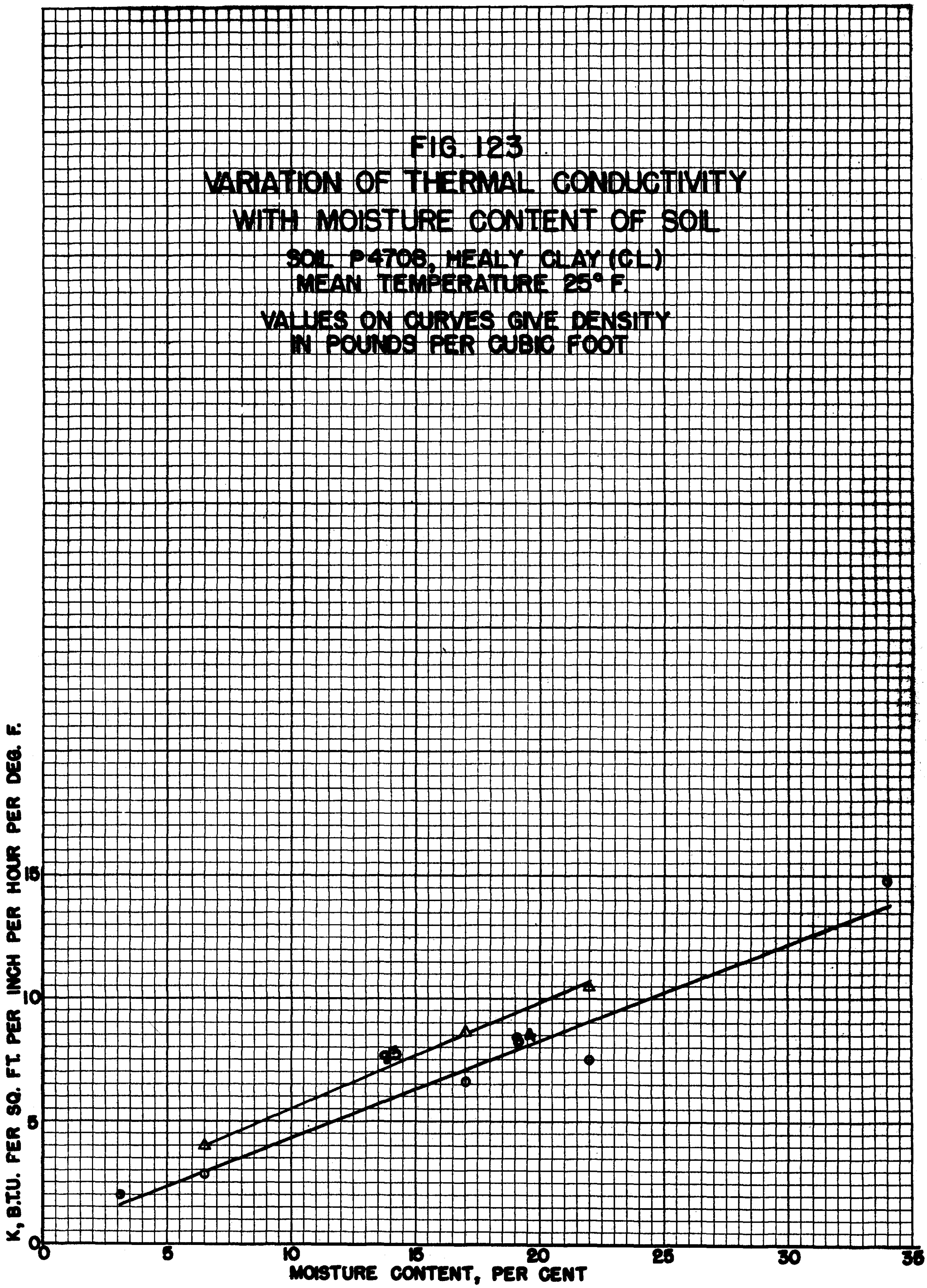


FIG. 123
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
84
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
0
5
10
15
20
25
30
35
MOISTURE CONTENT, PER CENT

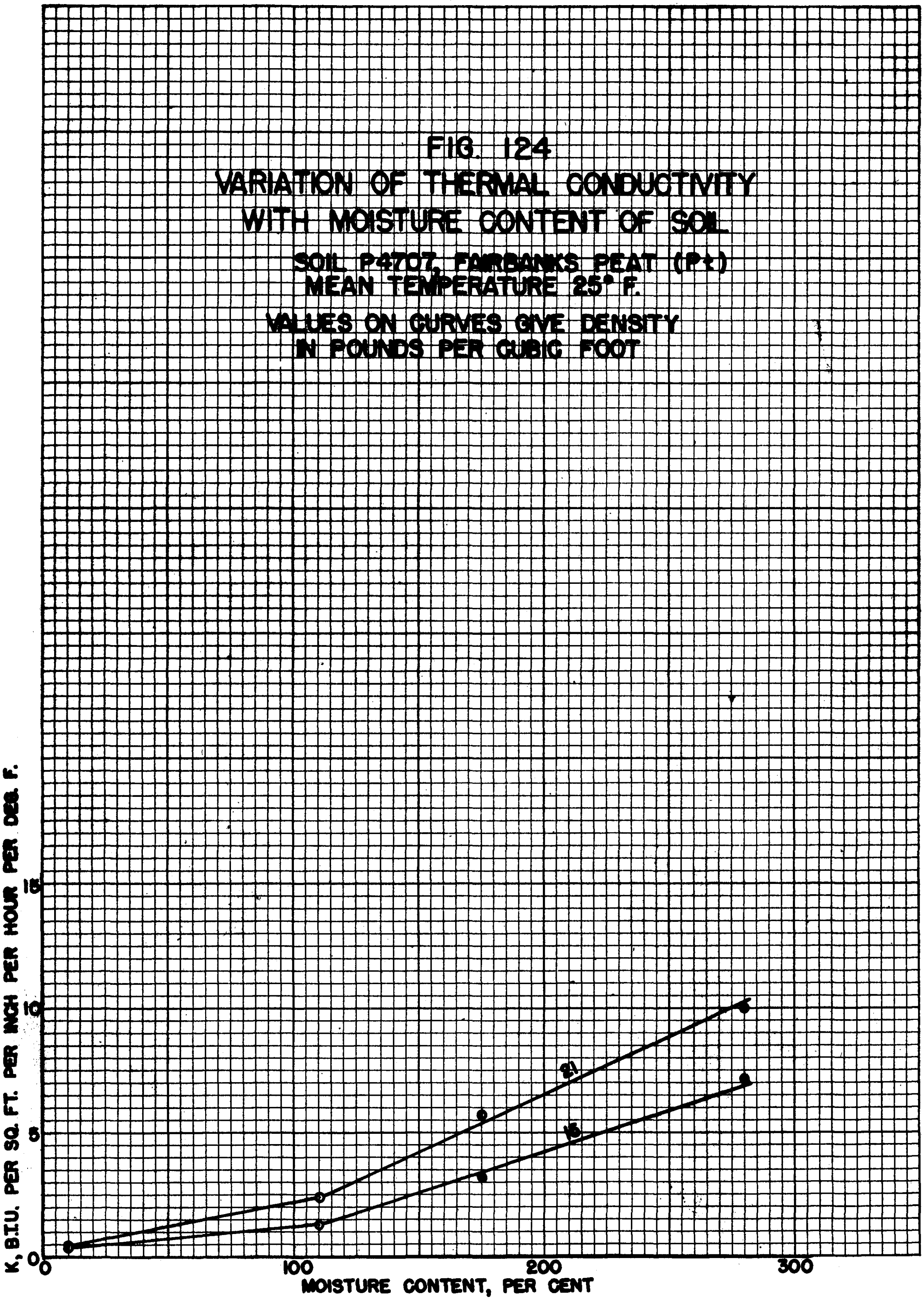


FIG. 124
VARIATION OF THERMAL CONDUCTIVITY
WITH MOISTURE CONTENT OF SOIL
SOIL P4707, FAIRBANKS PEAT (Pt)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
21
15
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
5
10
15
0
100
200
300
MOISTURE CONTENT, PER CENT

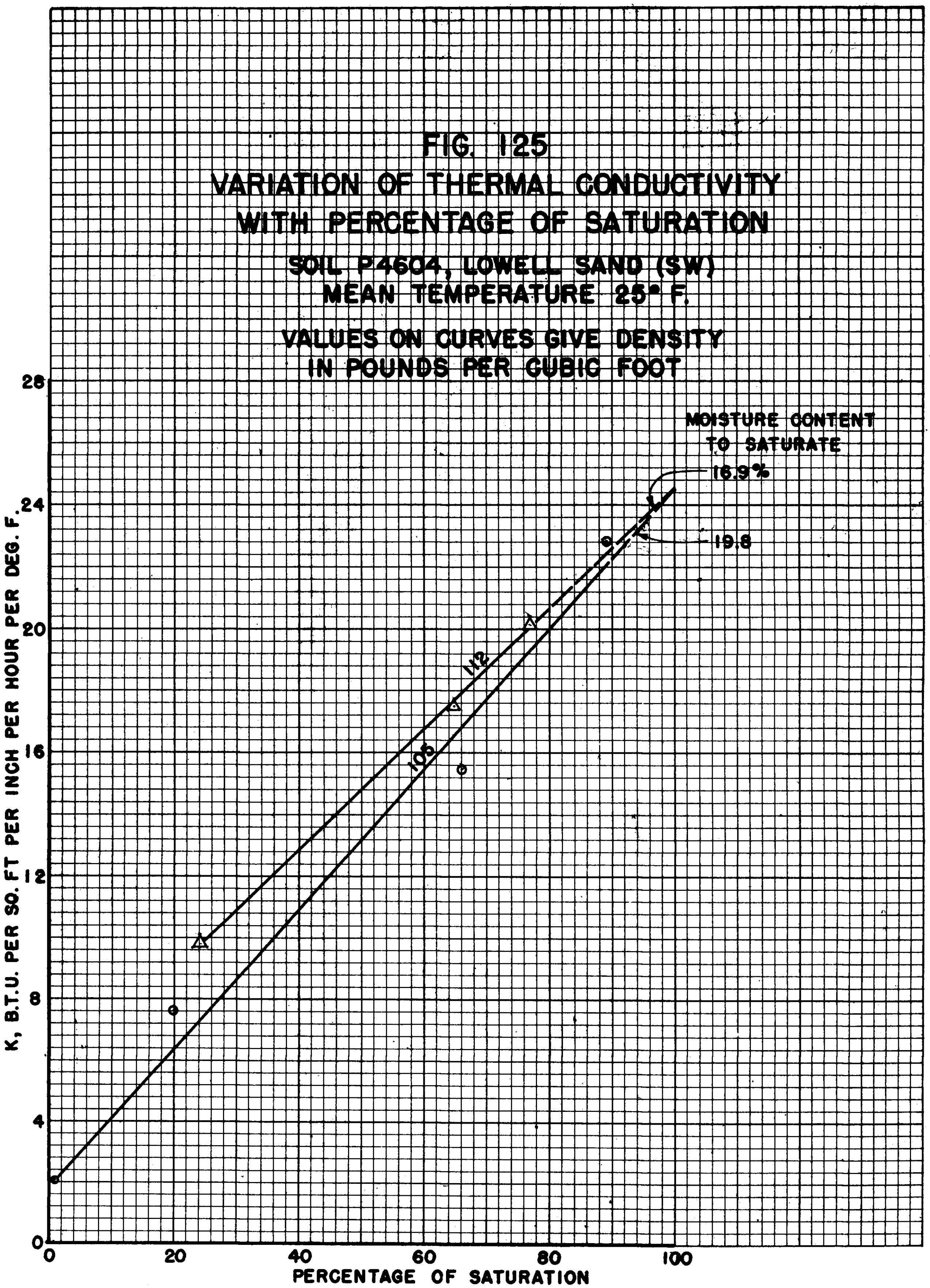


FIG. 125
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4604, LOWELL SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
16.9%
19.8
112
105
K, B.T.U. PER SQ. FT PER INCH PER HOUR PER DEG. F.
PERCENTAGE OF SATURATION
0
4
8
12
16
20
24
28
0
20
40
60
80
100

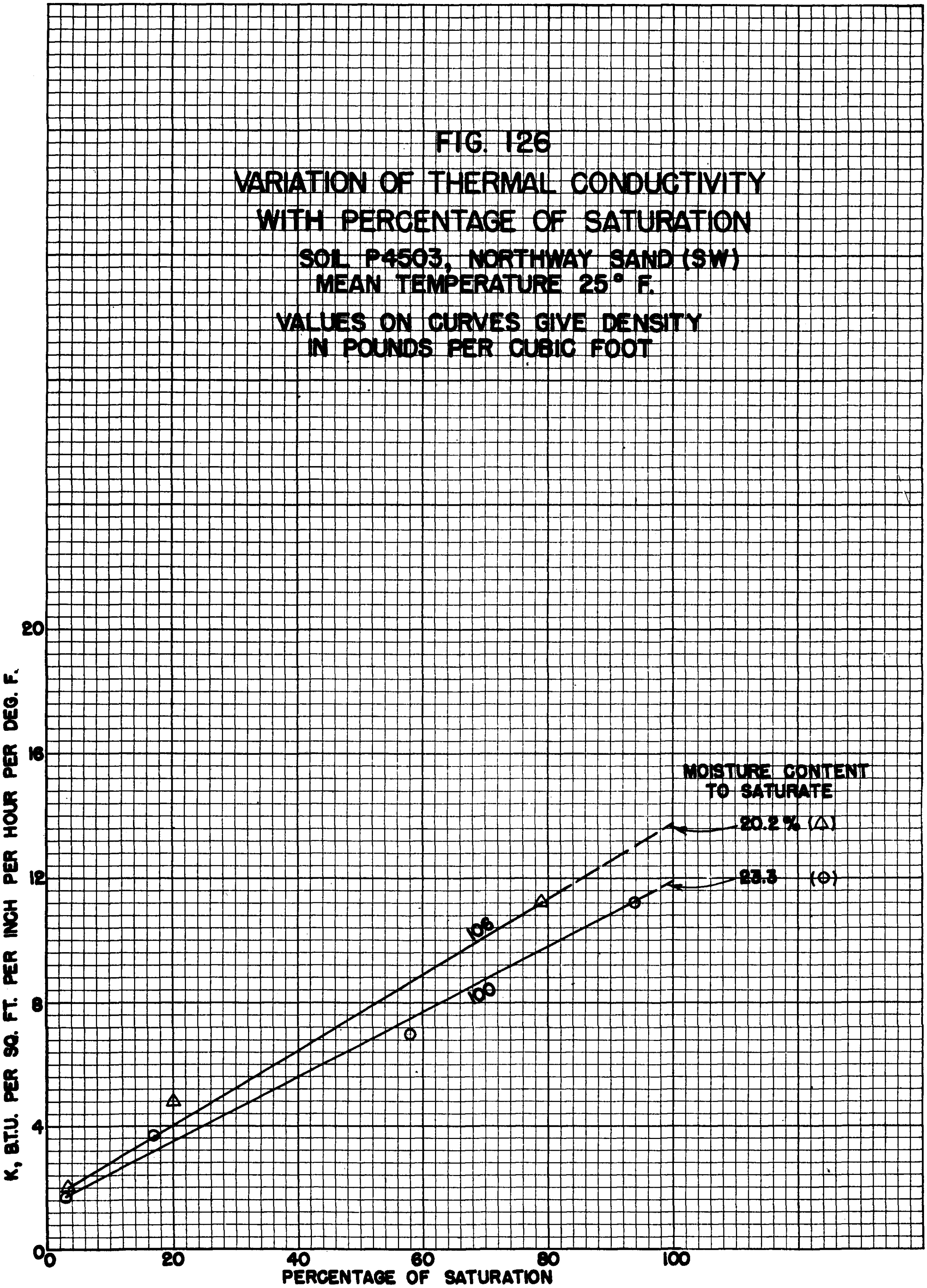


FIG. 126
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4503, NORTHWAY SAND (SW)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
20.2 % (△)
23.3 (⊖)
106
100
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
0
20
40
60
80
100
PERCENTAGE OF SATURATION

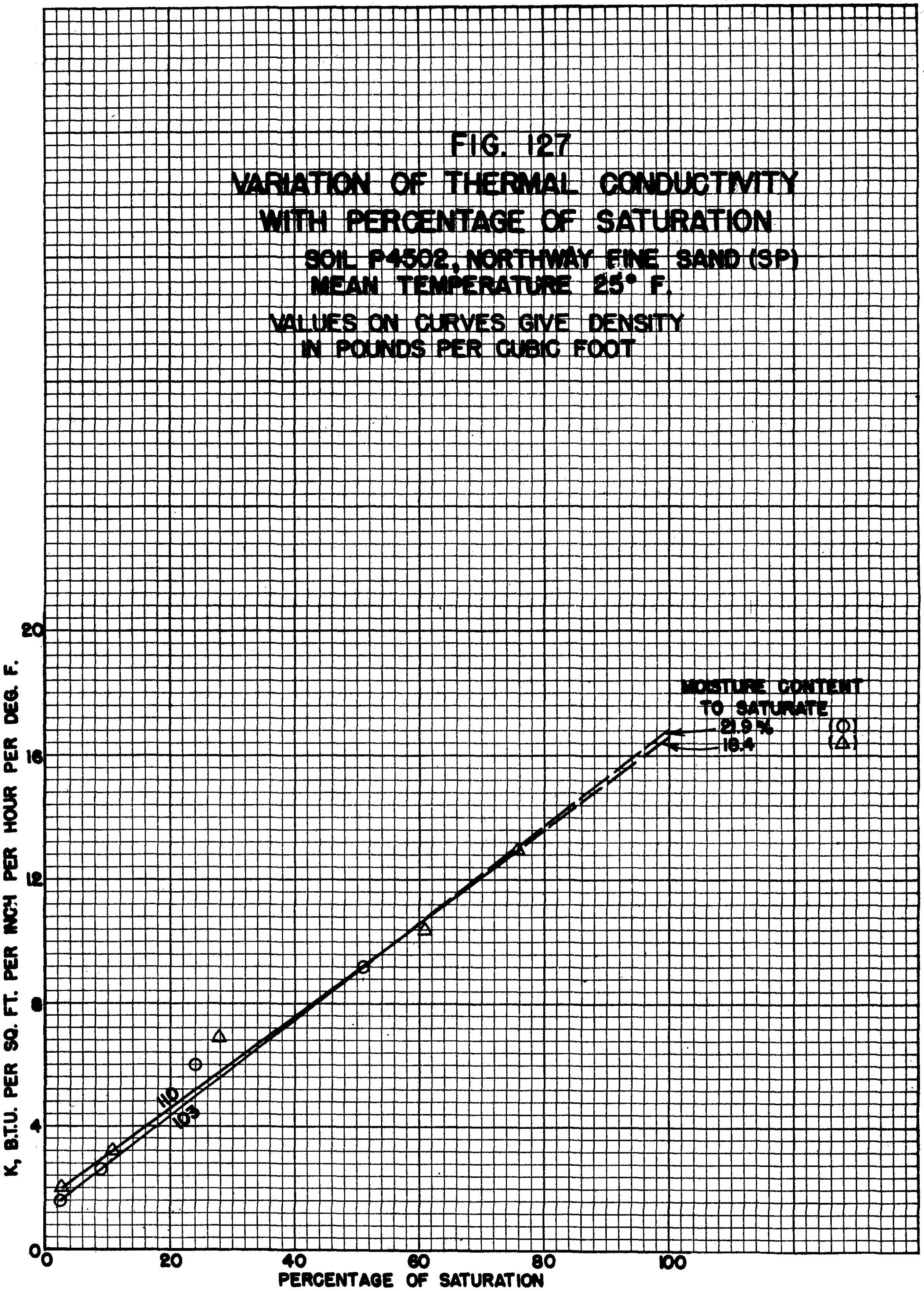


FIG. 127
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4502, NORTHWAY FINE SAND (SP)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
21.9 % (O)
18.4 (Δ)
110
103
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
PERCENTAGE OF SATURATION
0
4
8
12
16
20
0
20
40
60
80
100

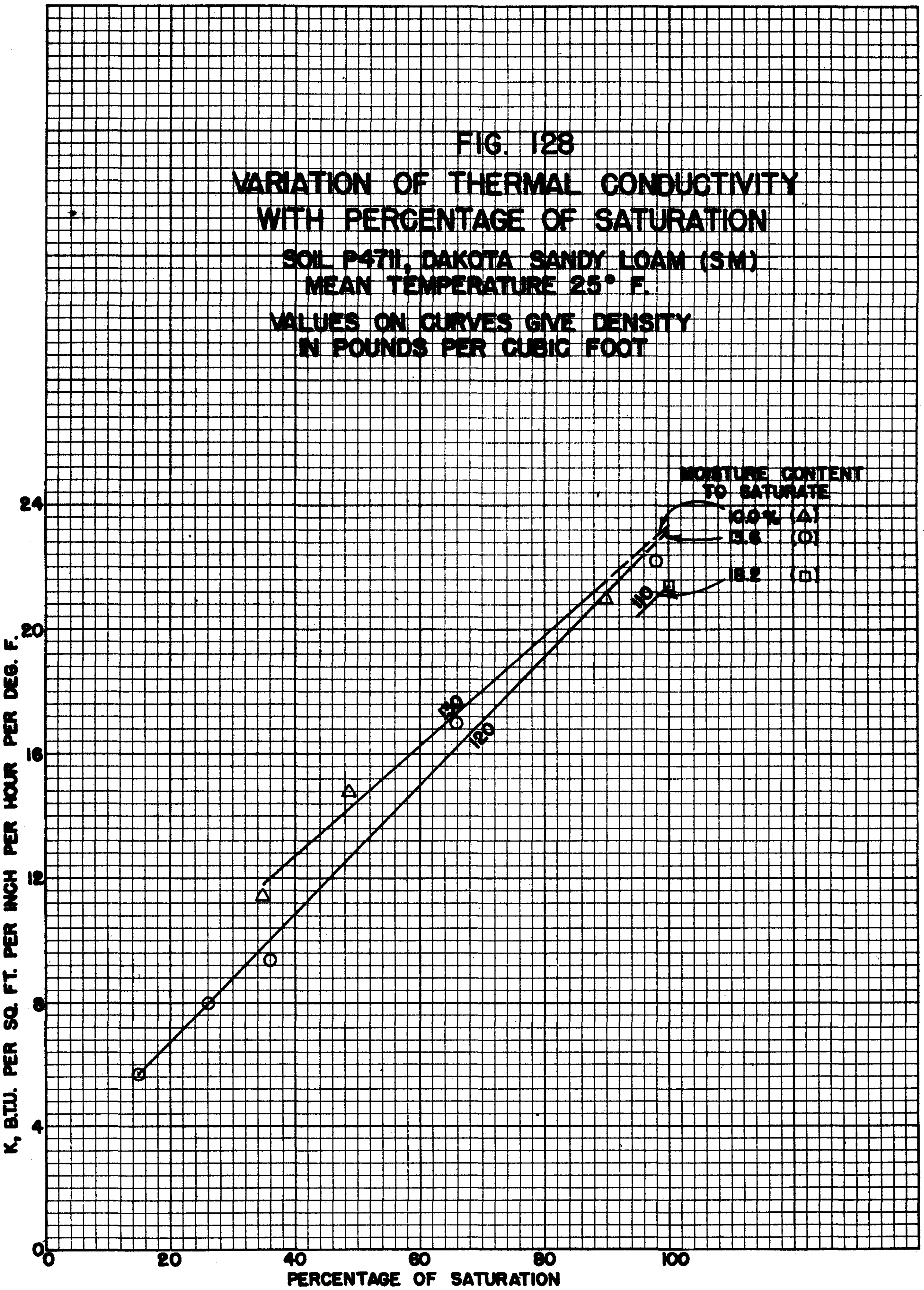


FIG. 128
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4711, DAKOTA SANDY LOAM (SM)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
10.0% (△)
13.6 (○)
18.2 (□)
110
120
130
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
24
0
20
40
60
80
100
PERCENTAGE OF SATURATION

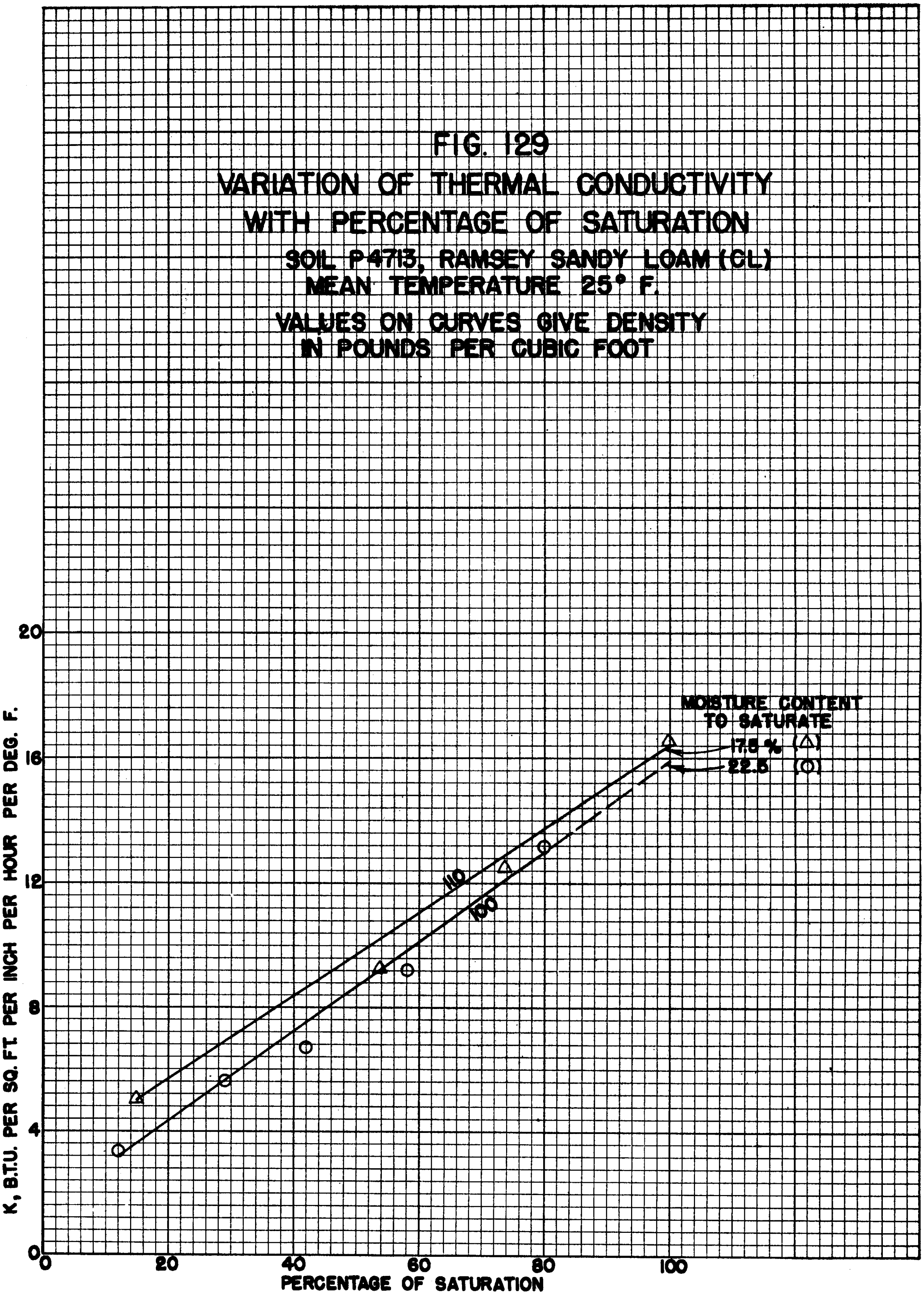


FIG. 129
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4713, RAMSEY SANDY LOAM (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
17.5 % (Δ)
22.5 (O)
110
100
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
20
0
20
40
60
80
100
PERCENTAGE OF SATURATION

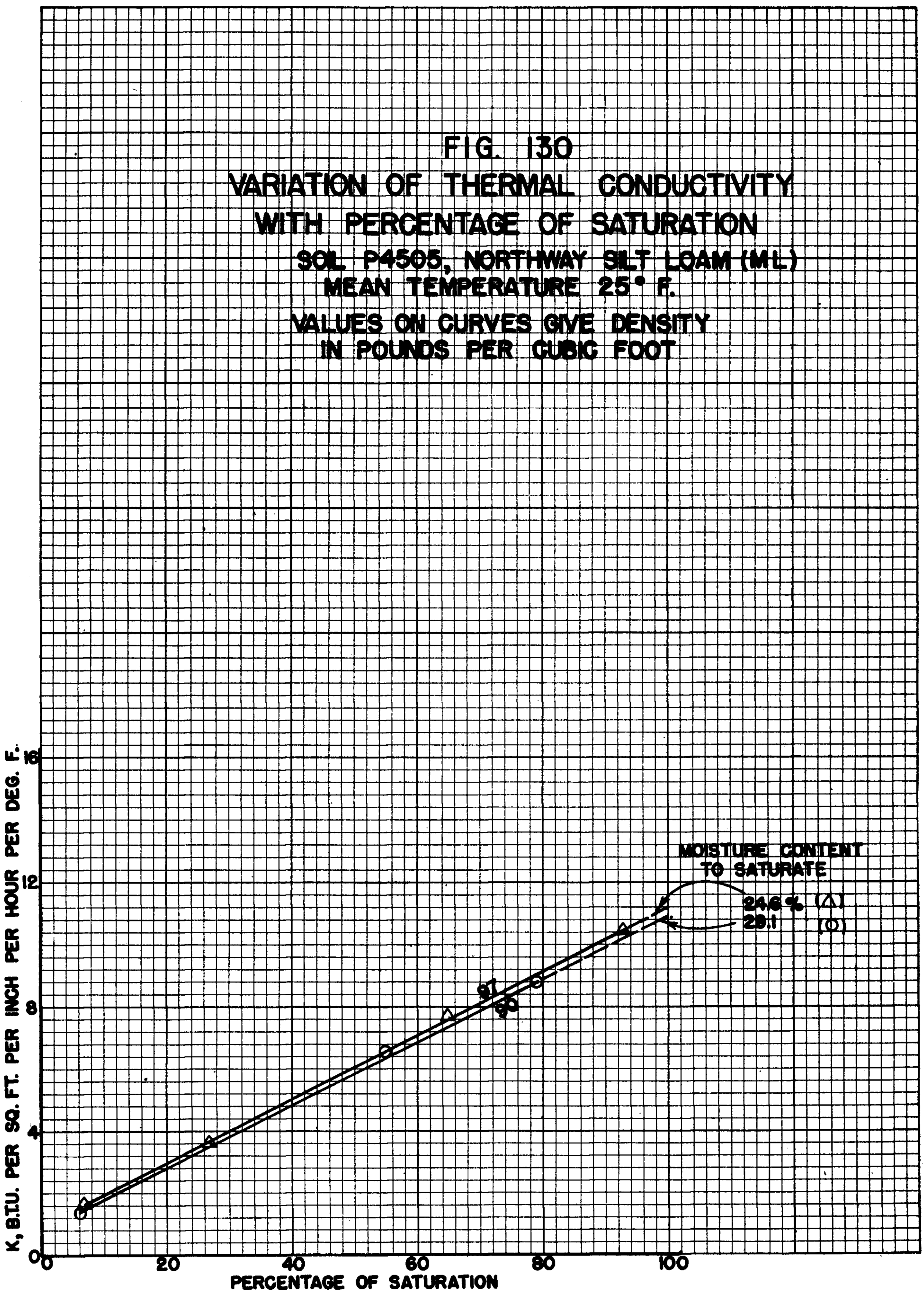


FIG. 130
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4505, NORTHWAY SILT LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
24.6 % (△)
29.1 (O)
97
90
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
0
20
40
60
80
100
PERCENTAGE OF SATURATION

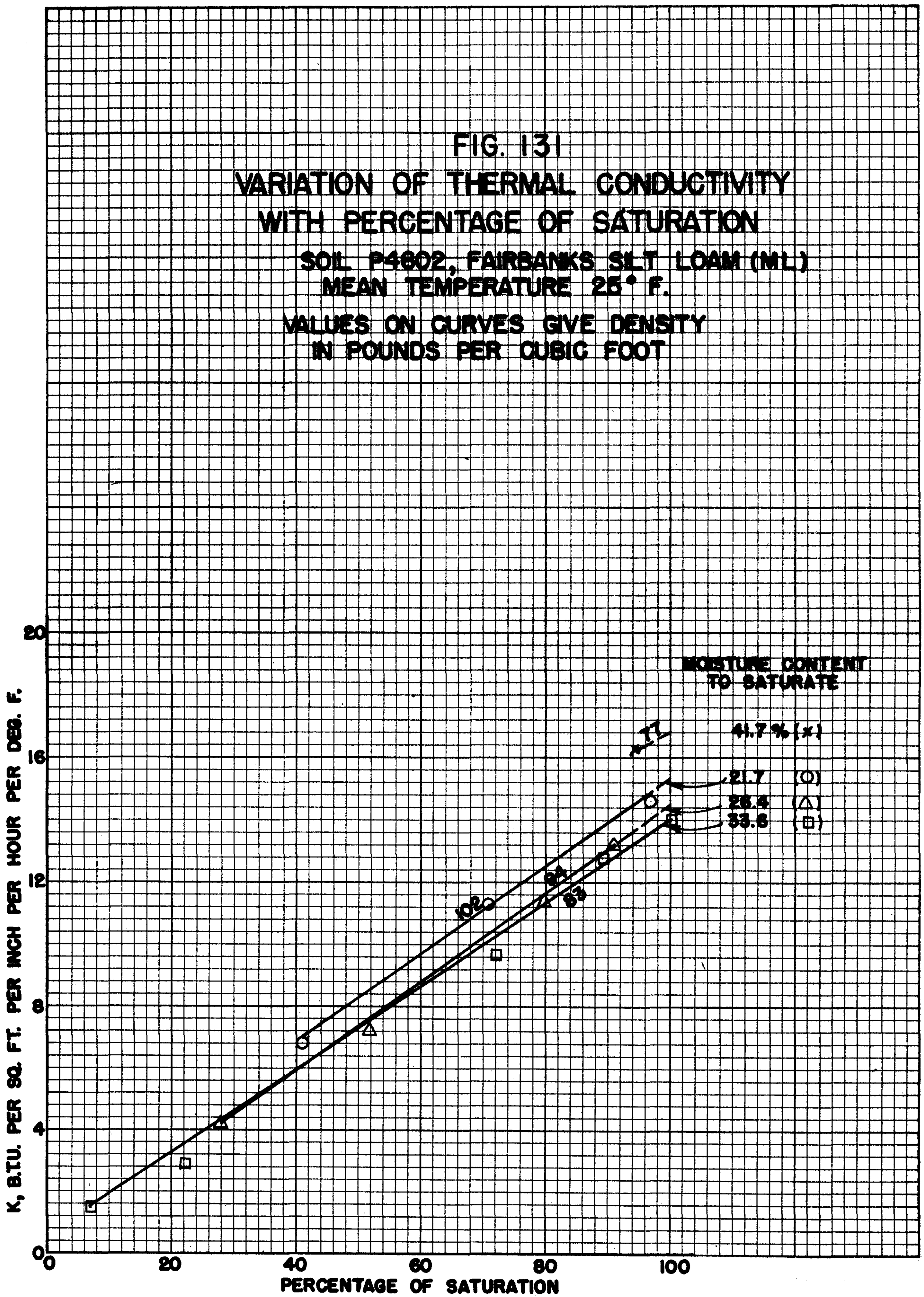


FIG. 131
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
41.7 % (x)
21.7 (O)
26.4 (△)
33.6 (□)
77
102
94
83
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
PERCENTAGE OF SATURATION
0
4
8
12
16
20
0
20
40
60
80
100

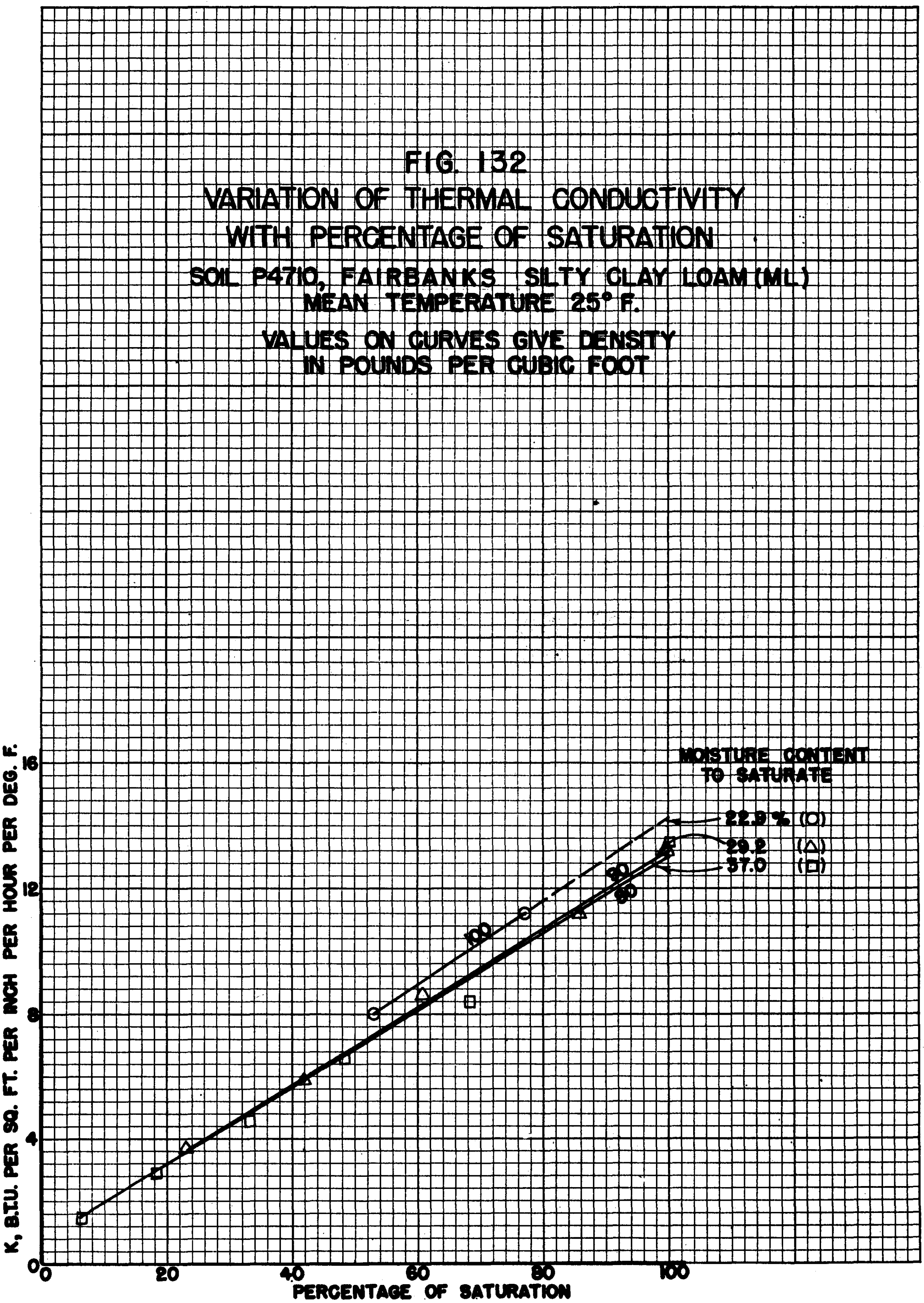


FIG. 132
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4710, FAIRBANKS SILTY CLAY LOAM (ML)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
22.9 % (○)
29.2 (△)
37.0 (□)
100
90
80
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
0
20
40
60
80
100
PERCENTAGE OF SATURATION

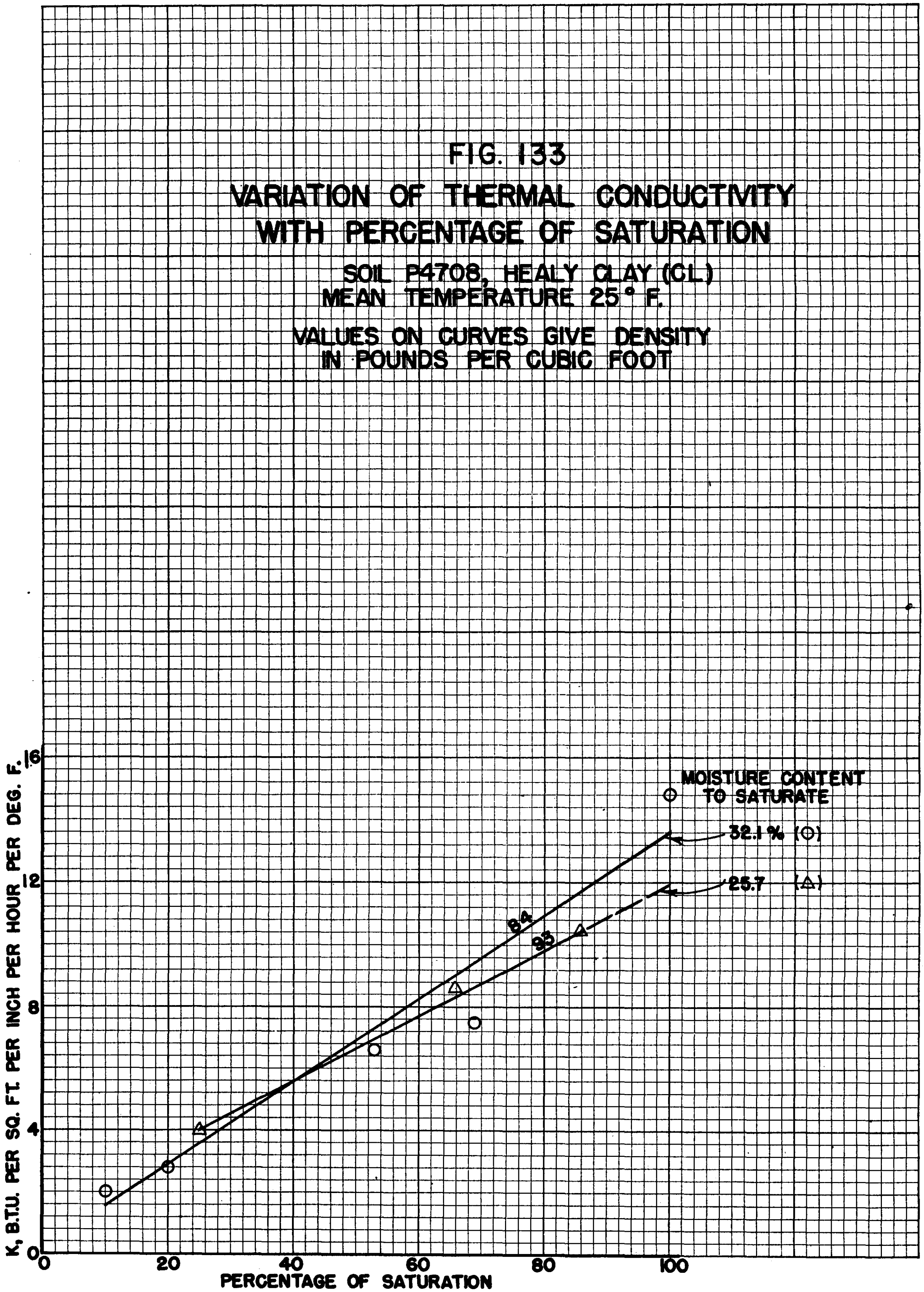


FIG. 133
VARIATION OF THERMAL CONDUCTIVITY
WITH PERCENTAGE OF SATURATION
SOIL P4708, HEALY CLAY (CL)
MEAN TEMPERATURE 25° F.
VALUES ON CURVES GIVE DENSITY
IN POUNDS PER CUBIC FOOT
MOISTURE CONTENT
TO SATURATE
32.1 % (O)
25.7 (Δ)
84
93
K, B.T.U. PER SQ. FT. PER INCH PER HOUR PER DEG. F.
0
4
8
12
16
0
20
40
60
80
100
PERCENTAGE OF SATURATION

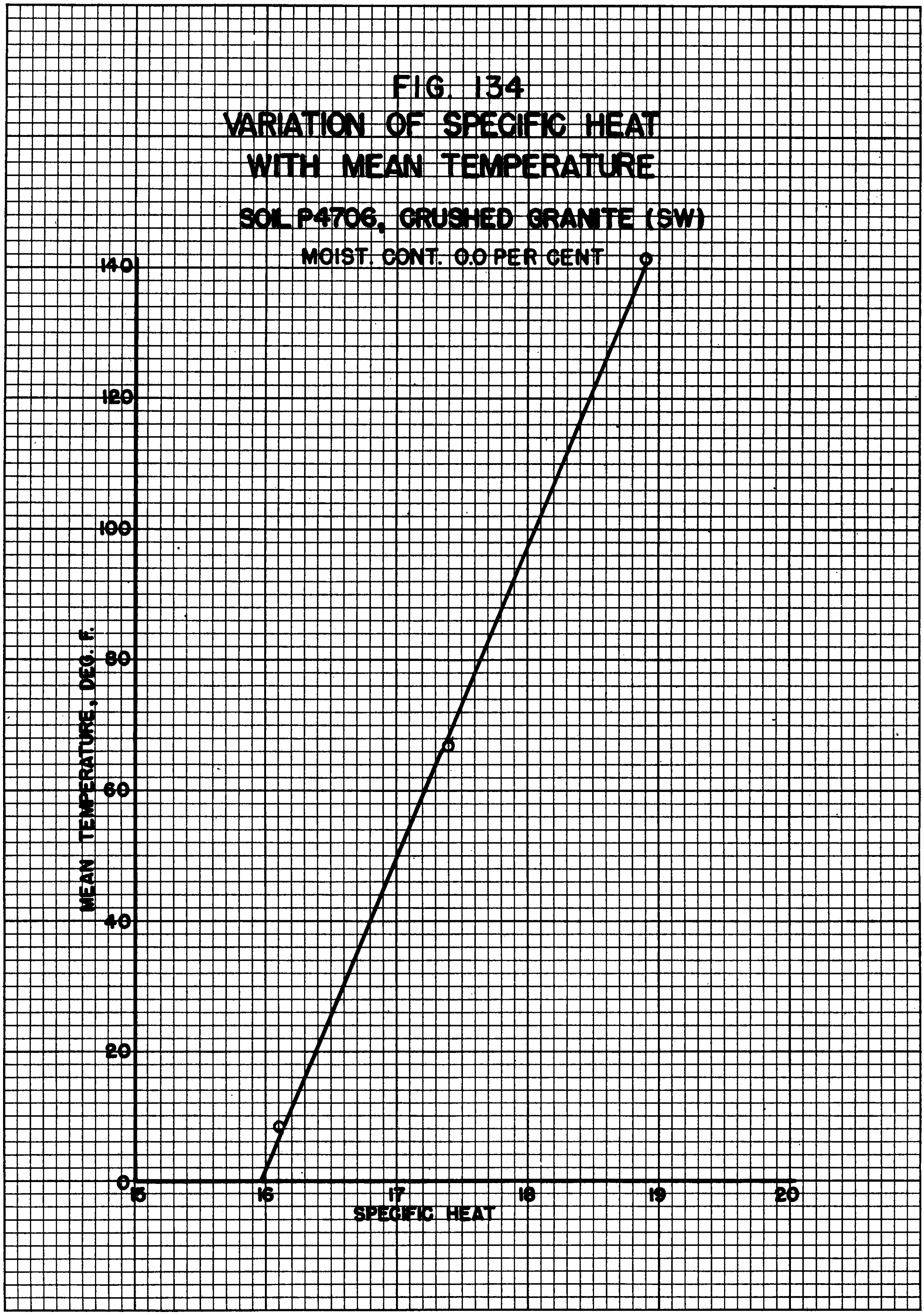
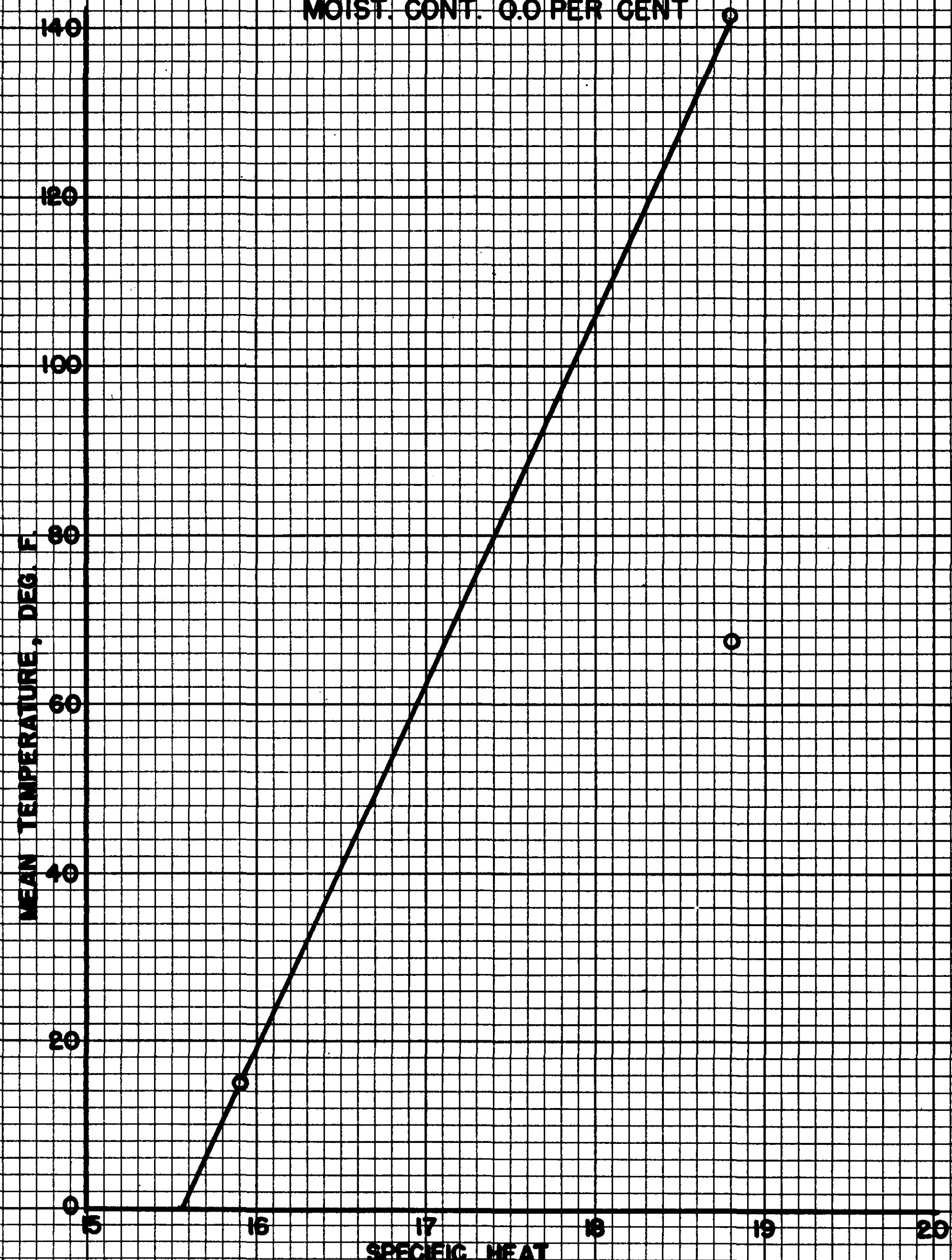


FIG. 134
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
SOIL P4706, CRUSHED GRANITE (SW)
MOIST. CONT. 0.0 PER CENT
MEAN TEMPERATURE, DEG. F.
140
120
100
80
60
40
20
0
15
16
17
18
19
20
SPECIFIC HEAT

FIG. 135
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE

SOIL P4604, LOWELL SAND (SW)

MOIST. CONT. 0.0 PER CENT



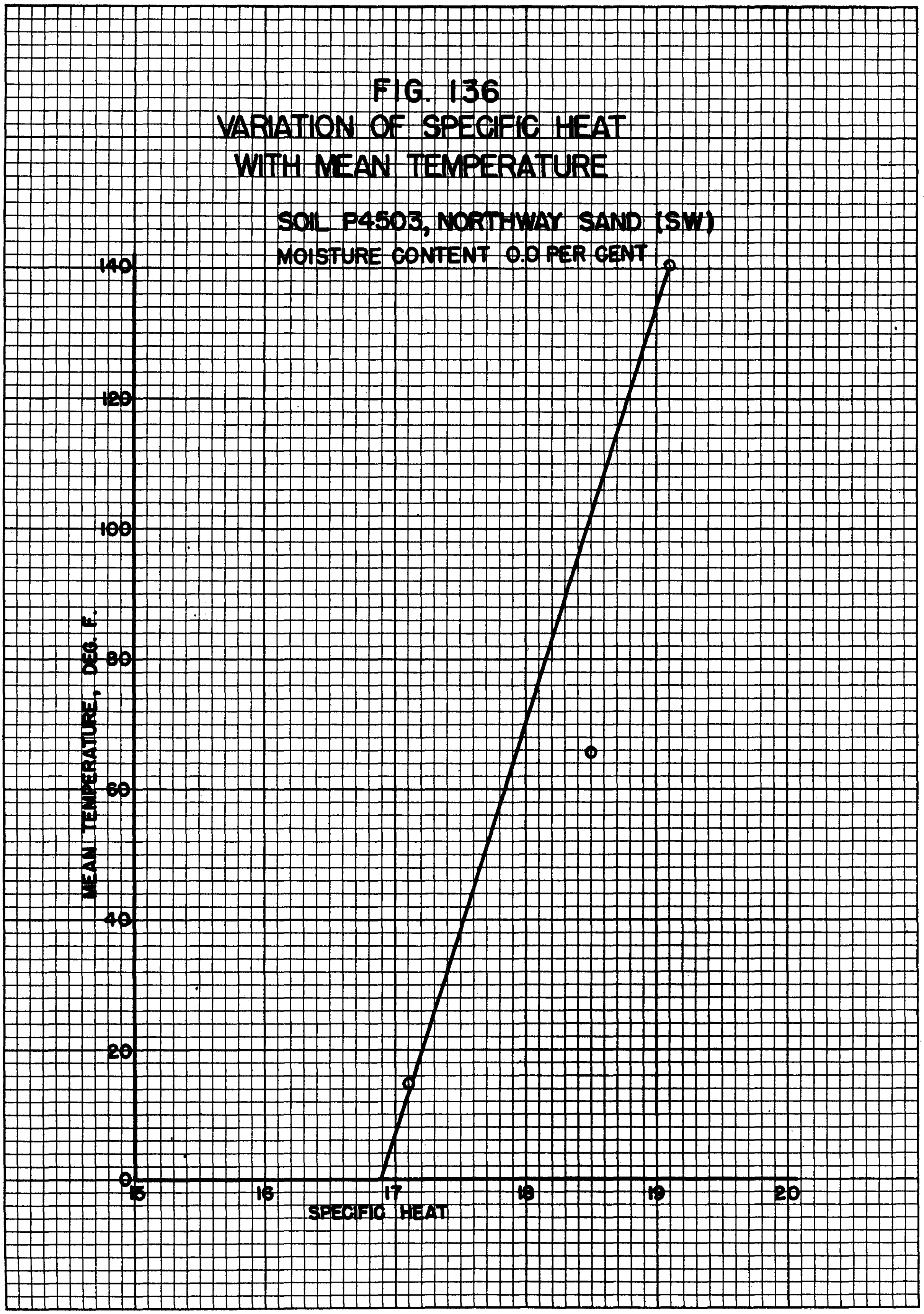


FIG. 136
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
SOIL P4503, NORTHWAY SAND (SW)
MOISTURE CONTENT 0.0 PER CENT
MEAN TEMPERATURE, DEG. F.
0
20
40
60
80
100
120
140
15
16
17
18
19
20
SPECIFIC HEAT

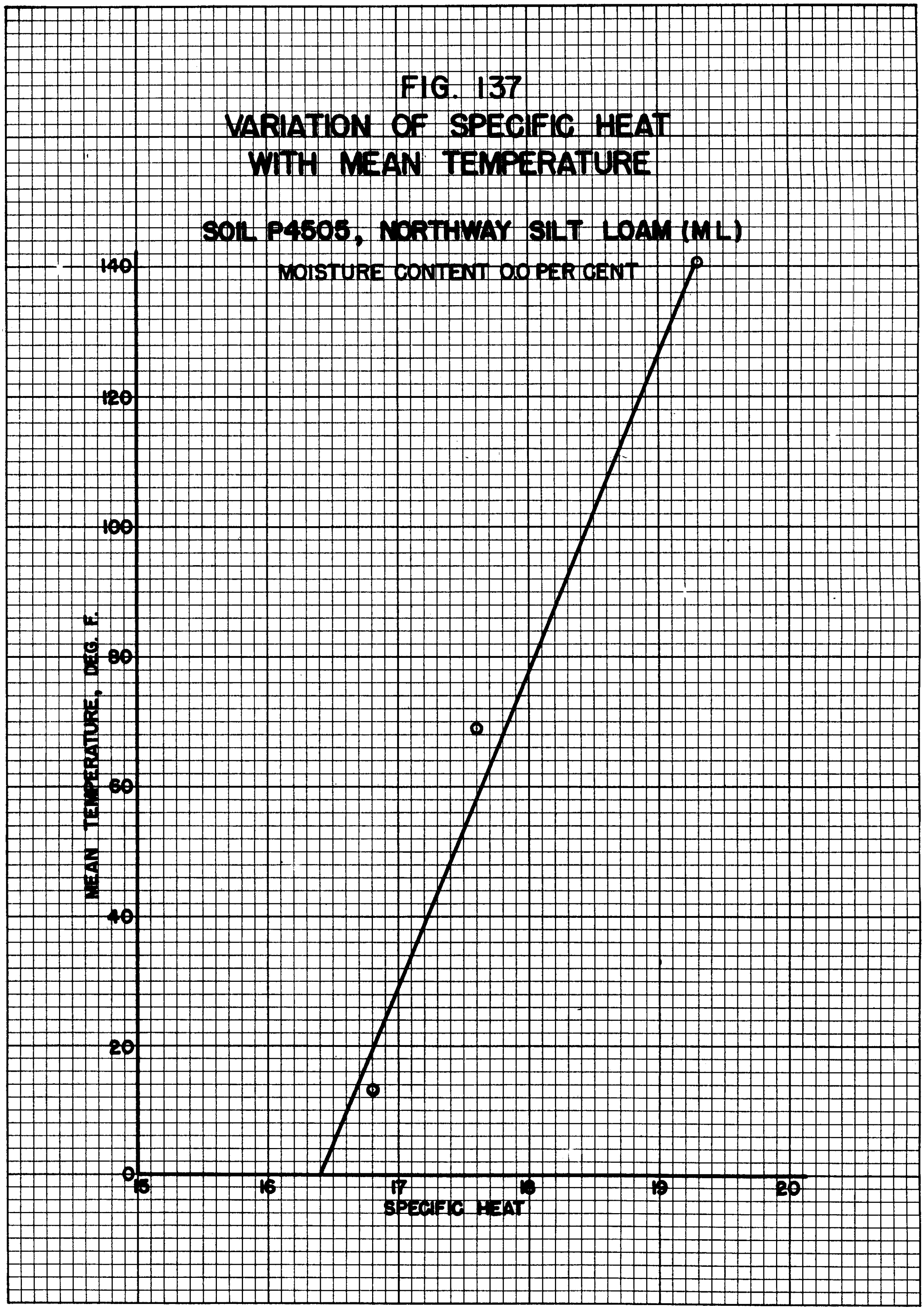


FIG. 137
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
SOIL P4505, NORTHWAY SILT LOAM (ML)
MOISTURE CONTENT 0.0 PER CENT
MEAN TEMPERATURE, DEG. F.
SPECIFIC HEAT
0
20
40
60
80
100
120
140
15
16
17
18
19
20

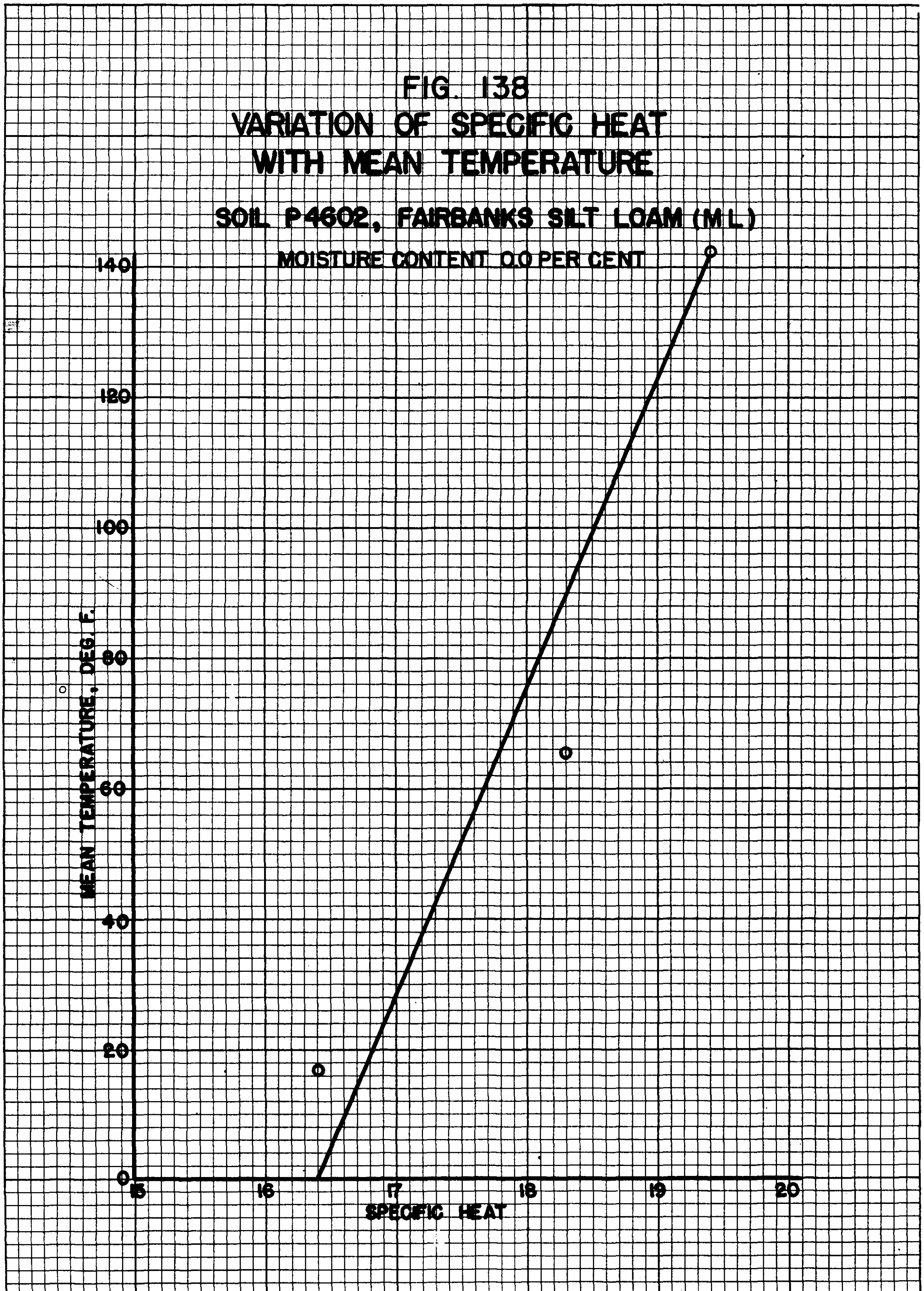


FIG. 138
VARIATION OF SPECIFIC HEAT
WITH MEAN TEMPERATURE
SOIL P4602, FAIRBANKS SILT LOAM (ML)
MOISTURE CONTENT 0.0 PER CENT
MEAN TEMPERATURE, DEG. F.
0
20
40
60
80
100
120
140
15
16
17
18
19
20
SPECIFIC HEAT

APPENDIX III

Corps of Engineers Uniform Soil Classification

CORPS OF ENGINEERS

UNIFORM SOIL CLASSIFICATION
(Based on Casagrande Classification)

The classification of most soils consists of two parts, a name and a letter symbol, and can be determined by considering the following factors:

a. Plasticity of minus 40 mesh material

b. Per cent gravel

c. Per cent sand

d. Per cent minus 200 mesh material (fines)

e. Shape of grain size distribution curve

These factors are discussed in the following paragraphs.

Plasticity: The words "silt" and "clay" are used to denote non-plastic and plastic materials, respectively. Both words can not appear in the same classification. The minus 200 mesh material is "silt" if the liquid limit is 28 or less and the plasticity index (based on minus 40) is 6 or less, and is "clay" if the liquid limit is over 28 or the plasticity index is over 6. Either word can be used as a noun or adjective, depending on the quantity of minus 200 mesh material present, as will be discussed later. If the soil is plastic according to the above criteria, the letter symbol can generally be determined immediately by reference to the Plasticity Chart, Figure 1.

Per Cent Gravel, Sand, and Fines: The limiting sizes of these materials are as follows:

Name	Passing	Retained On
Gravel	3 in.	#10 (2.0 mm)
Sand	#10 (2.0 mm)	#200 (0.074 mm)
Fines (Silt or clay)	#200 (0.074 mm)	----

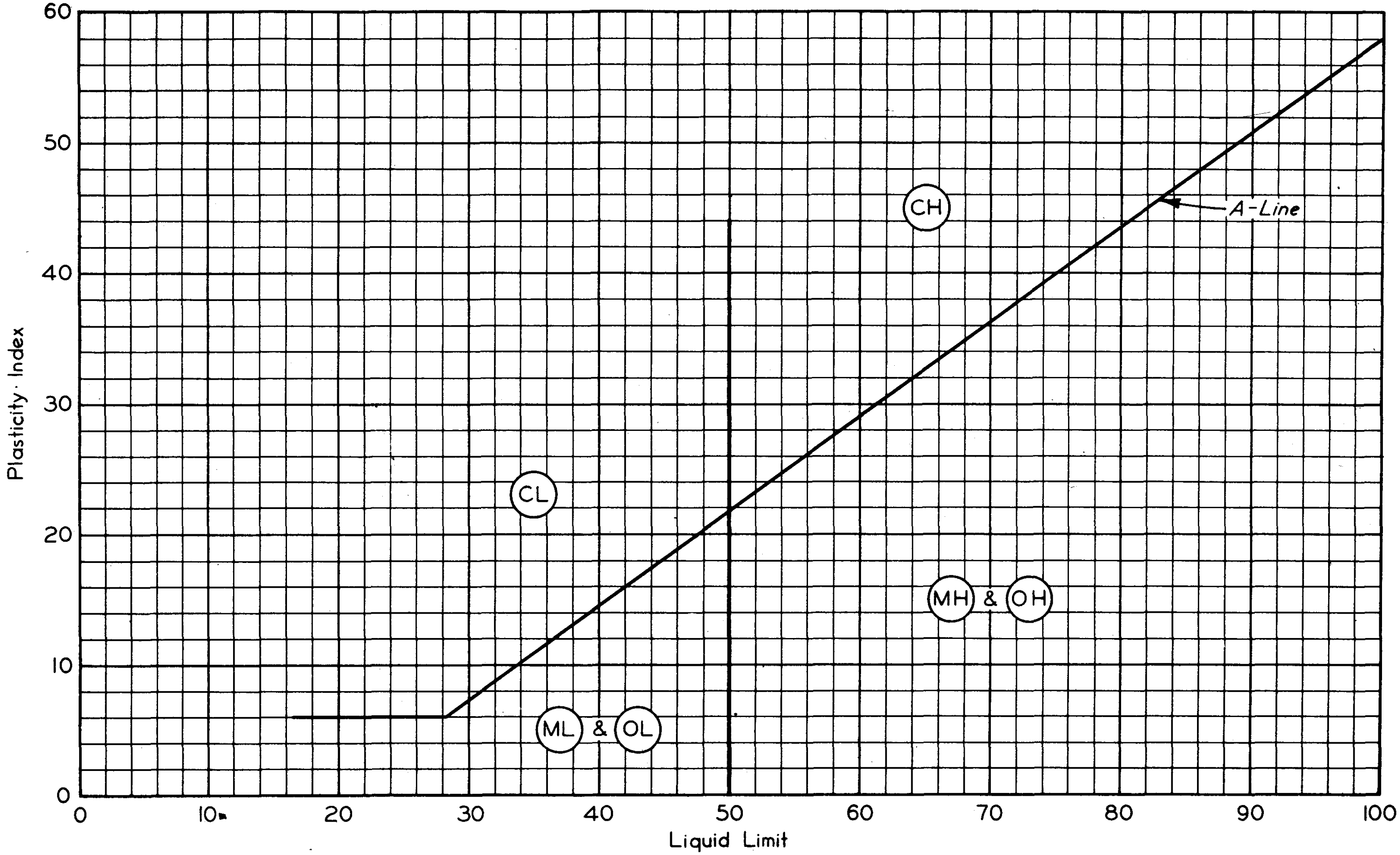
The sieves referred to are U. S. Standard sieves. A further breakdown of these groups is shown on Figure 2. The name portion of the classification for most soils is determined by the above three size groups as shown by Figure 3, the corresponding letter symbol from the chart on Figure 4.

Shape of Curve: The shape of the grain size distribution curve determines the letter symbol of coarse-grained non-plastic soils. A soil is considered poorly-graded if the sizes of the grains are relatively uniform, that is, the difference in size between the largest and smallest grains is small. A soil is also considered poorly-graded if, between the largest and smallest grains, there is a range that contains little or no soil. These soils are usually called skipgraded or step-graded. The grain size distribution curve for this type of soil is almost horizontal in the range of grain sizes containing the relatively small portion of the sample. For example, a sandy gravel, GP, consisting of sand and coarse gravel and practically no fine gravel is poorly-graded.

Additional Information: The foregoing criteria establish the minimum necessary elements in the classification of a soil but this classification is not always sufficient. The classification of some soils must be amplified in order to obtain a true picture of the material. If a soil contains concretions, shell, cinders, shale fragments, organic matter, etc., pertinent phrases should be added to the classification. Another example of soils that require additional information are gravels and sand that contain less than 10% fines when, however, the minus 40 mesh fraction is plastic; that is, liquid limit greater than 28 and PI greater than 6.

In addition to the graphical symbols and classification shown on logs of borings, the effective size, D_{10}, of coarse-grained soils and the natural water content of fine-grained soils should be shown. A description of the relative fineness or softness of the material at natural water content should also be given; especially for foundation samples. Locally accepted soil names should also be used to clarify the data to local bidders and to protect the Government against later legal claims.

Use of the Classification: It is intended that the classification of soils in accordance with this system be given some degree of elasticity and that it should not be followed blindly nor to be regarded as a rigid system. It is proposed that after a year of use by the Corps of Engineers that comments and suggestions to improve the system and its use be sent to the Office, Chief of Engineers.



PLASTICITY CHART

Figure

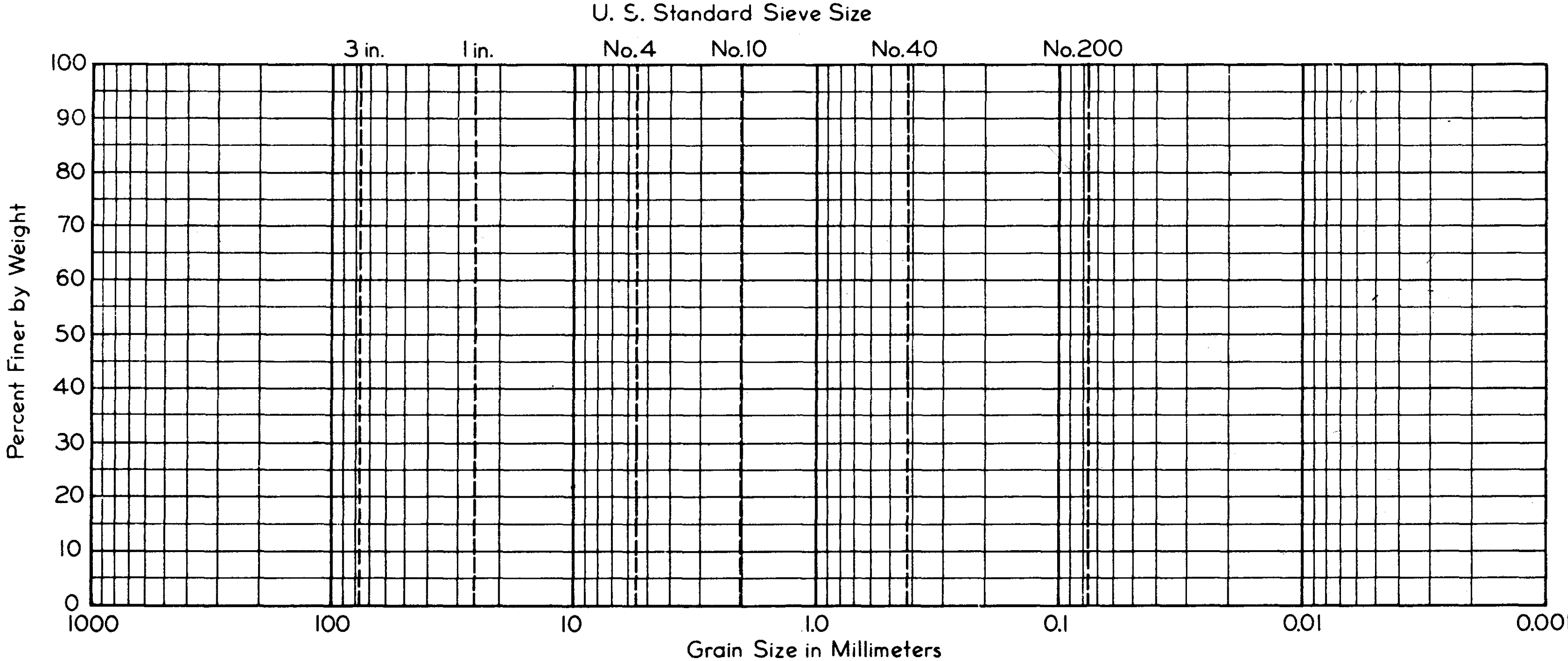
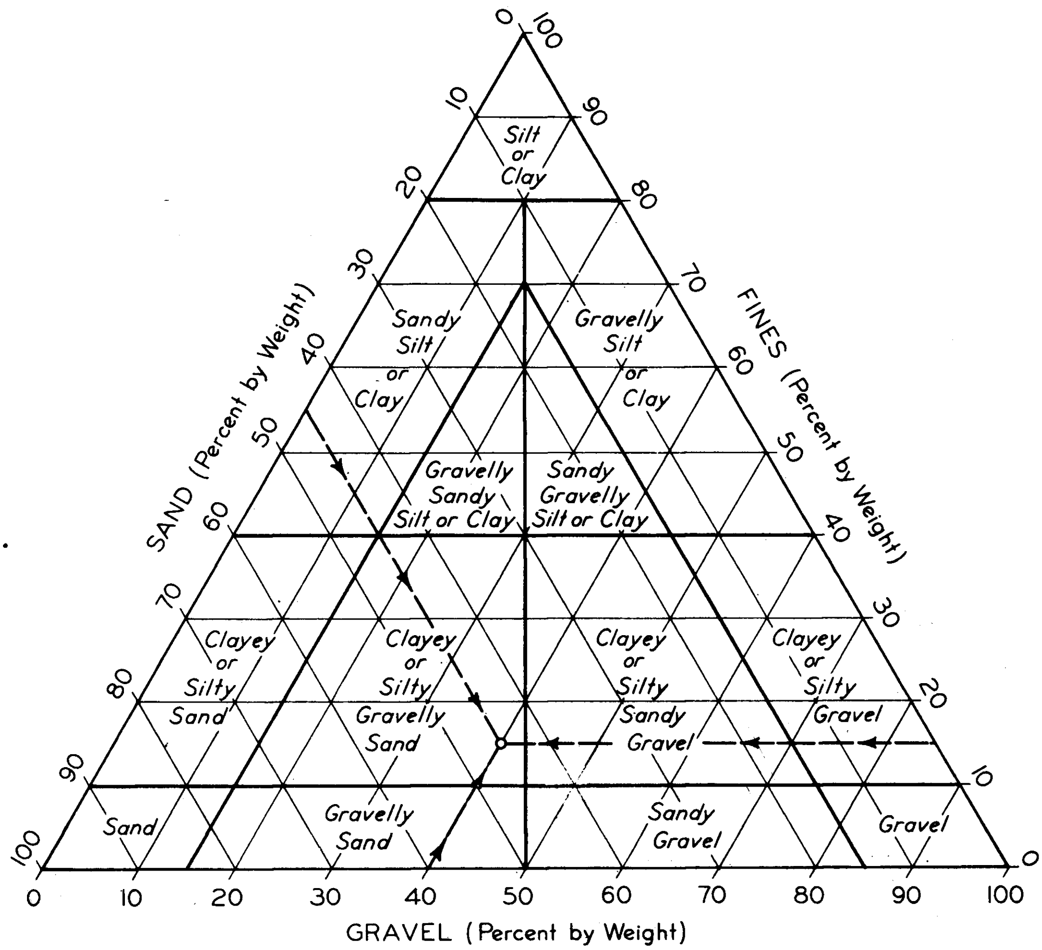


Figure 2

COBBLES	GRAVEL			SAND		SILT or CLAY
	Coarse	Medium	Fine	Coarse	Fine	

Number	Natural %Moisture	LL	PL	PI	Classification	Remarks	TITLE



NOTES:

1. Identification based on following grain size ranges:
   Gravel: 3 in. to no. 10 sieve (2.0 mm.).
   Sand: No. 10 (2.0 mm.) to no. 200 (0.074 mm.).
   Fines (silt or clay): Below no. 200 (0.074 mm.).
2. Soil is called "silt" or "clay" based upon Atterberg limits values of minus 40 mesh fraction as follows:
   Silt: LL 28 or less, and PI 6 or less.
   Clay: LL over 28 or PI over 6.
3. Sieve sizes are U. S. Standard.

SOIL TRIANGLE

Figure 3

CLASSIFICATION OF SOILS

MAJOR DIVISIONS (1)	(2)	LETTER (3)	SYMBOL Hatching (4)	SYMBOL Color (5)	NAME (6)	GENERAL IDENTIFICATION Dry Strength (7)	GENERAL IDENTIFICATION Other Pertinent Features (8)	PRINCIPAL CLASSIFICATION TESTS (9)
COARSE GRAINED SOILS	GRAVEL AND GRAVELLY SOILS	GW		RED	Gravel or Sandy Gravel, well-graded	None	Gradation, grain shape	Sieve Analysis
		GP		RED	Gravel or Sandy Gravel, poorly-graded	None	Gradation, grain shape	Sieve Analysis
		GM		YELLOW	Silty Gravel or Silty Sandy Gravel	None to slight	Gradation, grain shape, examination of fines	Sieve Analysis LL & PL on "Minus 40"
		GC		YELLOW	Clayey Gravel or Clayey Sandy Gravel	Medium to high	Gradation, grain shape, examination of fines	Sieve Analysis LL & PL on "Minus 40"
	SAND AND SANDY SOILS	SW		RED	Sand or Gravelly Sand, well-graded	None	Gradation, grain shape	Sieve Analysis
		SP		RED	Sand or Gravelly Sand, poorly-graded	None	Gradation, grain shape	Sieve Analysis
		SM		YELLOW	Silty Sand or Silty Gravelly Sand	None to slight	Gradation, grain shape, examination of fines	Sieve Analysis LL & PL on "Minus 40"
		SC		YELLOW	Clayey Sand or Clayey Gravelly Sand	Medium to high	Gradation, grain shape, examination of fines	Sieve Analysis LL & PL on "Minus 40"
FINE GRAINED SOILS	LOW PLASTICITY	ML		GREEN	Silts, Sandy Silts, Gravelly Silts, or Diatomaceous Soils	None to slight	Examination wet (shaking test)	Sieve Analysis LL & PL on "Minus 40"
		CL		GREEN	Lean Clays, Sandy Clays, or Gravelly Clays	Low to medium	Examination in plastic range	Sieve Analysis, if applicable. LL & PL on "Minus 40"
		OL		GREEN	Organic Silts or Lean Organic Clays	None to slight	Examination in plastic range, color, odor, organic content	LL & PL before and after oven drying
	HIGH PLASTICITY	MH		BLUE	Micaceous Clays or Diatomaceous Soils	None to slight	Examination wet (shaking test)	Sieve Analysis LL & PL on "Minus 40"
		CH		BLUE	Fat Clays	High	Examination in plastic range	Sieve Analysis, if applicable. LL & PL on "Minus 40"
		OH		BLUE	Fat Organic Clays	Medium to high	Examination in plastic range, color, odor, organic content	LL & PL before and after oven drying
PEAT AND OTHER FIBROUS ORGANIC SOILS		Pt		ORANGE	Peat, Humus, and other Organic Swamp Soils	Readily Identified		Consistency, Texture, and Water Content

NOTE: Column 9, "Minus 40" refers to the fraction of a soil that passes the No. 40 mesh sieve.

FIGURE 4