A LABORATORY INVESTIGATION OF THE THERMAL PROPERTIES OF SOIL IN RELATION TO GROUND COIL DESIGN FOR THE HEAT PUMP

by

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INTRODUCTION

Heating and cooling residences with the heat pump has become satisfactory and economical in many sections of this country where there is a reasonably low electric energy rate and a satisfactory heat source and heat sink for the heat pump system.

Although many problems exist in the development of the heat pump for residential heating and cooling, the most urgent is the study of media to serve as a heat source and sink. At present, only two media have been successfully utilized for that purpose--water and air. Well water is a satisfactory medium in areas where it is available in sufficient quantity to allow its use for heat pumps. Air as a heat source for an economically operated system is limited to areas where the air temperature seldom drops below 20° F. Thus, a more universal medium which will serve as a satisfactory heat source and sink is needed.

The earth offers possibilities, as a third medium, and there is no doubt of its capacity to act as a heat source and sink for the heat pump system. There is, however, the problem of collecting heat from and delivering it to the soil.

Because of the complexity of soil composition and structure, it would be difficult to predetermine the size and nature of an earth imbedded heat exchanger which would be necessary to dissipate a given quantity of heat to or absorb it from the different soils. The problem is further complicated by variations in compaction and moisture content of the different soils under field conditions.

There is a regrettably small amount of information available on the heat transfer characteristics of soils. Even such information as is available usually is the result of field studies conducted in a specific locality and the use of such data for design purposes in other areas would be questionable.

Heat transfer in soil is directly affected by moisture, density, thermal conductivity, and specific heat.

REVIEW OF LITERATURE

According to Sporn, Ambrose, and Baumeister (18) there is no fundamental difference between the conventional refrigeration system and the so-called "heat pump" system. Both systems consist of compressor, condenser, evaporator, and expansion valve to absorb heat from a low temperature level and reject it at a higher temperature level. A system making use of the rejected heat, as the heat pump does, cannot be correctly called a refrigeration system since cooling is not the primary objective of the cycle. The heat pump system is sometimes erroneously called the "reverse-refrigeration cycle."

Kemler, Oglesby, and Pease (11) point out that the heat pump is not a new idea, its having been proposed by Lord Kelvin as early as 1852. However, the heat pump had very limited use before 1930. An abundance of electric power in some regions of the world gave rise to its use in some industrial applications after this date. One such region was Switzerland where industrial heat pumps proved to be competitive when the cost of 1 ton of coal was approximately equal to the cost of 900 KWH of electrical energy. The present trend in the manufacture of heat pumps is toward small "package type" units, from 3 to 10 hp. These package units are being utilized for both home and industrial applications.

Ambrose (1) says that an ideal source of heat for the heat pump is one which is abundant and inexpensive and having an average year round temperature of 40 to 80° F. According to Kemler (10) the earth is the most universal source of heat available. He states that a cylinder of earth 30 feet in diameter and 100 feet deep will give up 28,000,000 BTU if its temperature is lowered 10° F. This shows the earth's capacity to act as a heat source.

In ground coil design for the heat pump, Smith (16) says that the soil characteristics must be considered. These soil characteristics include type of soil, natural density, and moisture conditions at various seasons. The interchange of heat from tube to soil and reverse is a function of the tube diameter, tube surface condition, and of the soil and tube temperature as well as of the soil characteristics.

In studies of the heat transfer characteristics of soils, a consideration of the effect of density and moisture on thermal conductivity is significant. Smith and Yamauchi (17) found that thermal conductivity varied greatly with density and to a lesser extent with moisture content. In their tests they encountered difficulty in duplicating values of thermal conductivity with any great accuracy. They noticed that an error occurred in calculations close to the heated side of the soil sample. They concluded that moisture movement next to the heated surface caused a change in conductivity in that region.

Thermal conductivity tests were conducted by Kersten (12) at the University of Minnesota on 14 different soils. He found the thermal conductivity of these soils to vary in the following ways:

1. Increases with an increase in mean temperature above freezing.

2. Shows very little change below freezing.

3. From above to below freezing, varies according to moisture content. For dry soils there is no change; for low moisture contents the frozen value is lower than the unfrozen; for high moisture contents the frozen value is higher.

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

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

6. It is higher for well graded soils with angular particles than for poorly graded soils with rounded particles.

7. It differs appreciably for different soil minerals.

He also conducted specific heat tests on 12 of these 14 different soils. He concluded that the specific heat values of a wide variety of soils differ by only a small amount and average 0.19 at 140 degrees Fahrenheit. Based on tests on one soil he states that the specific heat of soil-water mixtures may be computed by weight proportion of the components and the respective specific heats.

Coogan (2) worked out a mathematical solution for heat absorbed by a pipe buried in the soil and developed the following equation:

$$q = \frac{2\pi k \ (T_g - T_c)}{\ln\left[\frac{4D}{d} - 1\right]} \qquad (1)$$

where

q = heat absorbed per foot of pipe - BTU/hr.ft.

k = thermal conductivity of the soil - BTU/hr.ft.°F.

T_g = the average undisturbed earth temperature - °F.

T_c = the surface temperature of the pipe - °F.

D = the depth of the pipe below the surface - ft.

d = the pipe diameter - ft.

This equation was developed with the following assumptions: (a) A steady state condition of heat flow is reached; (b) the undisturbed earth temperature is uniform; (c) the thermal properties of the soil are constant during operation and extend throughout the soil mass. A comparison of this theoretical computation and experimental results showed reasonable agreement considering the assumptions made.

Another mathematical method of estimating the amount of underground tubing necessary for a given heat pump installation is presented by Ingersoll and others (7). The following equation was developed:

$$q = k\,\Delta T\,F(z) \qquad (2)$$

where

$$z = \frac{\alpha\, t}{R^2} \quad \text{and} \quad F(z) = \frac{\pi}{8}\int_0^{\infty} \frac{e^{-z\beta^2}}{Jo^2(\beta) + Yo^2(\beta)} \cdot \frac{d\beta}{\beta}$$

and where

q = rate of heat transfer - BTU/hr.ft.

k = thermal conductivity of soil - (BTU)(ft.)/(hr.)(sq.ft.)(°F.)

ΔT = temperature differential between the heat exchanger and the initial temperature of the surrounding soil - °F.

β = variable of integration.

Jo, Yo = Bessel functions.

α = thermal diffusity of soil $\frac{k}{c\rho}$, sq. ft./hr.

t = time since start of operation - hr.

R = radius of cylindrical heat exchanger - ft.

ρ = density of soil - lbs./ cu. ft.

In developing equation (2) assumptions (b) and (c) for equation (1) are made but equation (2) assumes that the earth extends to infinity in all directions. Since time is taken into consideration in equation (2) an unsteady state is indicated. Equation (2) appears involved but after z is evaluated tables are available which give values of F(z).

Values of thermal conductivity have been determined for various soils by several investigators. Thermal conductivity values reported by Kemler (10) are given in Table 1.

Table 1. Thermal conductivities of various soils.

Material	K, $\frac{(BTU)(ft)}{(sq. ft.)(hr)(^{o}F.)}$
Very light and dry soil	0.21
Clay soil (65.7)*	0.14
Clay soil (78)*	0.26
Clay soil (96)*	0.38
Dry soil	0.08
Wet (maximum) soil	2.62
Wet soil	0.39
Moist soil	0.83
Dry clay soil	0.50
Moist clay soil	0.90
Well drained soil	0.55 to 0.57
Wet sub soil	1.34
Dry sandy soil	0.45 to 0.65
Moist sandy soil	1.1
Soaked sandy soil	2.4
Dry sand	0.19 to 0.22
Moist sand	0.67

*Figures in parentheses are densities in pounds per cubic foot.

Goethe, Sutton, and Leffler (4) state that the addition of water to the soil surrounding the ground coil of a heat pump would increase the thermal conductivity and subsequently the heat flow would be increased. However, the cost of installing perforated pipe above the ground coil would make its use objectionable. They conclude that dissipation of heat to the soil is a greater problem than absorption due to the moisture movement away from the hot pipe.

It should be remembered that the ground coil is often operated at a

Table 2. Thermal characteristics of soils.[1]

Soil constant		Dry soil	Saturated soil	Frozen Saturated soil	Units
K	Maximum S	.0133 ≠ .001782d	.337 ≠ .0068d	1.10 ≠ .003182d	(BTU)(ft) / (hr)(sq.ft.)(°F.)
	Wtd. Avg. S	.0133 ≠ .001381d	.337 ≠ .006525d	1.10 ≠ .003162d	"
	Mean S	.0133 ≠ .001335d	.337 ≠ .006421d	1.10 ≠ .003154d	"
	Minimum S	.0133 ≠ .000839d	.337 ≠ .005822d	1.10 ≠ .003107d	"
Specific heat		.17	(62.43 - .2004d) / (62.43 ≠ .6296d)	(28.05 ≠ .0036d) / (57.25 ≠ .6604d)	BTU / (lb.)(°F.)
Density		d	62.43 ≠ .6296d	57.25 ≠ .6604d	(lb) / (cu. ft.)

[1]S = structural factor which is the ratio of the volume of air space to the volume of soil.
d = apparent dry density of soil - lbs./cu.ft.

temperature below the freezing point of water when the heat pump is operating on the heating cycle. This results in a frozen cylinder of soil around the pipe. Ingersoll and others (7) conclude that the frozen moist soil increases slightly the efficiency of heating cycle operation. Thus moisture movement in the direction of the lower temperature, while an advantage on the heating cycle, is a disadvantage on the cooling cycle.

A recent analysis of available information by Parkerson (13) suggests a theoretical approach to the problem of heat transfer in soils. His analysis proposes evaluation of thermal conductivity of the soil by combining the values of thermal conductivity for the components, modified by the fractions of void and solid in the soil mass. This method would appear to be valid for evaluating the thermal properties of soil when it acts as a heat source. Once the apparent dry density of an undisturbed sample of soil is determined, the other soil characteristics will follow from Table 2.

It is not claimed that this theoretical analysis approaches reality. However, a correlation of the various soil characteristics essential to ground coil design is demonstrated.

THE INVESTIGATION

This investigation was initiated for the purpose of studying the heat transfer characteristics of different soils under various laboratory controlled conditions.

From observation, it appears that because of the drying effect near the heat exchanger, when the heat pump system is operating on the cooling cycle, it is likely that the amount of tubing necessary in a given installation will be determined by the amount of heat which must be dissipated to the soil. Whether this is true or not will depend on the ratio of heating to cooling requirements. Nevertheless, this investigation was planned to study the dissipation of heat to soil from a cylindrical heater, simulating the condenser of a heat pump system.

A consideration of heat transfer characteristics of soil brings to question its thermal properties and in particular a consideration of thermal conductivity.

Unlike most solids, soil is a porous substance varying in both density and moisture. Not only are its thermal properties affected by density and moisture but each type of soil is essentially a different material with a different grain structure. This makes the study of the thermal properties of soils in reality a study of many different materials.

The thermal conductivity of a porous substance is a function of the moisture content, usually increasing with increasing moisture content. When a temperature differential is applied across a specimen of a porous material, a moisture movement occurs from the high temperature side to the low temperature side, resulting in a varying conductivity through the section. Even if it were possible to determine accurately the thermal conductivity of a porous substance at a given moisture content, the use of such a value for design purposes would be questionable because of the moisture migration (mass transfer) resulting from the application of a temperature differential. Thus it appears that knowledge of thermal conductivity, without knowledge of soil type, density, and moisture content, is of little value in heat transfer computations.

The problem necessitating this project was twofold: First, to develop a method of determining the heat transfer characteristics of a material in the presence of various amounts of moisture; second, to establish a method of classifying soils according to their heat transfer characteristics.

It was recognized that field testing could not be very accurate because of the uncontrollable factors involved. These factors include density, moisture, and the surrounding temperature field. Any data obtained in the field would be difficult to analyze and conclusions drawn from these data, without verification by experiments conducted under controlled conditions, would be questionable. For this reason laboratory testing was chosen in preference to field testing.

LAYOUT OF TEST EQUIPMENT

Thermal Conductivity

Test Apparatus. The laboratory test system as completed is shown in Fig. 1 of Plate I. The large drum near the center of the picture is the soil chamber into which the soil specimen is compacted and prepared for the test. The soil specimen is packed into the test chamber around a centrally located electric heating element. A photograph of the heating element is shown in Fig. 2 of Plate I. This element is made up in three sections as shown schematically in Fig. 3.

Each of these three sections has a specific purpose. The center section, six inches long, is called the test section and is the key part of the system. The two end sections, each twelve inches long, are called end guards. The purpose of the end guards is to eliminate end losses so that all heat leaving the test section must pass radially through the sample and into the surrounding water jacket. During a test, all sections are maintained at a constant pre-selected temperature as is the surrounding water jacket. The quantity of heat passing through the test section of the soil specimen is determined by measuring the electrical energy supplied to the test section of the heating element.

To assist the end guards in maintaining radial heat flow in the test section, a disc of foamglas insulation, three inches thick, is located at the top and bottom of the soil chamber. The bottom disc is supported to prevent destruction of the foamglas when the soil specimen is compacted. These discs have brackets for centering the heating element in the test chamber. Figure 4 is a schematic diagram of the test system.

EXPLANATION OF PLATE I

Fig. 1. Laboratory test apparatus for thermal conductivity tests.

A. Soil test chamber.

B. Hammer and anvil for compacting soil.

C. Refrigeration unit for cooling water to be circulated through water jacket.

D. Recording potentiometer.

Fig. 2. Photograph of cylindrical heating element used in thermal conductivity tests.

PLATE I

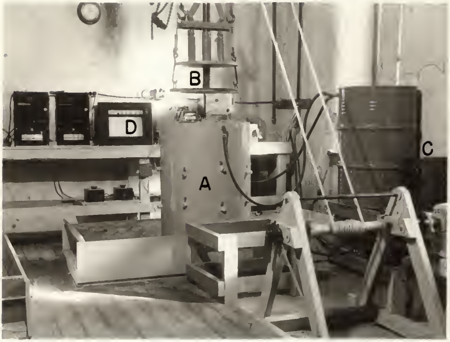

Fig. 1

Fig. 2

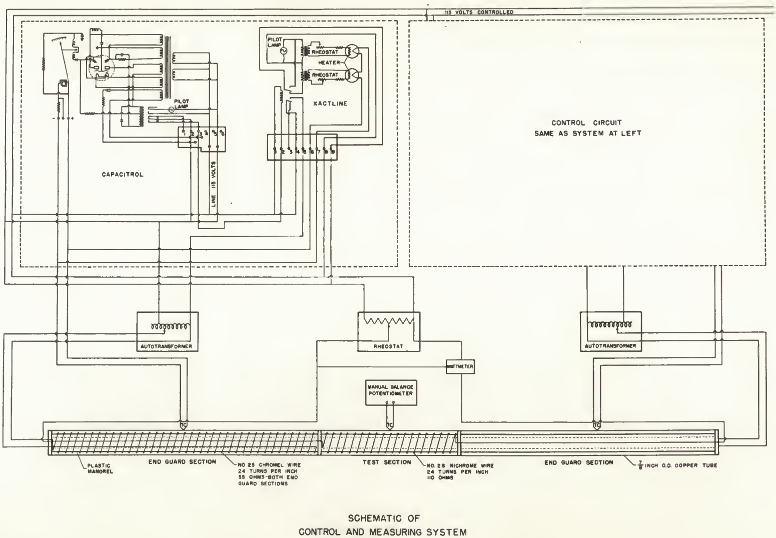

Figure 3. Schematic diagram of heating element and control system.

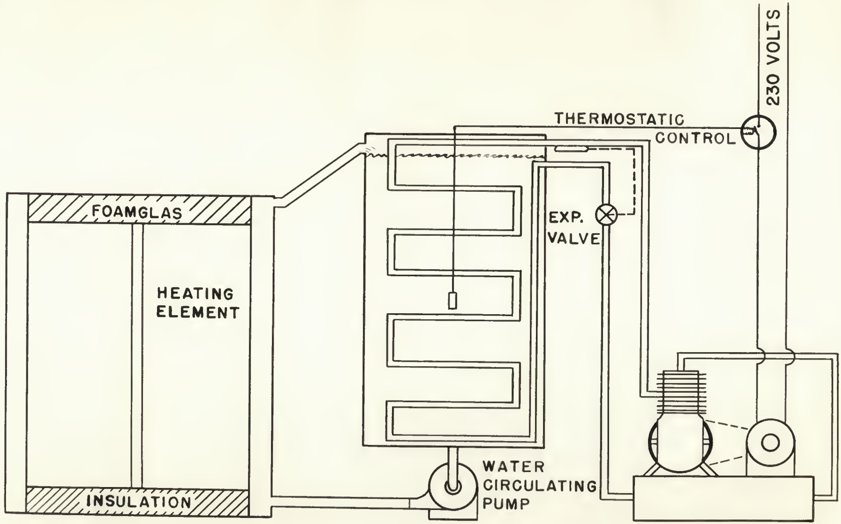

Figure 4. SCHEMATIC OF
TEST CHAMBER AND REFRIGERATION SYSTEM

The soil is packed into the test chamber with the hammer and anvil depicted in Fig. 1 of Plate I. Soil is compacted into the test chamber in layers. Each layer is compacted by placing the lower steel plate (anvil) on the soil mass and dropping the upper steel plate (hammer) until the desired compaction is obtained.

No reliable indirect method of measuring soil moisture during testing was found. Therefore, a method was developed which allowed taking of a soil core from the test specimen from which the moisture distribution could be determined gravimetrically. The detailed drawing of the test chamber in Fig. 5 shows the provisions made for allowing a soil core to be taken from the test specimen. It will be noted from Fig. 5 that the soil core is not actually taken from the test section. This procedure is justified since observations of the temperature field indicate essentially radial heat flow, from the heating element, as far as six inches above and below the test section. Soil cores removed at this distance from the test section do not affect the heat flow through the test section.

The soil core is taken with a soil sampling tube. The soil sampling tube consists of a thin wall seamless steel tube with a sharp leading edge, a close fitting rubber piston, and a piston rod. The sampling tube is placed in a guide, which is screwed to one inch pipe threads provided at the sample hole. As penetration is made by the sampling tube a partial vacuum is created on the core by the rubber piston which is held fast by a set screw on the outer end of the guide. Thus the soil core can be withdrawn from the test specimen. After the core is removed it is pressed from the sampling tube, divided into sections, and placed in cans for moisture determination.

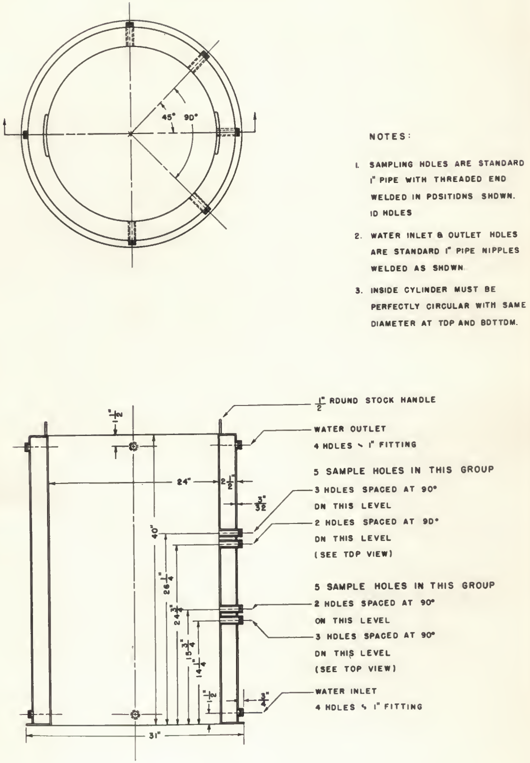

Figure 5. TEST CHAMBER

In pressing the soil from the sampling tube it is almost invariably compressed slightly. Therefore, linear measurements proved to be an unsatisfactory method of determining points where moisture measurements had been made. A method of point location by percentage of total dry weight proved to be more acceptable.

Instrumentation. The schematic diagram of Fig. 3 shows the control system for the heating element. The temperature of each end guard is maintained at a pre-selected value by one of two identical on-off temperature controllers, each operating from a thermocouple. It was necessary to control the temperature of the test section in such a manner that the power input could be read at any instant. Since no automatic control was found which would satisfy this requirement it was necessary to resort to a manual control. The temperature of the test section was therefore controlled by a manually adjustable rheostat. The adjustable autotransformers connected to the on-off controllers assist in maintaining an accurate temperature control on the end guards.

In addition to the instrumentation shown in Fig. 3, a 16-point multipoint temperature recorder is provided to record the temperature distribution in the soil specimen. This distribution is determined by 14 copper-constantan thermocouples placed in the test section. The thermocouples are located on a radial line in a horizontal plane passing through the center of the test section and extending from the heating element surface to the water jacket surface. The spacing of these thermocouples in inches from the heating element surface is 0", ¼", ½", 3/4", 1 1/4", 1 3/4", 2 3/4", 3 3/4",5½", 6 3/4", 8¼", 9 3/4", 11", and 11 9/16".

Five thermocouples are attached to the heating element surface. Two are located at the mid-point of each end guard section and one at the center of the test section as stated above. One thermocouple on each end guard is used for operating the control units as shown in Fig. 3. The second is connected to the temperature recorder to provide a check on the accuracy of the control.

The wattmeter shown symbolically in Fig. 3 represents one of two wattmeters used in the tests. One is a recording wattmeter with a 0-100 watt scale, with an accuracy of plus or minus one watt. The accuracy of this wattmeter was unsatisfactory when the power input dropped below 25 watts. Its use was limited to the "starting up" period of the test when the heat flow was high and a continuous record of the power input was required. As the test run progresses, the power input decreases and often drops below 25 watts. At this point, an indicating wattmeter, with an accuracy of plus or minus two-tenths of one watt, is switched into the circuit to replace the less accurate recording meter.

Specific Heat

The test apparatus used for specific heat determinations on soil is shown in Fig. 6 of Plate II. The method used for this determination is known as the method of mixtures. The principal parts of the system are soil flask, vacuum jacketed calorimeter, steam jacket, steam generator, vessel for boiling water, stop watch, and thermometer.

Figure 7 of Plate II is a close-up of the soil flask used. It is approximately four inches in height and one inch in diameter. This container was used to prevent the soil from coming in direct contact with the water used in

EXPLANATION OF PLATE II

Fig. 6. Test apparatus for specific heat determination.

A. Soil flask.

B. Calorimeter cylinder.

C. Vacuum jacketed calorimeter.

D. Steam jacket.

E. Steam generator.

F. Vessel for boiling water.

Fig. 7. Close-up of soil flask used for specific heat determination.

PLATE II

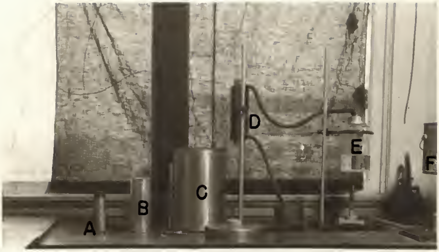

Fig. 6

Fig. 7

the calorimeter. This arrangement eliminated the necessity of determining the heat of wetting of the soil which is a major problem itself. The grid work shown inside the container was employed to assist the flow of heat from the soil to the water in which it was immersed. The expandable rubber stopper was provided so that pressure, built up in the sample during testing, would not force the cover off.

TEST PROCEDURE

Thermal Conductivity

After a soil was selected for testing, the following determinations were made for purposes of classification:

Mechanical analysis	Plastic limit
Specific gravity	Plastic index
Liquid limit	Optimum moisture
Specific heat	

It was believed that these properties, which are easily measured, could be correlated with the heat transfer characteristics of soils.

With the desired dry density and moisture content selected for the test, the soil was prepared and compacted into the soil chamber. Preparation consisted of mixing the soil to the desired moisture content and running it through a $\frac{1}{4}$ inch screen. Compaction was effected in layers, each about two inches thick. The desired density was obtained by placing the weight of soil in each layer which upon compacting to a two inch thick layer gave the pre-selected weight per unit volume. Compacting was effected by the hammer and anvil system. The anvil was placed on the soil mass and successive dropping of the hammer compacted the soil into a layer of the desired thickness.

During the filling of the soil chamber the thermocouples were carefully placed in the soil at the center of the test section. After the soil chamber had been filled to within approximately four inches of the top, the upper disc of foamglas insulation was put in place.

After the soil specimen had been placed in the test chamber, the entire soil mass temperature was reduced to 60 or 70 degrees F. depending on the heat sink temperature chosen for the test. This soil temperature was effected by circulating water through the water jacket. To obtain uniform temperature throughout the soil specimen two or three days were usually required. With this accomplished, testing could begin.

First the temperature controllers were set at the selected temperature. This temperature varied from 100 to 140 degrees F. depending on the test. Voltage was then applied to all three sections of the heating element. As the temperature of each end guard was raised automatically the temperature of the test section was raised at the same rate, manually. Usually about three minutes were required to reach the selected temperature. At the same time the voltage was applied, the temperature recorder and the recording wattmeter were started. Thus a continuous record of test results was obtained.

For the first 12 to 24 hours of the test, it was necessary to make frequent manual adjustments of power supplied to the test section. From then until an equilibrium condition was reached very little adjustment was required. The time required to reach equilibrium varied from 72 to 144 hours depending on the soil and its condition. When the wattage input to the test section dropped below 25 watts the recording wattmeter was replaced by the more accurate indicating wattmeter. Readings of power input and temperature distribution were taken at frequent intervals throughout the test run.

Method of Calculating Thermal Conductivity

For the steady state condition, the heat flow from a cylindrical heat source, with two finite boundaries, is represented by the following equation:

$$q = \frac{2\pi k\,(\Delta t)}{\ln\left(\frac{r_2}{r_1}\right)}$$

or

$$k = \frac{q\,\ln\left(\frac{r_2}{r_1}\right)}{2\pi\,(\Delta t)}$$

where q = heat flow - BTU/hr.ft.

k = thermal conductivity - (BTU)(ft.)/(hr.)(sq. ft.)(°F.)

Δt = temperature differential - °F.

r_1, r_2 = radial distance from centerline of cylindrical heat source to high temperature boundary and low temperature boundary, respectively.

ln = natural logarithm.

The test data included values for all functions in this equation except thermal conductivity. Thus evaluation of thermal conductivity was possible.

Since temperature varies as the logarithm of the radius in steady state cylindrical heat flow, a plot of these two functions on semilogarithmic paper, with the radius as the logarithmic function, results in a straight line when thermal conductivity is constant. Applying this to the test results, a curve was obtained which was found to deviate from a straight line close to the heating element surface. Therefore the thermal conductivity was approximated in the region near the heating element surface by taking small finite distances and the corresponding boundary temperatures from the semilogarithmic curve. Greater distances were used for thermal conductivity calculations in the straight line portion of the curve since thermal conductivity was constant in this region. Representative semilogarithmic curves used for thermal conductivity computations are shown in Figs. 9 and 11.

Specific Heat

For specific heat determination a representative sample of the soil to be tested was taken and prepared. The soil sample was then packed very carefully into the soil flask shown in Fig. 7 of Plate II. The weight of the flask, stopper, and its contents was then determined and recorded. This done, the soil flask was suspended in a vessel of boiling water.

A known weight of water (about 500 milliliters) was placed in the calorimeter cylinder. The calorimeter cylinder was then placed in the vacuum jacketed calorimeter and allowed to stand until the water had reached a constant temperature.

After the soil flask and its contents had reached the temperature of boiling water it was transferred quickly to the steam jacket. In the steam jacket the soil flask was dried and maintained at the temperature of boiling water. Barometer readings were taken during the test so that the exact boiling temperature of water was known.

These things accomplished, the soil flask and specimen were ready to be placed in the calorimeter. A stop watch was started and temperature readings of the water in the calorimeter were taken and recorded for five minutes prior to placing the soil flask in the water. At exactly the end of five minutes the soil flask was lowered from the steam jacket into the calorimeter. Temperature readings of the water were then taken and recorded at intervals of 30 seconds until the highest temperature had been reached and the temperature of the water began dropping off. Gentle stirring of the water, to prevent stratification, was effected throughout the test.

The specific heat values of all parts of the system except the soil specimen were known and their respective temperature changes during the test could be obtained from the test results. Thus the dry specific heat of the soil specimen was determined from the following formula:

$$W_f C_f (T_s - T_f) + W_s C_s (T_s - T_f) = W_c C_c (T_f - T_i) + W_w C_w (T_f - T_i)$$

where

T_s = temperature of boiling water or saturated steam at the time of the test.

T_f = final temperature of water in calorimeter at conclusion of test.

T_i = initial temperature of water in calorimeter at start of test.

W_f, W_s, W_c, W_w = respective weights of soil flask, soil specimen, calorimeter cylinder, and water in calorimeter cylinder.

C_f, C_s, C_c, C_w = respective specific heat values for soil flask, soil specimen, calorimeter cylinder, and water.

TEST RESULTS

Tests were conducted on two soils which will be designated as Soil A and Soil B throughout the discussion. The following properties will serve to identify the two soils studied:

Soil A.

Specific gravity------------------------------2.71

Mechanical analysis

Sand---------------50 percent
Silt---------------36 percent
Clay---------------14 percent

Dry specific heat----------------------------0.185 BTU/lb/°F.

Liquid limit----------------------------------26.3 percent

Plastic limit--------------------------------19.8 percent

Plastic index-------------------------------- 6.5 percent

Field capacity moisture----------------------44.8 percent

Soil B.

Specific gravity-----------------------------2.63

Mechanical analysis

Sand---------------98 percent
Silt--------------- 1 percent
Clay--------------- 1 percent

Dry specific heat----------------------------0.187 BTU/lb/°F.

Liquid limit---------------------------------Indeterminate

Plastic limit--------------------------------Non-plastic

Plastic index--------------------------------Non-plastic

Field capacity moisture----------------------20.4 percent

These two soils were chosen by physical appearance because they appeared to represent the two extremes in soil type, one a heavy clay and the other a fine sand. Soil A appeared to be a heavy clay although mechanical analysis later showed it to contain 50 percent sand. Nevertheless, it was a well graded soil with a tight structure and would suffice to represent the opposite of Soil B. Soil B appeared to be a fine sand as mechanical analysis later indicated. Soil A was a subsoil obtained during excavation for the Field House at Kansas State College, Manhattan, Kansas. Soil B was obtained at the sand pit in Manhattan, Kansas, where it was discarded as being too fine for use in concrete.

A total of 15 thermal conductivity tests was completed on the two soils at one density and one moisture content for each soil. Dry specific heat determinations were carried out on both soils and specific heat tests at several moisture contents were conducted on Soil B.

It was fully realized that such a limited study could not be expected to produce the necessary information to solve the problem of heat dissipation to soil. However, the tests were carefully planned and conducted, and it was hoped that the results of this study would lead to a shorter solution of the problem by future investigators.

Test Results on Soil A

Testing began on Soil A April 9, 1951 and was completed August 17, 1951.

A density of 128 lbs./cu. ft. was selected for the thermal conductivity tests on Soil A. It was assumed this density would approximate that in an actual ground coil installation since the soil would be compacted somewhat during installation. An initial moisture content of 19 percent on a dry basis was chosen as a conservative value for this soil.

Seven thermal conductivity tests were carried out on Soil A at this density and moisture content. In each test a different temperature differential was applied across the soil specimen. A series of three tests was conducted with the temperature of the water jacket or heat sink at 60° F. The heating element or heat source temperatures were 100, 120, and 140° F. respectively for these three tests. The sink temperature was then raised to 70° F. and a series of four tests were run at heating element temperatures of 100, 110, 120, and 140° F. Temperatures of 100, 110, 120, and 140° F. were chosen as heating element temperatures because it was observed that condenser temperatures most commonly used with the heat pump system were included in this interval. Water jacket temperatures of 60 and 70° F. were selected because the undisturbed earth temperature usually falls in this range. The test results on Soil A are given in the upper part of Table 3.

The curves in Fig. 8 are the final test results for one of the thermal conductivity tests on Soil A. These curves are representative of the other tests on Soil A and will serve to illustrate the conditions existing at the conclusion of each test. The upper curve in Fig. 8 shows the temperature distribution; the center curve, the moisture distribution; and the lower curve shows the variation of thermal conductivity with distance from the heating element.

The curve in Fig. 9 is a plot of temperature versus distance from the centerline of the heating element (heat exchanger) on semilogarithmic paper for the same test as described in Fig. 8. The straight line portion of the curve in Fig. 9 indicates a constant thermal conductivity in this region of the soil specimen since the heat flow is essentially constant.

A series of three dry specific heat tests were conducted on Soil A and an average of the three tests was taken as the dry specific heat of the soil. The average value obtained was 0.185 BTU/lb/°F.

Test Results on Soil B

Testing on Soil B began November 11, 1951, and was completed December 13, 1951.

Difficulties were encountered in obtaining a uniform moisture distribution throughout the test chamber with Soil B. Uniform moisture distribution was finally obtained at a moisture content of 2.7 percent (dry basis). Although this was a very low moisture content, it was reasoned that a fine sand such as Soil B would drain to a relatively low moisture over a period of time if no moisture was added.

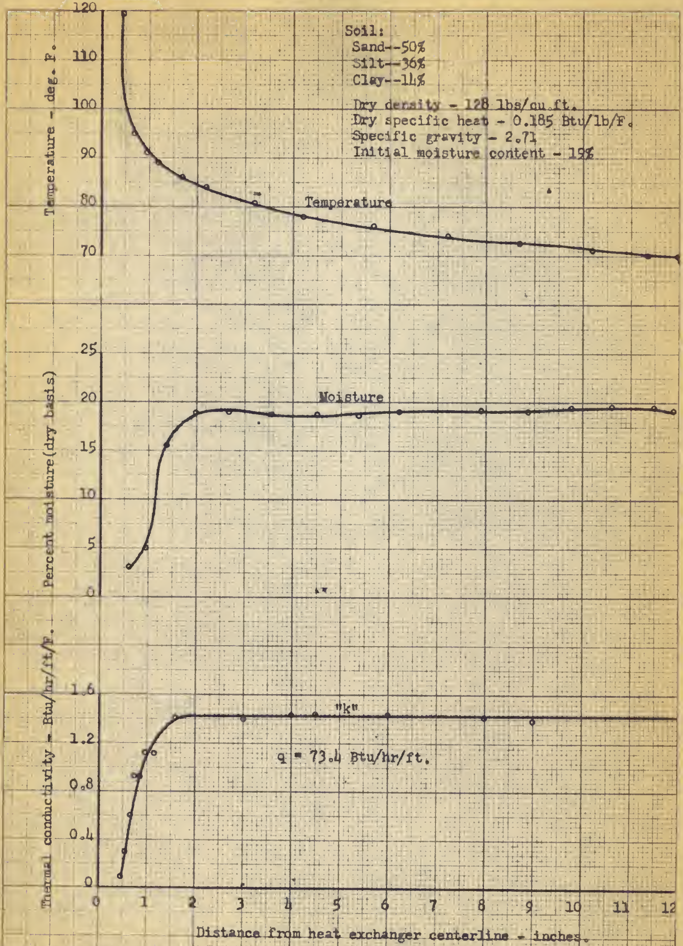

Figure 8. Temperature, moisture, and thermal conductivity vs. distance.

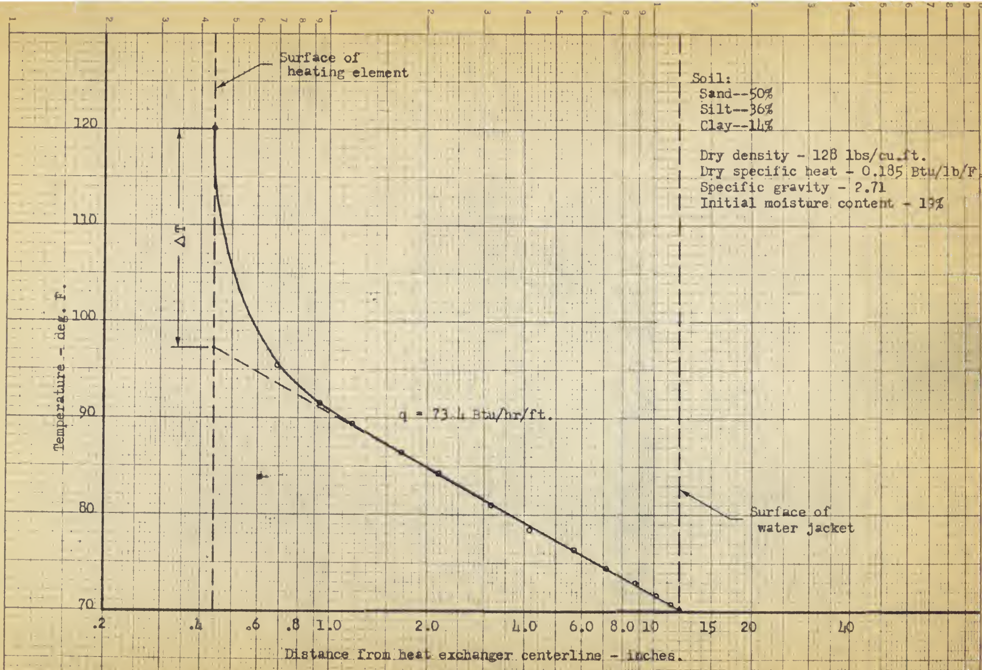

Figure 9. Temperature gradient in soil on semilogarithmic scale.

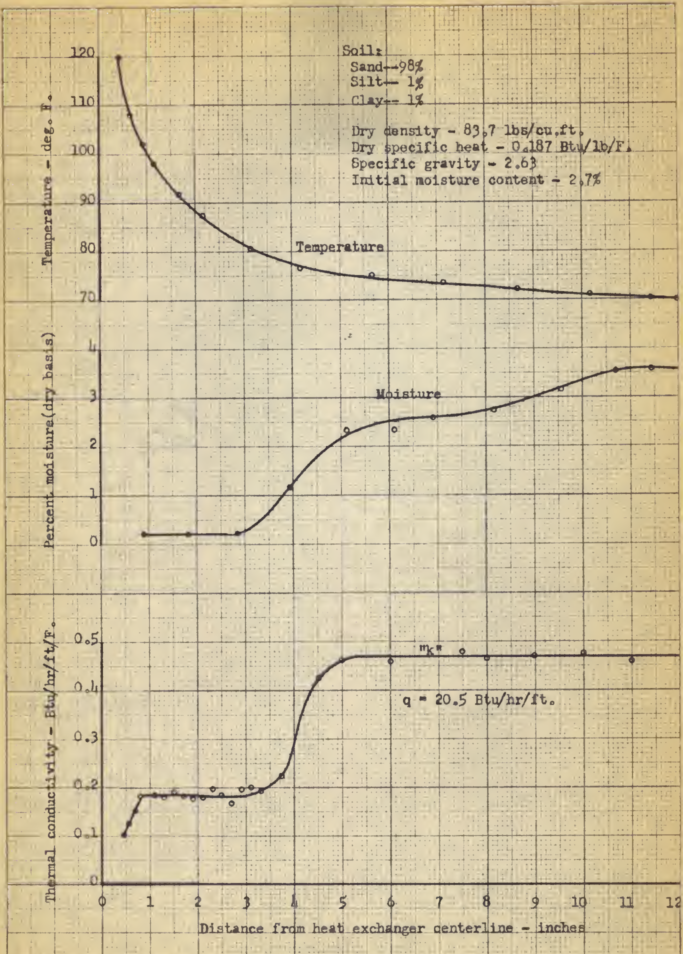

Figure 10. Temperature, moisture, and thermal conductivity vs. distance.

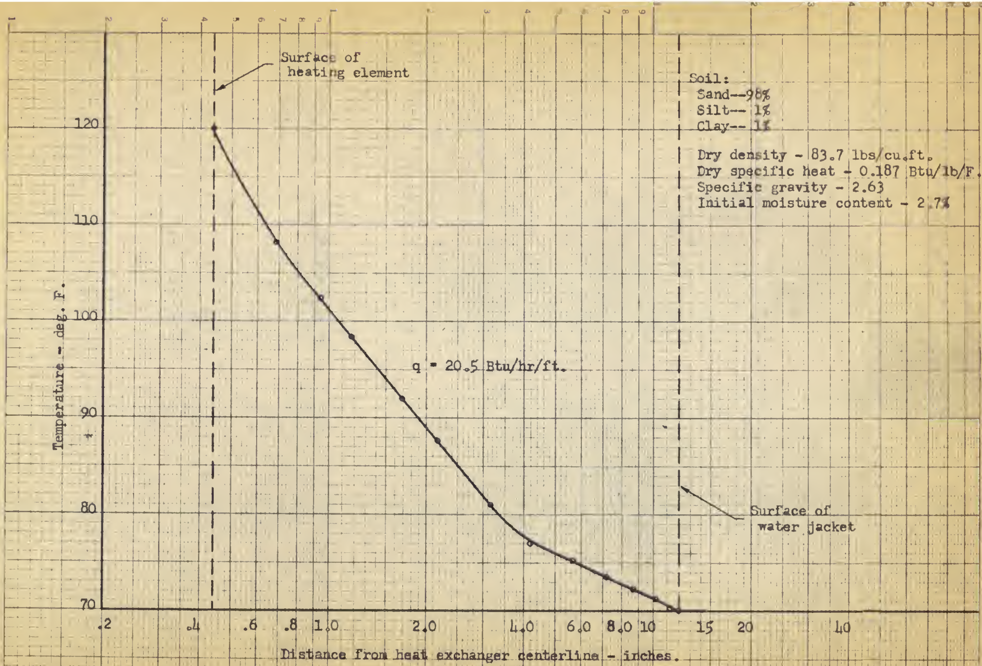

Figure 11. Temperature gradient in soil on semilogarithmic scale.

Since little compaction can be effected on a sand soil, Soil B was not compacted in the test chamber. Thus a density of 83.7 lbs. per cu. ft. was chosen since that was the resulting density when Soil B was poured into the test chamber.

Eight thermal conductivity tests were conducted on Soil B at this density and moisture content. Four tests were run with heating element temperatures of 100, 110, 120, and 140° F. and the water jacket temperature at 60° F. Then the water jacket temperature was raised to 70° F. and another series of four tests conducted at the same heating element temperatures. The test results for Soil B are given in the lower part of Table 3.

The curves in Figs. 10 and 11 show the conditions existing at the conclusion of one of the tests conducted on Soil B. These curves are also representative of the results obtained in the other tests on Soil B.

The curves of Fig. 12 show the variation of specific heat with moisture content for Soil B. The lower curve was plotted with experimental data obtained from specific heat tests conducted at various moisture contents. The upper curve is the result of theoretical computation using the fractional parts of water and soil based on the dry specific heat of soil determined experimentally for Soil B (0.187 BTU/lb/°F.).

DISCUSSION OF TEST RESULTS

Soil A

The curves of Figs. 8 and 9, representative of thermal conductivity tests conducted on Soil A, are the final test results for a test with 120° F. heating element temperature and 70° F. water jacket temperature.

In Fig. 8, it is interesting to note the similarity between the thermal

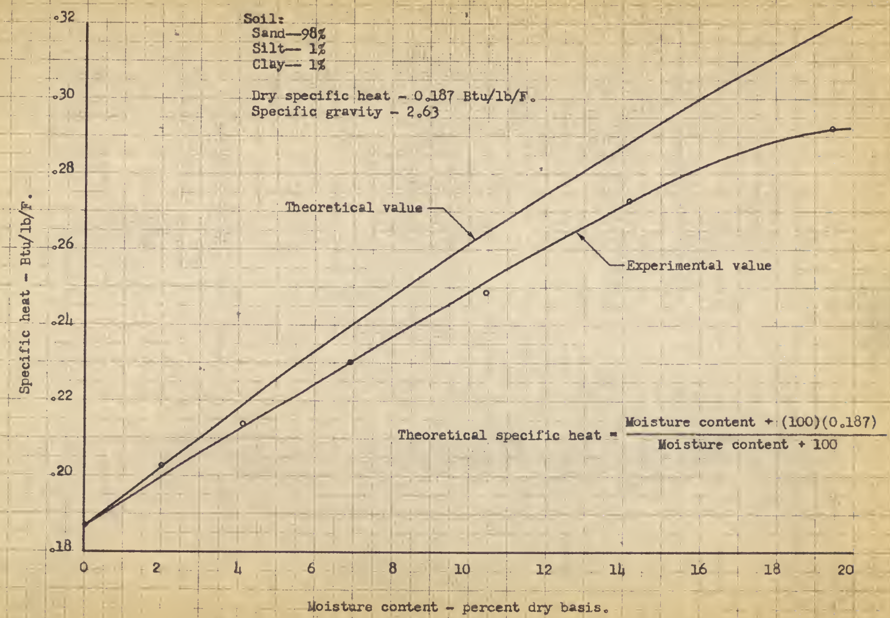

Figure 12. Variation of specific heat with moisture content.

Table 3. Summary of thermal conductivity tests.

Initial moisture	Dry density	Heating element temperature	Water jacket temperature	Heat flow	Thermal conductivity[1]
Percent dry basis	lbs. / cu. ft.	°F.	°F.	BTU / (hr)(ft)	(BTU)(ft) / (hr)(sq ft)(°F.)
		Soil A			
19	128	100	60	76.8	1.50
19	128	120	60	104.1	1.50
19	128	140	60	139.0	1.49
19	128	100	70	44.4	1.39
19	128	110	70	59.0	1.42
19	128	120	70	73.4	1.44
19	128	140	70	104.0	1.50
Average					1.46
		Soil B			
2.7	83.7	100	60	14.30	0.385
2.7	83.7	110	60	18.42	0.400
2.7	83.7	120	60	21.20	0.375
2.7	83.7	140	60	28.70	0.425
2.7	83.7	100	70	14.33	0.500
2.7	83.7	110	70	17.40	0.442
2.7	83.7	120	70	20.50	0.470
2.7	83.7	140	70	28.00	0.480
Average					0.435

[1]The values of thermal conductivity given were computed for that region of the soil adjacent to the low temperature boundary. Thermal conductivity was found to be constant in this region. This value appears to be the more desirable for classification purposes.

conductivity and moisture distribution curves. It will be observed that the thermal conductivity increases with increasing moisture content in the region near the heat exchanger and remains constant in the region where the moisture content is essentially constant. It appears from these data that the drying effect near the hot tube surface is a significant factor in the problem of heat dissipation to soil. However, an attempt to establish a definite relationship between moisture content and thermal conductivity in this region of the soil failed.

The semilogarithmic curve in Fig. 9 shows the temperature gradient across the soil specimen for the same thermal conductivity test as described in Fig. 8. It will be noted in Fig. 9 that the curve is essentially a straight line beyond 1.5 inches. The straight line portion of the curve indicates a constant thermal conductivity in that region. Apparently the curved portion of the temperature distribution line is associated with moisture movement near the heating element surface. The extent of this region increased slightly with increased heating element temperature in tests on Soil A.

By projecting the straight line portion of the curve in Fig. 9 to a point directly below the point representing the surface of the heating element (120° F.), an accelerated temperature change, (ΔT in Fig. 9) is observed. The data obtained from the thermal conductivity tests on Soil A showed this temperature change to vary directly with the heating element temperature as shown in Fig. 13. The curve in Fig. 13 also shows this relationship to be independent of the water jacket temperatures (60 and 70° F.) employed in these tests. This phenomenon appears to be worthy of consideration in solving the problem of heat transfer in soil.

Soil B

The curves of Figs. 10 and 11, representative of thermal conductivity tests conducted on Soil B, are the final test results for a test with 120° F. heating element temperature and 70° F. water jacket temperature.

As was found with Soil A, the thermal conductivity and moisture distribu-

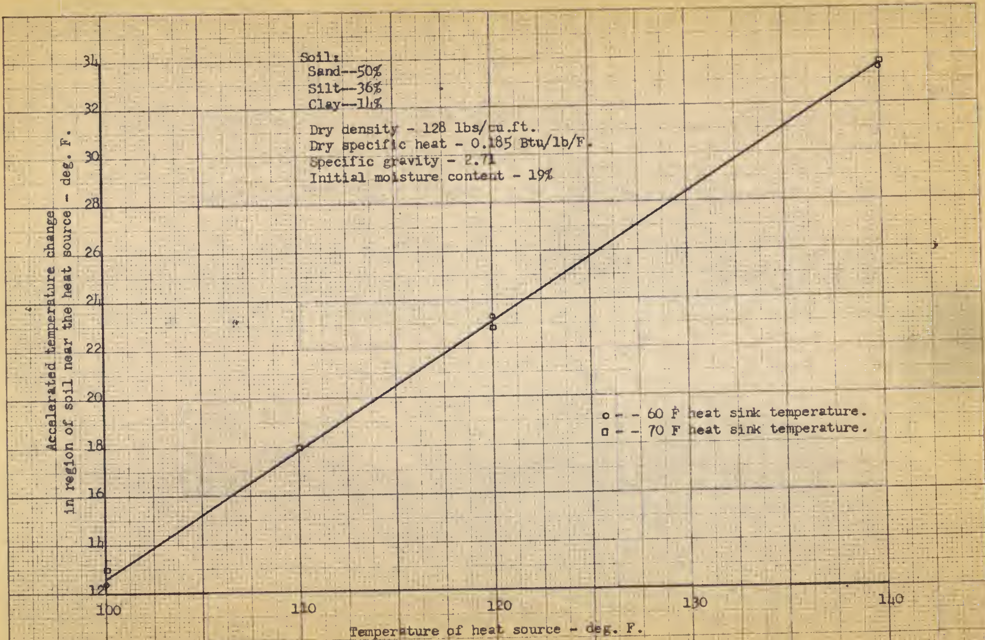

Figure 13. Relation of source temperature to the accelerated temperature change in region of soil near the heat source.

tion curves follow the same pattern. However, it will be noted that a concentration of moisture occurs in the last 1.5 inches near the water jacket surface. This concentration of moisture was probably due to the low moisture content of the soil which allowed free movement of the water in the direction of the lower temperature. Because of the extremely low moisture content close to the heating element surface it was impossible to obtain a soil sample from this region. Thus the initial change in thermal conductivity (.45 to .80 inch from pipe centerline in Fig. 10) could not be associated with a change in moisture content in this region of the soil.

It will be observed from the thermal conductivity curve of Fig. 10 that a constant value of thermal conductivity occurs in two sections of the soil. The thermal conductivity is constant from one inch to three inches from the heating element centerline and constant again from five to twelve inches. The semilogarithmic curve in Fig. 11, which shows the temperature gradient for the same test, reveals the reason for thermal conductivity being constant in two sections of the soil. The temperature gradient curve has two distinct straight line portions corresponding to the two regions of the soil having constant thermal conductivity. Of course, when the temperature gradient plots a straight line on semilogarithmic scale, a constant thermal conductivity is indicated.

The reason for this temperature gradient in Soil B cannot be fully explained. However, the moisture distribution in the soil was apparently responsible, at least in part, for this occurrence.

The tests on Soil B showed the relationship of source temperature to the accelerated temperature change in the region near the heat source to hold true for source temperatures of 100, 110, and 120° F.

The experimental results obtained from specific heat tests on Soil B differed from specific heat values calculated for the same water and soil mixtures. The curves in Fig. 12 show how the deviation of the experimental results from theoretical computations increased with increased moisture content. A careful study of the test procedure and equipment failed to reveal any reason for error in conducting the specific heat determinations and it did not seem likely that a mixture of Soil B and water could react in any way to change the specific heat of the mixture from that of a combination of the two components treated as separate materials. Nevertheless a decided difference was found between theoretical values of specific heat and experimental results for mixtures of Soil B and water.

SUMMARY

Although it was not possible to draw definite conclusions from the meager data obtained, the following observations were made:

1. The test equipment provides an excellent means of measuring thermal conductivity of soil under various conditions of moisture and density. With this method moisture movement is taken into consideration and therefore it is possible to determine the actual thermal conductivity at any point in the soil specimen.

2. On the basis of the tests completed it may be stated that continuous heat flow to soil from a cylindrical heat source reaches essentially a steady state condition after a relatively short period of time.

3. It appears that moisture movement in soil, away from a cylindrical heat source, is one of the most important factors governing the rate of heat transfer.

4. In tests completed, no direct relationship between moisture content and thermal conductivity was established in the region near a cylindrical heat source buried in soil. However, thermal conductivity was found to increase with an increase in moisture content in this region.

5. In tests on Soil A, a direct relationship was found between source temperature and the accelerated temperature change in the region of the soil near the cylindrical heat source. The tests on Soil A also showed this relationship to be independent of the two sink temperature used (60 and 70° F.). Tests on Soil B showed this relationship to hold true for source temperatures of 100, 110, and 120° F. This phenomenon may be worthy of consideration in solving the problem of heat transfer in soil.

6. The specific heat test apparatus appeared to provide a satisfactory method of determining the specific heat of soil. The soil flask employed to eliminate the necessity of determining the heat of wetting of the soil performed very well.

7. The dry specific heat value for the two soils tested compared very closely. The values for Soil A and Soil B were found to be 0.185 and 0.187 BTU/lb/°F., respectively. This would seem to indicate that the dry specific heat of all soils does not vary greatly since the two soils tested were quite different in soil type.

8. Specific heat tests on Soil B at various moisture contents showed the experimental value to differ from the theoretical value, computed with the value of dry specific heat determined experimentally. The deviation between experimental and theoretical values increased with increased moisture content.

9. It appears that further investigation of the drying effect in soil,

near a cylindrical heat source, will be necessary in order to predict the performance of an earth imbedded heat exchanger of this type.

ACKNOWLEDGMENTS

The author wishes to express gratitude to W. C. Trent of the U. S. Department of Agriculture for his invaluable assistance and advice in directing this study, and to Professor F. C. Fenton, Assistant Professor R. I. Lipper, and P. L. Lyman, all of the Department of Agricultural Engineering, for their time and energy in helping to conduct this study, and to the U. S. Department of Agriculture and Kansas State College for the equipment and funds to make this investigation possible.

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A LABORATORY INVESTIGATION OF THE THERMAL PROPERTIES
OF SOIL IN RELATION TO GROUND COIL DESIGN
FOR THE HEAT PUMP

by

DONALD RAY KELLY

B. S., Kansas State College of Agriculture
and Applied Science, 1951

AN ABSTRACT OF A THESIS

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OF AGRICULTURE AND APPLIED SCIENCE

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INTRODUCTION

Heating and cooling residences with the heat pump has become satisfactory and economical in many sections of this country where there is a reasonably low electric energy rate and a satisfactory heat source and heat sink for the heat pump system.

Although many problems exist in the development of the heat pump for residential heating and cooling, the most urgent is the study of media to serve as a heat source and sink. At present, only two media have been successfully utilized for that purpose--water and air. Well water is a satisfactory medium in areas where it is available in sufficient quantity to allow its use for heat pumps. Air as a heat source for an economically operated system is limited to areas where the air temperature seldom drops below 20° F. Thus, a more universal medium which will serve as a satisfactory heat source and sink is needed.

The earth offers possibilities, as a third medium, and there is no doubt of its capacity to act as a heat source and sink for the heat pump system. There is, however, the problem of collecting heat from and delivering it to the soil.

Because of the complexity of soil composition and structure, it would be difficult to predetermine the size and nature of an earth imbedded heat exchanger which would be necessary to dissipate a given quantity of heat to or absorb it from the different soils. The problem is further complicated by variations in compaction and moisture content of the different soils under field conditions.

There is a regrettably small amount of information available on the heat transfer characteristics of soils. Even such information as is available usually is the result of field studies conducted in a specific locality and the use of such data for design purposes in other areas would be questionable.

Heat transfer in soil is directly affected by moisture, density, thermal conductivity, and specific heat.

THE INVESTIGATION

This investigation was initiated for the purpose of studying the heat transfer characteristics of different soils under various laboratory controlled conditions. It was recognized that field testing could not be very accurate because of the uncontrollable factors involved. Data obtained in the field would be difficult to analyze and conclusions drawn from these data, without verification by experiments conducted under controlled conditions, would be questionable. For this reason laboratory testing was chosen in preference to field testing.

From observation, it appears that because of the drying effect near the heat exchanger, when the heat pump is operating on the cooling cycle, it is likely that the amount of tubing necessary in a given installation will be determined by the amount of heat which must be dissipated to the soil. Whether this is true or not will depend on the ratio of heating to cooling requirements. Nevertheless, this investigation was planned to study the dissipation of heat to soil from a cylindrical heater, simulating the condenser of a heat pump system.

TEST EQUIPMENT

Thermal Conductivity

For thermal conductivity tests the soil specimen was compacted around a cylindrical heating element, 7/8 inch in diameter, located at the axis of a cylindrical soil chamber, 40 inches in height and 24 inches in diameter. The heating element is made up in three sections. The center section, six inches long, is the test section. The two end sections, each twelve inches long, serve as end guards to eliminate end losses so that all heat leaving the test section must pass radially through the soil and into a water jacket surrounding the test chamber.

During testing, all sections of the heating element were maintained at a constant pre-selected temperature as was the surrounding water jacket. The test section of the heating element was maintained at a constant temperature by adjusting manually the electrical energy supplied to it. The two end sections had on-off temperature controllers operating from a thermocouple to maintain them at a constant temperature. The water jacket was held at constant temperature by circulating water, cooled by a refrigeration unit, through it. The quantity of heat passing through the test section of the soil was determined by measuring the electrical energy supplied to the test section of the heating element. The soil specimen was sealed in the test chamber by discs of foamglas insulation, three inches thick, located at the top and bottom.

Soil cores were taken from the soil specimen during testing to determine moisture distribution. The soil core was taken with a sampling tube through holes provided in the test chamber. Temperature distribution in the soil specimen was measured with 14 copper-constantan thermocouples located on a radial line in a horizontal plane extending from the heating element surface to the surface of the water jacket.

Specific Heat

The method used for specific heat determination is known as the method of mixtures. The principal parts of the system are soil flask, vacuum jacketed calorimeter, steam jacket, steam generator, vessel for boiling water, stop watch, and thermometer.

The soil flask, a small cylindrical container about four inches in height and one inch in diameter, was employed to prevent the soil from coming in direct contact with the water in the calorimeter. This arrangement eliminated the necessity of calculating the heat of wetting of the soil.

TEST PROCEDURE

Thermal Conductivity

After the soil was selected for testing it was mixed to the desired moisture content and compacted into the soil chamber to the desired density. The thermocouples were placed in the test section during the placing of the soil in the test chamber. After the soil had been sealed in the test chamber, the soil mass was then reduced to a temperature of 60 or 70° F., depending on the heat sink temperature chosen for testing. This soil temperature was effected by circulating water through the water jacket. With this accomplished, testing could begin.

First, voltage was applied to the three sections of the heating element and adjustments made to obtain the desired temperature. This temperature varied from 100 to 140° F., depending on the test. At the same time the voltage was applied, a recording potentiometer and a recording wattmeter were started so that a continuous record of the test was obtained. Later, after an equilibrium condition was approached, a manual potentiometer and indicating wattmeter were employed to obtain more accurate readings. The time required to reach equilibrium varied from 72 to 144 hours depending on the soil and its condition.

After a steady state condition of heat flow was reached, the equation for steady heat flow from a cylindrical heat source was used to compute thermal conductivity of the soil. Since the temperature distribution throughout the soil was recorded, it was possible to calculate the actual thermal conductivity at any point in the soil.

Specific Heat

For specific heat determinations a representative sample of soil was taken and prepared for testing. It was then packed very carefully in the soil flask and its exact weight determined.

The soil flask and its contents were heated in boiling water and then placed in the steam jacket to dry and retain the temperature of boiling water. After the soil flask had reached the desired temperature it was lowered into a known quantity of water in the calorimeter. Temperature readings were then taken at regular intervals until the system reached an equilibrium temperature.

The specific heat value for all parts of the system, except the soil sample, were known and the temperature change and respective weights were available from the test data. Thus, the specific heat of the soil sample could be computed.

TEST RESULTS

Tests were conducted on two soils which will be designated as Soil A and Soil B throughout the discussion. The following properties will serve to identify the two soils studied:

Soil A.

Specific gravity----------------------------2.71

Dry specific heat---------------------------0.185 BTU/lb/°F.

Mechanical analysis

Sand---------------50 percent
Silt---------------36 percent
Clay---------------14 percent

Soil B.

Specific gravity----------------------------2.63

Dry specific heat---------------------------0.187 BTU/lb/°F.

Mechanical analysis

Sand---------------98 percent
Silt--------------- 1 percent
Clay--------------- 1 percent

These two soils were chosen for testing because from physical appearance they appeared to represent the two extremes of soil type. One appeared to be a heavy clay and the other a fine sand.

A total of 15 thermal conductivity tests were conducted on the two soils at one density and one moisture content for each soil. Dry specific heat tests were carried out on both soils and specific heat tests were conducted at several moisture contents on Soil B.

Test Results on Soil A

A density of 128 lbs/cu. ft. and a moisture content of 19 percent (dry basis) were selected as conditions of the soil for thermal conductivity tests on Soil A.

Seven thermal conductivity tests were conducted on Soil A. A series of three tests was conducted with heating element (heat source) temperatures of

100, 120, and 140° F., all at a water jacket (heat sink) temperature of 60° F. The sink temperature was then raised to 70° F. and a series of four tests conducted at source temperatures of 100, 110, 120, and 140° F. The test results on Soil A are given in the upper part of Table 3.

The curves in Fig. 8 are representative of the final test results obtained for Soil A and will serve to illustrate the conditions existing at the conclusion of all tests on Soil A. The upper curve in Fig. 8 is the temperature distribution, the center curve, the moisture distribution, and the lower curve shows the variation of thermal conductivity with distance from the heating element.

It is interesting to note the similarity between the moisture distribution and thermal conductivity curves in Fig. 8. It will be observed that thermal conductivity increases with increasing moisture and remains constant in the region of the soil where the moisture is essentially constant. It appears from these curves that the drying effect near the heat source is an important factor influencing heat transfer in soil.

Figure 9 shows on semilogarithmic scale the temperature gradient in the soil at the conclusion of a thermal conductivity test on Soil A. This curve is for the same test as illustrated in Fig. 8 and is also representative of the other tests on Soil A. The straight line portion of the curve in Fig. 9 indicates constant thermal conductivity in that region of the soil. This curve demonstrates very clearly the effect of moisture movement near the heated surface as evidenced by the accelerated temperature change in that region of the soil. The test results for Soil A indicated a direct relationship between the accelerated temperature change (ΔT in Fig. 9) near the heated surface and the source temperature. The two different sink temperatures employed did not affect this relationship.

Test Results on Soil B

A density of 83.7 lbs/cu. ft. and a moisture content of 2.7 percent (dry basis) were chosen as conditions of the soil for thermal conductivity tests on Soil B.

Eight thermal conductivity tests were conducted on Soil B. A series of four tests was conducted with heating element (heat source) temperatures of 100, 110, 120, and 140° F., all at a water jacket (heat sink) temperature of 60° F. Another series of four tests was conducted at the same heat source temperatures but with a sink temperature of 70° F. The test results on Soil B are given in the lower part of Table 3.

The curves of Fig. 10 are representative of the test results on Soil B. It will be noticed, as with Soil A, that the moisture distribution and thermal conductivity curves follow the same pattern. An exception to this is found near the water jacket surface where the moisture content is higher. This is probably due to the low moisture content of the soil, thus allowing free movement of the moisture toward the low temperature side.

It will be noticed from the thermal conductivity curve in Fig. 10 that the thermal conductivity was constant in two different regions of the soil. This is also evident from the semilogarithmic curve in Fig. 11. This phenomenon is not fully understood but may be due to the moisture distribution in the soil. A direct relationship between source temperature and the accelerated temperature change in the region of the soil near the heated surface was found to hold true for source temperatures of 100, 110, and 120° F. for Soil B.

Table 3. Summary of thermal conductivity tests.

Initial moisture	Dry density	Heating element temperature	Water Jacket temperature	Heat flow	Thermal conductivity[1]
Percent dry basis	Lbs. / cu. ft.	°F.	°F.	BTU / (hr)(ft)	(BTU)(ft) / (hr)(sq ft)(°F.)
			Soil A		
19	128	100	60	76.8	1.50
19	128	120	60	104.1	1.50
19	128	140	60	139.0	1.49
19	128	100	70	44.4	1.39
19	128	110	70	59.0	1.42
19	128	120	70	73.4	1.44
19	128	140	70	104.0	1.50
Average					1.46
			Soil B		
2.7	83.7	100	60	14.30	0.385
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2.7	83.7	140	60	28.70	0.425
2.7	83.7	100	70	14.33	0.500
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2.7	83.7	120	70	20.50	0.470
2.7	83.7	140	70	28.00	0.480
Average					0.435

[1]The values of thermal conductivity given were computed for that region of the soil adjacent to the low temperature boundary. Thermal conductivity was found to be constant in this region. This value appears to be the more desirable for classification purposes.

The dry specific heat value for Soil B was found to be 0.187 BTU/lb/°F. Specific heat tests conducted at various moisture contents for Soil B gave values of specific heat of the mixture which differed from those computed theoretically, based on the dry specific heat determined experimentally.

The deviation is shown by the curves in Fig. 12.

SUMMARY

Although it was not possible to draw definite conclusions from the meager data obtained, the following observations were made:

1. The test equipment provides an excellent means of measuring thermal conductivity of soil under various conditions of moisture and density. With this method moisture movement is taken into consideration and therefore it is possible to determine the actual thermal conductivity at any point in the soil specimen.

2. On the basis of the tests completed it may be stated that continuous heat flow to soil from a cylindrical heat source reaches essentially a steady state condition after a relatively short period of time.

3. It appears that moisture movement in soil, away from a cylindrical heat source, is one of the most important factors governing the rate of heat transfer.

4. In tests completed, no direct relationship between moisture content and thermal conductivity was established in the region near a cylindrical heat source buried in soil. However, thermal conductivity was found to increase with an increase in moisture content in this region.

5. In tests on Soil A, a direct relationship was found between source temperature and the accelerated temperature change in the region of the soil near the cylindrical heat source. The tests on Soil A also showed this relationship to be independent of the two sink temperatures used (60 and 70° F.). Tests on Soil B showed this relationship to hold true for source temperatures of 100, 110, and 120° F. This phenomenon may be worthy of consideration in

solving the problem of heat transfer in soil.

6. The specific heat test apparatus appeared to provide a satisfactory method of determining the specific heat of soil. The soil flask employed to eliminate the necessity of determining the heat of wetting of the soil performed very well.

7. The dry specific heat value for the two soils tested compared very closely. The values for Soil A and Soil B were found to be 0.185 and 0.187 BTU/lb/°F., respectively. This would seem to indicate that the dry specific heat of all soils does not vary greatly since the two were quite different in soil type.

8. Specific heat tests on Soil B at various moisture contents showed the experimental value to differ from the theoretical value, computed with the value of dry specific heat determined experimentally. The deviation between experimental and theoretical values increased with increased moisture content.

9. It appears that further investigation of the drying effect in soil, near a cylindrical heat source, will be necessary in order to predict the performance of an earth imbedded heat exchanger of this type.

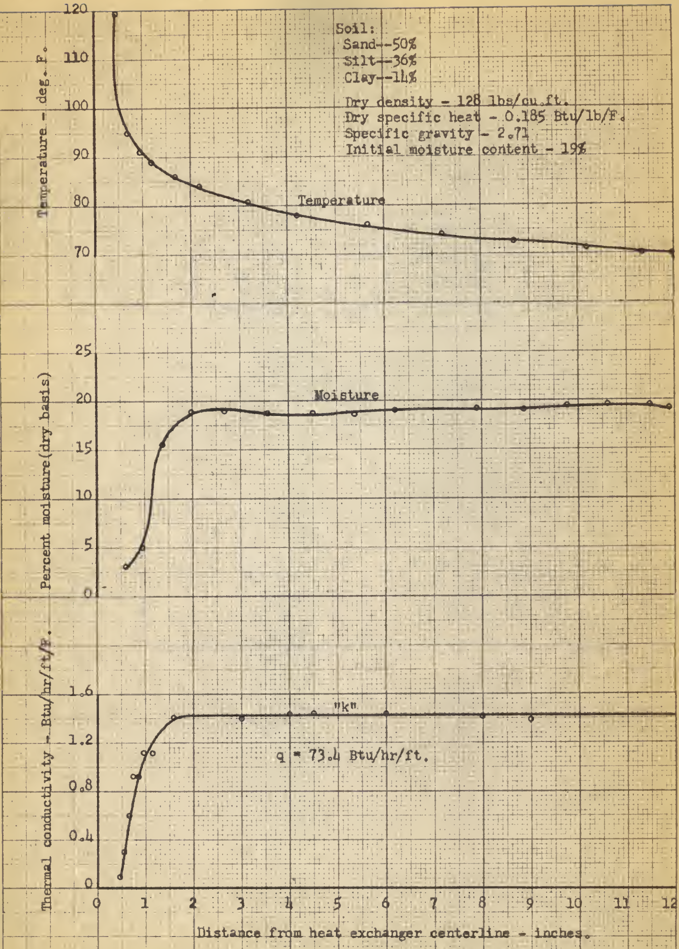

Figure 8. Temperature, moisture, and thermal conductivity vs. distance.

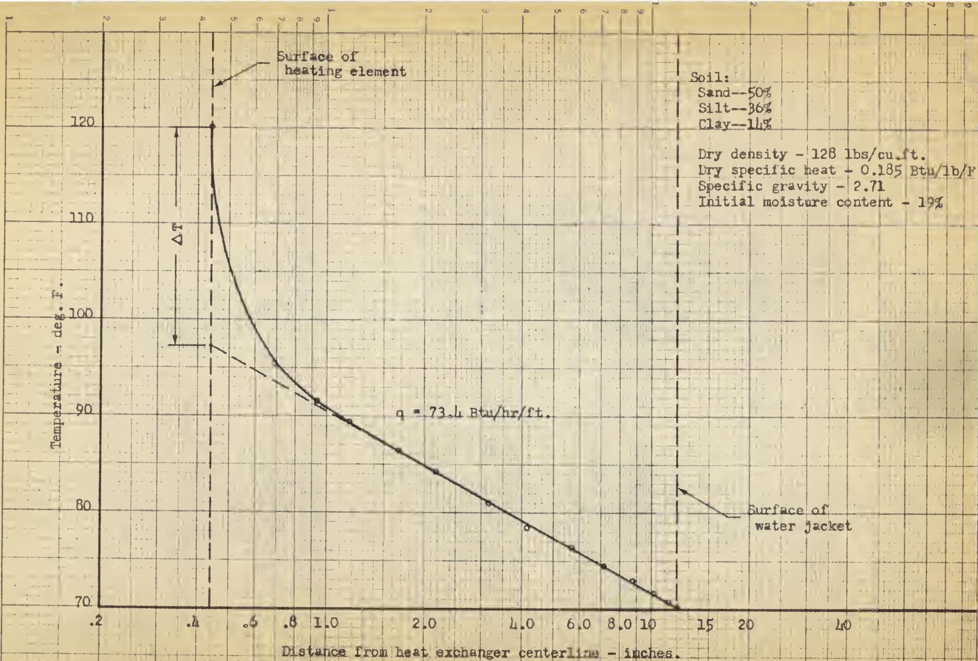

Figure 9. Temperature gradient in soil on semilogarithmic scale.

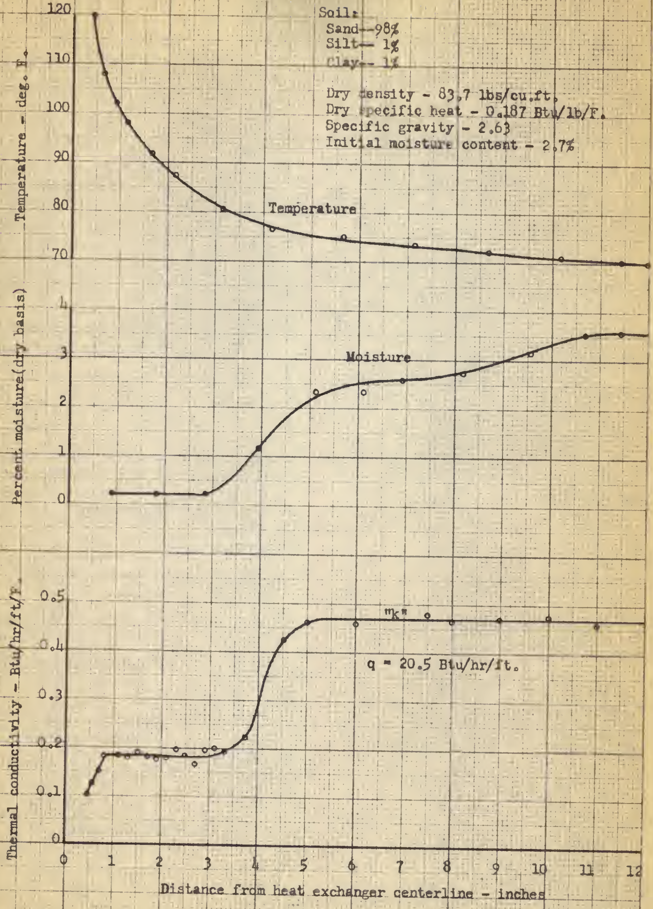

Figure 10. Temperature, moisture, and thermal conductivity vs. distance.

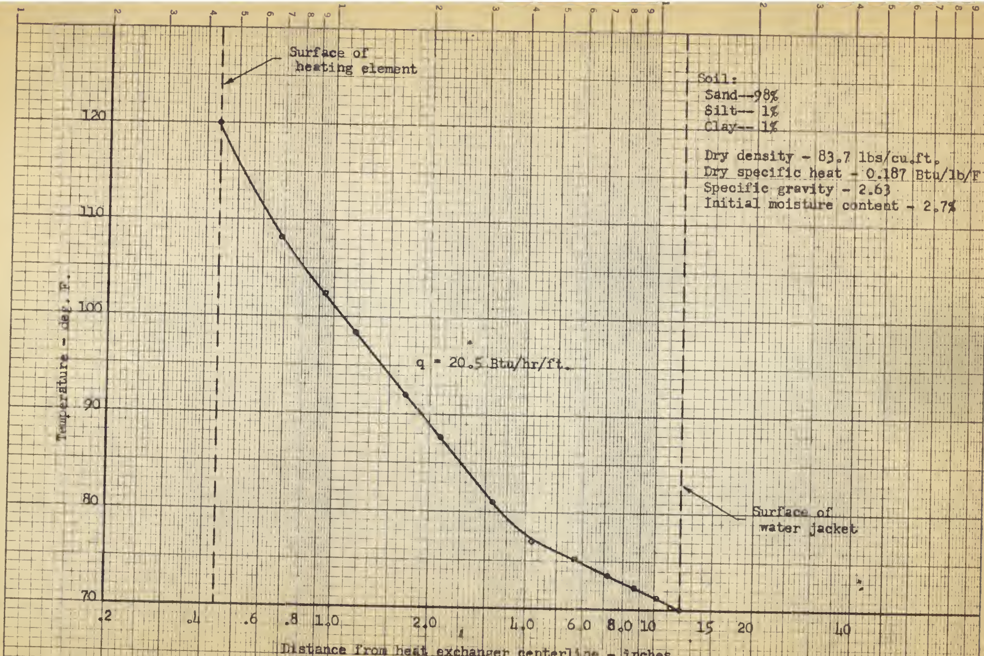

Figure 11. Temperature gradient in soil on semilogarithmic scale.

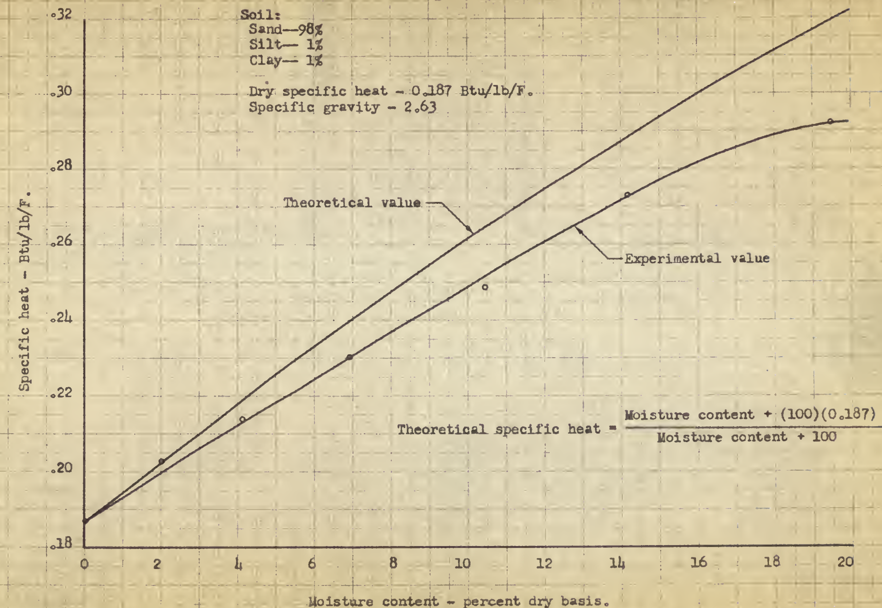

Figure 12. Variation of specific heat with moisture content.