THE ASSEMBLAGE AND CALIBRATION
OF
APPARATUS FOR THE DETERMINATION OF THERMAL CONDUCTIVITIES
OF
INSULATING MATERIALS

by

R. M. Johnston

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Approved:

Head of Major Department

Dean of Engineering

Director of Graduate Studies

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I. INTRODUCTION

Historical (2)

Technical information on heat flow is readily available to those interested in the subject in the form of tables and charts in modern handbooks and reference material. Of those whose interest in this field is of a purely practical nature, few have a true conception of the huge amount of research required for the compilation of the material so casually used.

As early as 1789, Ingen-Hausz was conducting experiments to determine the thermal conductivity of metal rods. His methods were necessarily crude for many reasons and were considerably improved by Biot, in 1816. Briefly, Ingen-Hausz attempted to establish points of equal temperature on several metal rods, all of different composition, by coating them with equal thicknesses of wax, applying heat simultaneously to the ends of the rods, and measuring the distances from the point of application of the heat to the point of solidity of the wax. In this manner, using one material of known conductivity, a simple ratio for the remainder of the rods was established.

Despretz, in 1822, derived the mathematical expression under the conditions established by Ingen-Hausz and Biot by using a single rod and measuring the temperatures at different points along the rod by thermocouples. Wiedemann and Franz, following the same principle as Despretz, improved upon the accuracy of this method.

Another method for determining the conductivity of cylindrical rods is that devised by Searle. It is a simple procedure and is extensively used in physics courses. The rod is heated at one end by means of a steam bath while the other end projects into a water cooled chamber. By measuring the temperature of the cooling water at the entry and exit of the cooling chamber, and observing the temperature at two points along the bar, the conductivity of the bar may be determined.

The use of cylinders evolved from the use of rods, and was probably first attempted by Niven and later by Clement and Egy. Briefly, this method consists of electrically heating along the axis of a cylinder while maintaining a constant temperature on the outer cylinder walls. When a steady state prevails the power input ot the heating section is determined. With the power input established and the cylinder dimensions and temperatures on inner and outer surfaces determined, the conductivity of the cylinder is easily calculated. This method, with compensation for end losses, has lately been used by Heilman as a quick and accurate method of determining the insulating value of commercial pipe covering.

Experimentation with cylinders led, naturally, to the use of plates; although the period of evolution was still controlled by accademic, rather than practical interest. With the turn of the century, however, engineers became aware of the significance of the phenomna of heat flow as directly applied to the design of buildings to resist the transmission of heat, boiler surfaces to promote this transmission, as well as many other applications.

With these applications in mind, it is not surprising to find that various kinds of "box" methods were advanced and used because it was believed that they simulated actual operating conditions more nearly than other methods. Many modifications have been proposed, but of these, the "guarded box" alone has survived because it is the only one which appears free from most of the objections that make the results obtained with other box methods unsatisfactory.

At the present time there are only two generally accepted methods for the determination of the thermal conductivities of solids. For homogenous materials, the use of a "hot plate" is generally recommended; while for sections composed of more than one material, such as built-up wall sections, the "guarded hot box" is considered superior, in many respects, to the hot plate.

Importance

The importance of a definite knowledge of the thermal conductivities of practically innumerable solids cannot be under-estimated. It is true that a practical application of this knowledge is, in almost all cases, complicated by many factors which lie without the scope of this thesis. It is also true that without reliable data pertinent to these conductivities many problems which the modern engineer solves with a fair degree of accuracy would, of necessity, still have to be approximated by some in-accurate, rule-of-thumb method as applied in the past.

This basic information is now used in a majority of engineering problems. It's importance, while intimately related with the field of heating and air conditioning, is far from being limited to this application. It is of primary importance in the design of condensers and feed-water heaters, as well as radiators and domestic hot water heaters. It is encountered in the design of all types of heat engines, in the selection of materials for electric light bulbs and radio tubes, and in the design of heating elements for the modern electric stove. It's application has made possible the development of high pressure boilers by virtue of the development high temperature without which maintainance costs would be prohibitive. It is also responsible for the development of the huge cold-storage plants in which fruits, meats and vegtables may be held prior to marketing, or stored for use in time of food shortage.

In view of these considerations, the problem of heat flow justly assumes a position of importance second to none in the engineering field; and there is no cause for wonder in the fact that engineering societies, through the National Research Council, have found it advisable to standardize test procedure and to codify practical test methods.

Object

This thesis presents the procedure which was followed in the design, construction, installation and calibration of a hot plate apparatus for the determination of the thermal conductivities of common insulating materials. No attempt is made to discuss heat flow through other materials, or that engendered by other means. Various types of hot plates, and different methods of application, however, are discussed in a latter part of this thesis.

Acknowledgements

The author wishes to express his appreciation for the active interest of Dean Earle B. Norris as exemplified by his pertinent advice and financial assistance through the V.P.I. Engineering Experiment Station; to the members of the Mechanical Engineering Department for their advice and useful suggestions; and for assistance in the form of correspondence and bulletins received from Prof. F. G. Hechler and Mr. E. R. Queer, of the Pennsylvania State College Engineering Experiment Station, and from Mr. R. H. Heilman, Industrial Fellow of the Mellon Institute.

II. REVIEW OF LITERATURE

Definitions and Formulas (3)

Definitions of terms dealing with the subject of heat transmission and the formulas contained herein are those adopted by the Committee on Heat Transmission, Division of Engineering and Industrial Research, of the National Research Council.

> "The Thermal Conductivity of a homogeneous material is the rate of heat flow, under steady conditions, per unit area, and per unit temperature gradient, in the direction perpendicular to the area.
>
> $$k = \frac{qL}{A(t_1 - t_2)}$$
>
> Thermal conductivity is usually expresses in English units as Btu per hour per square foot per degree Fahrenheit per inch. However, other units are also in the literature. ...
>
> The Thermal Conductance of a body per unit area of a specified isothermal surface is equal to the rate of heat flow through the body, per unit difference between the temperatures of the isothermal surfaces under consideration.
>
> $$C = \frac{q}{A(t_1 - t_2)}$$
>
> Thermal conductance is usually expressed in English units as Btu per hour per square foot

per degree Fahrenheit. ...

The Transmittance or "overall coefficient" of heat transfer per unit area is equal to the rate of heat flow divided by the difference in temperature between the air on the hot and cold surfaces of the material or wall construction in question.

$$U = \frac{q}{A(t_h - t_c)}$$

Where the above symbols have the following significance:

Q = total quantity of heat transferred

q = rate of heat flow = Q/time

A = actual area through which heat flows

t_1 = temperature of hot surface

t_2 = temperature of cold surface

t_h = temperature of air on hot side

t_c = temperature of air on cold side

L = length of path of heat flow (thickness)

C = conductance = $\frac{1}{R}$

R = resistance

U = transmittance or "overall coefficient" of heat transfer per unit area

Minimum Requirements for Homogeneous Materials (3)

Standard Method. The standard method of testing homogeneous insulating materials shall be by means of the guarded hot plate.

Heating Element. The heating elements in any type of apparatus used in testing shall be supplied with electrical energy at a rate held constant to within plus or minus one per cent. Where automatic regulation is not available the energy input shall be regulated by means of continuous manual adjustment.

Thermocouples. The thermocouples to be used in all forms of guarded hot plates shall be not larger than No. 25 Awg wire on 6 in. measuring areas and guard rings, but may be larger on larger areas, but shall never be larger than No. 20 Awg. The use of a potentiometer for all measurements of electromotive force is strongly recommended.

Location of Thermocouples. The guarded hot plate shall be equipped with at least two thermocouples on each face of the guard ring located at opposite sides of the measuring area, and at least two thermocouples on the face of the measuring area. If the conductance of the homogeneous material under test is 1.0 (Btu per hour per square foot per degree Fahrenheit) or less, the temperature of the plate is assumed to be the temperature of the surface of the specimen under test (extreme care should be exercised to secure even and continuous contact between the plate and specimen), and the couple should be attached directly to the plate with no intervening substances between the plate and the test specimen. If, however, the conductance of the specimen is greater than 1.0, the couples shall be cemented to the surfaces of thetest specimen itself, if necessary in shallow grooves of sufficient depth to accomodate fine wires, and greater care must be exercised to secure uniform thermal contact between plate and specimen.

The same arrangement of couples on the cold side of the specimen shall be followed as that given above for the hot plate.

Requirements of Plate. **For specimens of insulating material 1.5 in. thick or less, the minimum dimension of the measuring area of any type of hot plate shall be 6 in. in diameter, or 6 in. x 6 in.** square, so that the minimum distance from the center of the plate to the guard ring shall be 3 in. The minimum width of the guard ring on the above plate shall be 1.5 in. However, in testing certain materials the 4 in. x 4 in. guarded hot plate as designed and constructed by the U. S. Bureau of Standards may be employed.

Where it is necessary to conduct tests on specimens thicker than 1.5 in,, both the measuring area of the hot plates and their guard rings shall be proportionately increased. For example, if it is necessary to test the heat transmission of specimens 3 in. thick, the minimum sizes of the measuring area of the hot plate shall be 12 in. in diameter or a 12 in. x 12 in. square, with a guard ring at least 3 in. wide. ...

Test Procedure. In testing all forms of homogeneous insulating materials as true surfaces as possible of the material shall be obtained, by sanding or otherwise, in order that intimate contact between the hot and cold plates may be effected. The average distance between hot and cold plates with the specimen in place shall be used as the thickness of the specimen. In the case where the basis of calculating conductivity is the temperature indicated by thermocouples attached to the surfaces of the test specimen, account must be taken of the fact that the junctions of such thermocouples are slightly under either the effective surface (the plane envelope of the high spots) or the actual surface of the specimen. The calculation of temperature gradients in this case must be left to the judgment of the operator.

On the receipt of material for test the unit weight "as received" shall be recorded. The actual test specimen shall then be dried at 215°F. until all moisture is driven off, indicated by the usual constant weight procedure. If the material is one which may be chemically affected by heating to 215°F., drying in a dessicator shall be employed. The material shall also be weighed after the test is completed and the following physical characteristics reported:

1. Density (pounds per cubic foot)
    (a) "as received"
    (b) after drying
    (c) after test
2. Percent moisture

$$= \frac{\text{Weight as received} - \text{Weight dry}}{\text{Weight dry}} \times 100$$

3. Percent loss or gain during test

$$= \frac{\text{Weight dry} - \text{Weight after test}}{\text{Weight dry}} \times 100$$

In the case of a material being compressible, such as hair felt, the specimen shall be placed between two pieces of glass and sufficient pressure exerted so that intimate contact between the material and the glass is evident. The distance between the inner surfaces of the glass shall then be determined, and when subsequently the material is placed between the hot plate and the two cold plates this same distance between their respective faces shall be maintained. As noted above the average distance between hot and cold plates shall be used as the thickness of the specimen.

Four tests shall be conducted on each specimen in order that a curve may be drawn through the points obtained, showing the variation of conductivity with mean temperature of the specimen, and the 77°F. (25°C.) point from this curve is to be considered the standard temperature for purposes of comparison. It is recommended that the temperature gradient employed be not less than 40°F. per inch of thickness on specimens whose thickness is one inch or less, and that the above four mean temperatures of specimen shall differ from each other by at least 10°F. However, no individual observation shall depart from the best representative curve drawn through the points by more than 2 percent. If such variation does occur, the observation shall be discarded and another test shall be made at approximately the same temperature.

Hot Plates [5]

The apparatus to be described is practically identical with that in use at the U. S. Bureau of Standards for a number of years. It is the conclusion from the experience gained that an outfit accomodating specimens 12 in. square and less than 2 in. thick is sufficient for measuring the thermal conductivity of any insulating material. No particular advantage is gained by testing larger or thicker specimens. Even if the material varies greatly, it is more convenient to run several pairs of samples than to build a large apparatus, which is very cumbersome to handle, expensive to construct, and requires a long time to come to equilibrium when thick specimens are tested.

This apparatus consists of four copper plates suspended from a frame by means of small piano wires. The middle plates enclose an electric heating element. The heating grid, having a resistance of about twenty ohms, is built of 1/16 in. No. 36 constantan ribbon, wound diagonally on a sheet of fiber board, 11 in. square, so that the winding is distributed evenly over the entire surface. It is insulated with micanite sheets and placed between two 1/16 in. copper plates which are then held together tightly by means of a number of copper screws passing through holes in the fiber board. Each plate has a 3/32 in. saw-cut isolating an 8 in. square in the center. This arrangement tends to minimize the heat conduction between the center square and the outer or guard ring. The two outer cold-plates are identical in construction and consist merely of 1/8 in. copper plates with water or brine circulating tubes soldered to the backs.

Thermocouples are used to measure the difference in temperature between the hot and cold plates. A fine (No. 25 Awg) constantan wire is soldered directly to the center of the surface of each plate in contact with the insulating material, the outer plates serving as cold junctions and the two surfaces of the center plates as the corresponding hot junctions. The temperatures of the plates are sensibly the same as the temperatures of the surfaces of the test material in contact with them, provided the test material is not too good a conductor of heat. Each wire is led off from the center in a small groove cut in the surface of each plate. The copper leads to the measuring instrument are connected directly to the middle plates and to each of the outer plates. In this way, the copper plates themselves form the thermo-junctions with the constantan wires. Since there is no appreciable temperature gradient present in the heating plates, the junctions on those plates may be placed on the inside next to the heating grid. This eliminates the necessity of cutting grooves on the outside surfaces to accomodate the wires, but, on the other hand, the junctions are not conveniently accessible.

To compensate for heat loss from the edges of the heating plate, an auxiliary heating element consisting of ribbon similar to the main heating grid is wound on a hollow square of fiber board 1/2 in. wide around the edges of the plates. A small auxiliary current can be regulated in this heater in order to maintain the guard ring at the temperature of the inner square. Auxiliary thermocouples, the junctions of which are placed on each side of the saw-cut at the corners of the inner square, enable this adjustment to be effected. When the auxiliary thermocouples indicate a zero temperature difference across the saw-cut, no lateral heat flow can take place either in the central square or the hollow square surrounding it.

A reliable ammeter is used to measure the current supplied to the main heating grid and some form of potentiometer outfit to measure the electromotive forces of the thermocouples. The galvanometer used with the potentiometer can also be used as a direct deflection instrument, but this requires that all the couples have the same resistance. Furthermore, the galvanometer calibration is subject to change, so that it is desirable to use a null method of measurement. The relation between the thermal electromotive force of the thermocouples and the temperature is taken from a calibration of a thermocouple of the same material.

To determine the actual rate of energy supply per unit area to the inner squares of the heating plates, the resistance per unit area of the heating grid in that region is computed from the measured resistance of the metallic ribbon per unit length, its width and spacing. This is equivalent to determining the length of ribbon over the center square and one-half the area of the saw-cut, multiplying this length by the resistance of the ribbon per unit length, and dividing the product by the area of the center plus one-half the saw-cut. The rate of electrical energy supply per unit area to each slab of test material is evidently equal to one-half the ordinary expression for power in electrical units, viz., I^2R, provided the effective insulation on each side of the heating plate is the same. The quantity R in this case, is not the total resistance of the heating grid, but its resistance per unit area of surface covered. The temperature coefficient of resistance of the constantan ribbon used for the heating grid is so small that R remains practically constant throughout the range of temperature in which the apparatus can be used.

The two outer cold plates are kept at constant temperature by allowing water or brine to flow through them in sufficient quantity to carry off all the heat supplied without becoming appreciably heated. The cooling liquid must be kept at a fairly constant temperature during an experiment, otherwise a condition of equilibrium is never reached. If water is used, an apparatus for automatically mixing hot and cold water in the proper proportions will be found convenient to furnish a constant temperature supply, but in a great many places the tap water has a fairly constant temperature and no thermostatic devices need be employed."

The Alundum Guarded Hot Plate

The alundum guarded hot plate was developed by the Mellon Institute and has proved successful in both the low and the high temperature ranges of investigation. A description of this plate by Heilman[1] is herewith included, illustrated by Fig. 1.

> "It consists essentially ... of a circular heating plate, 3/8 in. thick and 9 in. in diameter. ... The plate has a spiral groove cut in its face to a depth of slightly more than 3/16 in. The groove has a width of approximately 1/16 in. and starting from the center of the plate continues to the outer edge at the rate of 10 turns per inch. The heating elements consist of No. 22 (B. & S.) gage Nichrome III resistance wire. The center heating extends over the center 7 in. of the plate, with a voltage lead taken out 3 in. from the center which gives a power reading over the center 6 in. of the plate. Two guard ring heating elements each 1/2 in. wide cover the remainder of the plate. The heating elements are cemented into the center of the heating plate with alundum cement.
>
> Embedded in one surface of the plate are 4 Chromel-Alumel thermocouples 1.75 in., 3.25 in., 3.75 in. and 4.25 in. respectively from the center of the plate. One Chromel-Alumel thermocouple is embedded on the other side of the plate at a distance of 1.75 in. from the center. ... "

ALUNDUM GUARDED

HOT PLATE

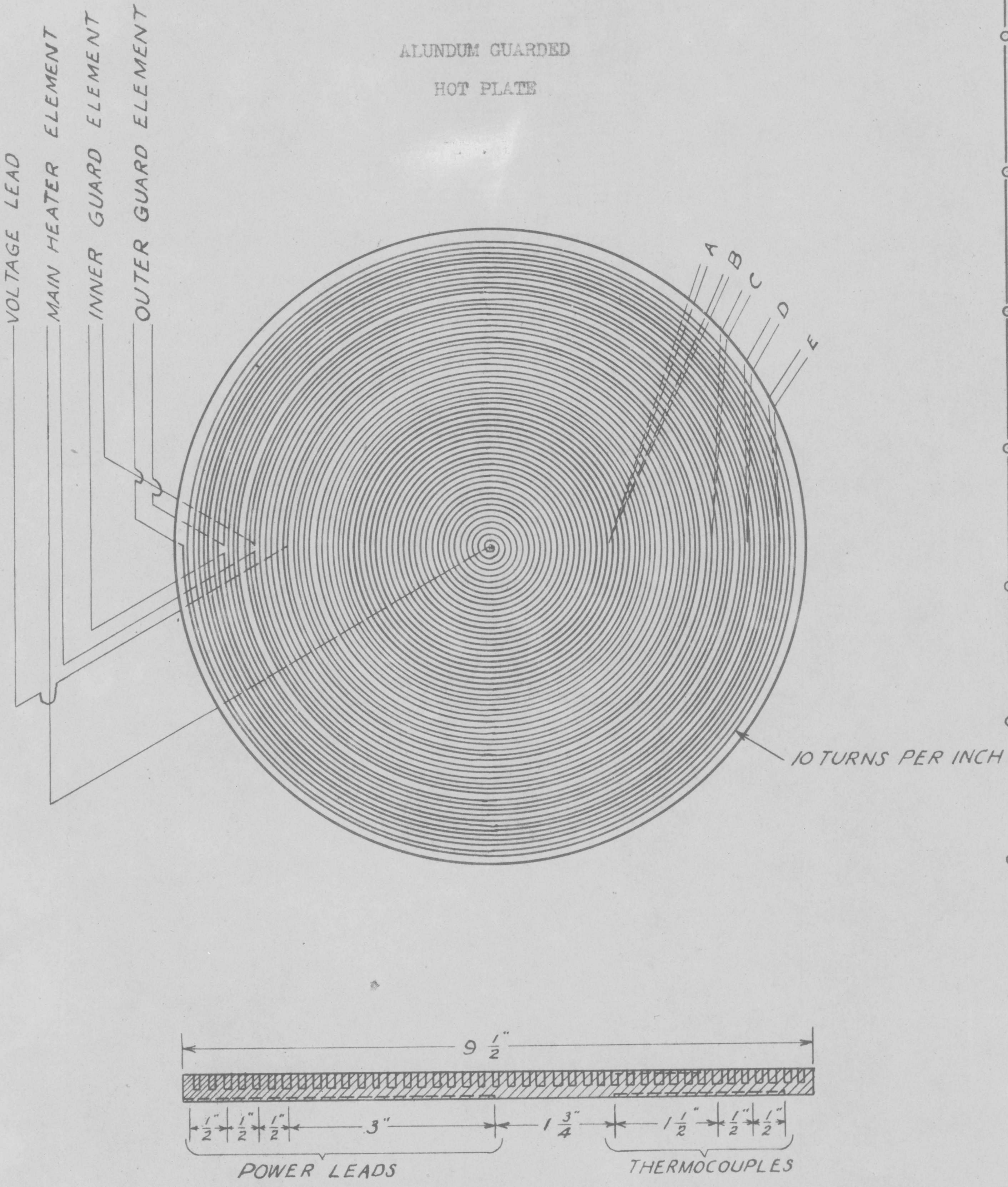

FIG. 1

ALUNDUM GUARDED HOT PLATE

III. SELECTION, CONSTRUCTION AND INSTALLATION OF APPARATUS

Hot Plate

The hot plate used in this apparatus is an alundum hot plate which was purchased from the Mellon Institute, Pittsburgh, Pa. It conforms to the description and illustration given in the "Review of Literature". The method used in its construction, as reported by R. H. Heilman, is as follows:

"A block of wood from 10-1/2 in. to 11 inches in diameter is bolted to the face plate of a lathe and recessed to a depth of 7/16 in. and 9-3/8 inches in diameter. The face plate is then removed from the lathe and the recess in the wood filled with paraffin.

After the paraffin has set the face plate is again placed on the lathe spindle and the paraffin is all removed with the exception of a 1/32 in wall at the bottom and sides.

The material for the alundum plate is then prepared as follows: to 800 grams of 200 mesh alundum is added 160 grams of 200 mesh plastic clay, 10 grams of gum tragacanth paste and 225 cc. of water, (these proportions can be changed considerably if desired). The entire mass is very thoroughly mixed and is then placed in the paraffined recess. Gently tapping the face plate on a block of wood will remove the air pockets which might be formed in the mix and will also cause the mix to be evenly distributed in the recessed plate.

The face plate with the wooden block still bolted to it is then placed in a very low temperature oven or allowed to dry in the air. After the alundum plate is thoroughly dried out, it is warmed in an oven and hot paraffin poured over it. The paraffin greatly strengthens the plate for the grooving process.

The face plate is then removed from the oven and placed on the lathe. A spiral groove of ten turns per inch, 1/16 inch wide, is then turned to a depth slightly below the center of the alundum plate.

The alundum plate is then removed from the wooden block by placing it in the oven face downward and heating at a low temperature until the plate drops from the wood container onto a soft pad placed beneath. The alundum plate can then be burned at a temperature of about 2500°F. which produces a plate hard enough to have considerable strength and desirable thermal properties and yet soft enough to enable the holes for the lead wires to be drilled with small drills. The grooves for the lead wires and the thermocouple wires can be cut in the back of the plates with a hack saw blade.

The plate is then wired, starting from the center and moving out toward the edge of the plate. The wires are cemented into the grooves with the same mixture as is used in making up the plates, leaving out the gum tragacanth, however, and substituting a small quantity of sodium silicate.

After the plate is completely wired and the cement thoroughly dried, the two surfaces are trued up with an emery stone so as to insure the plate being absolutely flat with parallel faces.

The lead wires and thermocouples coming out at the edge of the plate are insulated with small porcelain insulators. When installing the thermocouple wires on the back of the plate care should be taken to see that the junction of the wires is just beneath the surface of the plate."

In addition to its availability and its wide range of temperatures, the alundum plate posesses several advantages over other types of hot plates. The faces of the plate, as distinguished from all others, are non-metallic. Consequently, there can be no thermal electromotive force generated between the plate face and the thermocouples which it contains, regardless of the thermocouples used. (Where a metallic plate is used as the contact surface of a hot plate, it must also serve as one of the metals of the thermocouple employed, or correction must be made for the effect of the plate upon the couple.) Also, the power input to the test section is determined in terms of measurable quantities, i.e., the amperage flowing through the heating element, and the voltage drop across that part of the element heating the test section. In other types of plates the power input is determined by measuring the current flowing through a calculated resistance, the assumption being made that the characteristic resistance of the heating element remains constant for the temperature range used. These characteristics of the alundum plate should not be minimized.

The plate installed is shown clearly in Fig. 2. The circular discs in the immediate foreground are specimens of a material tested, the alundum hot plate having the central foreground position. The power and thermocouple leads show distinctly on the left and right sides of the plate, respectively. The cold plates appear in the horizontal position in the background with hose connections leading to the water lines.

Cooling Plates

The cooling plates used (Fig. 3) were designed as a part of this thesis, and constructed in the V.P.I. machine shop. Briefly, the plates consist of a cast brass cup 1/2-in. deep and 8-1/2 inches inside diameter which is covered by a 3/16-in. copper plate attached by a ring weld. Holes are drilled on opposite sides of the cup for the circulation of cooling water. The upper surface is tapered and filleted to a finished surface 3-5/8 inches in diameter and 1/2-in. thick which contains four threaded holes by which a floor flange may be bolted to the plate to facilitate its attachment to the wall of the test chamber, as illustrated in Figs. 2 and 11.

The copper face plate contains four milled slots in which constantan wires are run from their contact points with the plate 29/32-in., 1-1/8 in., 2-1/4 in. and 3-1/4 in., respectively, from the center of the plate. A copper lead not shown is soldered to the plate and is used as the common wire for all four thermocouples.

The constantan wires are soldered to the copper plate at their contact points and are insulated from the plate at all other points in their traverse of it. This insulation is accomplished by heating

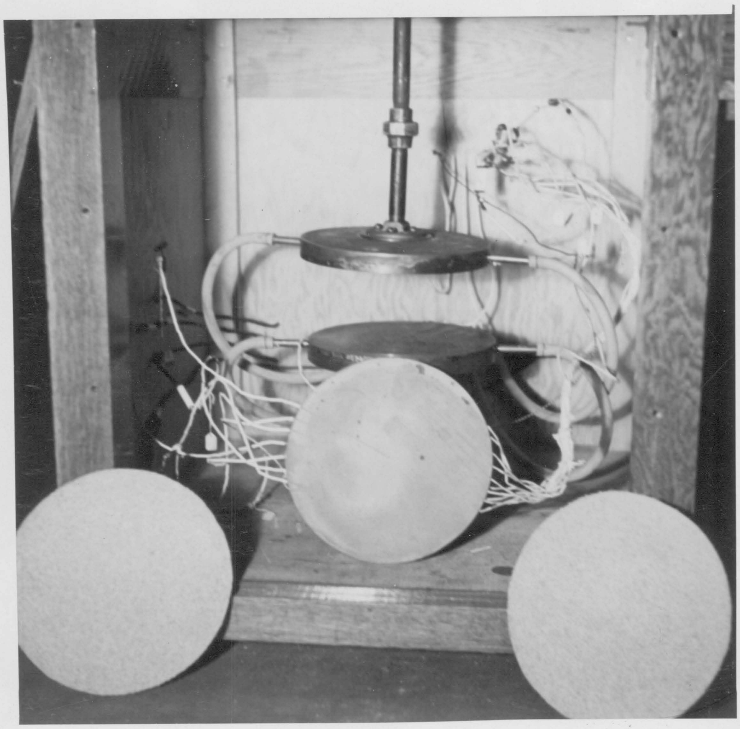

Fig. 2 - Alundum Hot Plate with Cooling

Plates and Specimens for Testing.

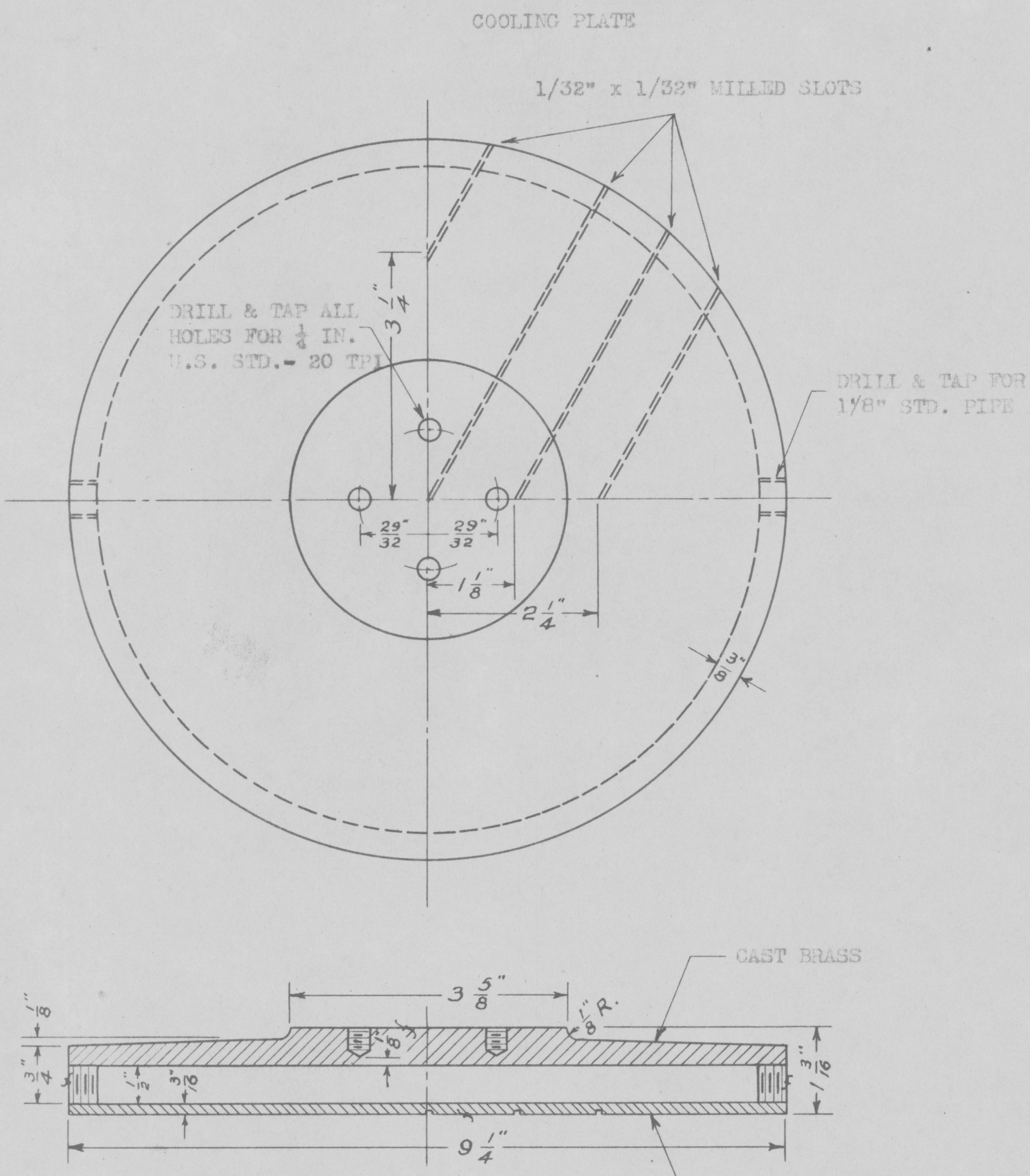

FIG. 3

COOLING PLATE

the plate by passing steam through it and filling the milled slots with de Kohtinsky cement. When the plates have cooled and the cement become solid, the cement is re-heated with a soldering iron until the surface becomes viscid, and the constantan wires pressed into place. When the cement solidifies with the wires in place, the plane of the surface is restored by removing the excess cement with emery cloth.

Determination of Resistances Required

The wiring diagram of the heating circuits is shown in Fig. 4. As indicated, the main heater (supplying the heat for the test section and the beginning of the guard ring) and both guard heaters are wired in parallel across a difect current source. Suitable external resistances, in the form of slide wire rheostats, are placed in series with each of the heating elements such that the power input to all may be individually controlled. The size and capacity of these rheostats are calculated from a knowledge of the approximate conductivities of the materials which are to be tested as outlined below.

From the table of conductivities and conductances in the "Heating Ventilating and Air Conditioning Guide for 1938", the maximum conductance listed for insulating materials is 3.73 Btu. per hr. per sq. ft. per deg. F. Using this value as the maximum likely to be encountered, the heating requirements of the test area of the alundum hot plate was calculated for a temperature gradient of 70°F. through the specimens as follows:

Area of test section;

$$A = \frac{2 \times 0.7854(d)^2}{144} = \frac{1.57 \times 36}{144} = 0.3928 \text{ sq. ft.}$$

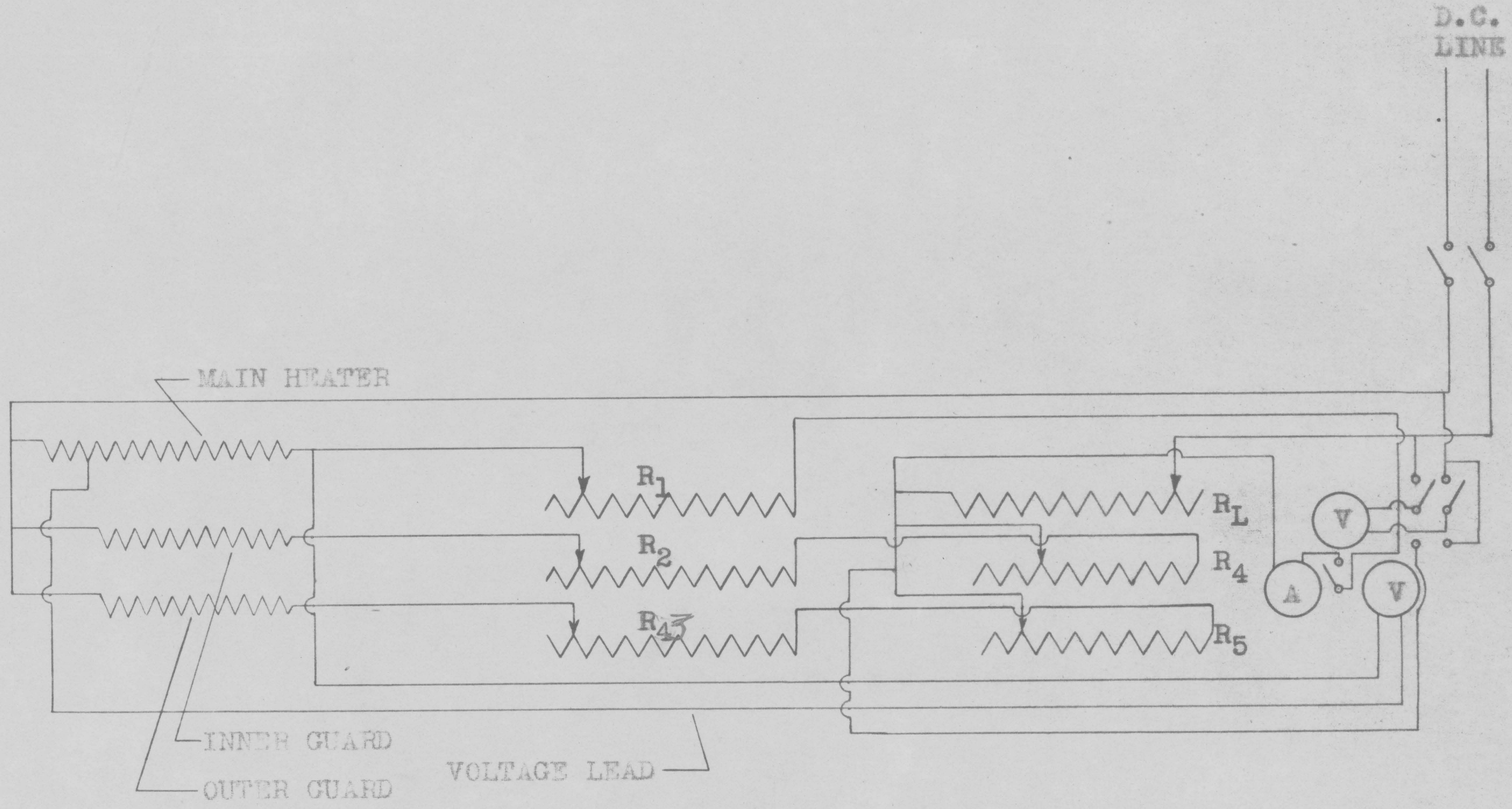

FIG. 4

POWER CIRCUIT FOR

ALUNDUM GUARDED HOT PLATE

Heat demand on test section;

$$q = C \times A \times (t_1 - t_2)$$

$$= 3.73 \times 0.3928 \times 70 = 102.7 \text{ Btu/hr.}$$

Power demand on test section;

$$P = \frac{q}{3.415} = \frac{102.7}{3.415} = 30.1 \text{ watts.}$$

Since the winding of the wire throughout the plate is spiral, the lengths may be determined by the formula,

$$L = \frac{r^2}{2k} \qquad \text{where } r = a\left(\frac{\phi}{360}\right) = 3 \text{ in.}$$

a = pitch of winding = 0.10 in.

ϕ = angle uncovered by generating radius

$$k = \frac{a}{6.28} = 0.0159 \text{ in./in.}$$

$$L = \frac{3 \times 3}{2 \times 12 \times 0.0159} = 23.55 \text{ ft.}$$

The resistance of No. 22 Nichrome wire is given by the manufacturers as 1.107 ohms per foot, therefore the resistance of the heater is

$$R = 23.55 \times 1.017 = 23.9 \text{ ohms;}$$

and the amperage required to produce 30.1 watts output from the test section is

$$I = \left(\frac{P}{R}\right)^{\frac{1}{2}} = (30.1/23.9)^{\frac{1}{2}} = 1.122 \text{ amps.}$$

The total length of the main heater is

$$L' = (3.5 \times 3.5)/(2. \times 12 \times 0.0159 = 32.2 \text{ ft.}$$

The total resistance of the main heater is

$$R' = 32.2 \times 1.017 = 32.75 \text{ ohms}$$

The line voltage required is

$$E_1 = I \times R = 1.122 \times 32.85 = 36.8 \text{ volts}$$

For the same material to maintain a temperature gradient of 20°F., external resistance must be added to the circuit if the line voltage is held constant. For this temperature gradient,

$$q = 0.3928 \times 3.73 \times 20 = 28.3 \text{ Btu/hr.}$$

$$P = (28.3/3.415) = 8.57 \text{ watts}$$

$$I = (8.57/23.9)^{\frac{1}{2}} = 0.599 \text{ amps.}$$

and the external resistance necessary under these conditions is

$$R_1 = (36.8/0.599) - 32.85 = 28.55 \text{ ohms.}$$

The determination of the magnitude of the external resistances required in the guard circuits was determined in a similar manner.

In these calculations it was found that the guard elements required approximately the same amperage as the main heater because the heating demand per unit length of element was practically constant for all circuits, since the lengths of wire in the individual elements is the same per unit of surface area supplied. It was further found that the resistances required in the external circuits were nearly the same for all elements, which follows from the above. The rheostats R_1, R_2, and R_3,Fig. 4, were therefore selected with a capacity of 1.5 amps., which is slightly in excess of the estimated maximum current. The resistances of these units is 175 ohms, which is greatly in excess of the value calculated above. However, this calculated value is the probable minimum resistance, and with a decrease in conductivity (or conductance) the external resistance must be increased, due to the decrease in power demand upon the heaters for a given temperature gradient.

The additional rheostats, R_4 and R_5, in series with R_2 and R_3, respectively, have resistances of approximately 3 ohms each and are used in obtaining final adjustments only.

Because the circuits are in parallel, any change in the resistance of one immediately affects the others. For this reason, a rheostat was placed in series with the power source such that when adjustments are made in any circuit, the voltage on all may be maintained by an adjustment of the line rheostat. This unit has a capacity of 4.6 amperes and a resistance of 22 ohms and can be used to compensate for fluctuations up to 15 volts.

Thermocouples

The thermocouples (Fig. 5) used in the hot plate are Chromel-Alumel, while those used for the cooling plates are Copper-Constantan.

In these latter couples, the copper plate was used as the common side and the junctions formed by soldering the Constantan wire to the plates at the points indicated.

A common lead is also secured for the Chromel-Alumel couples by soldering all of the Chromel wires into a binding post terminal from which a single Chromel wire is run to the control switches. The Alumel and the Constantan wires are carried directly to an ice-bath where junctions were made with Chromel and copper leads to the control switches. The common wires of both groups were connected to opposite sides of a

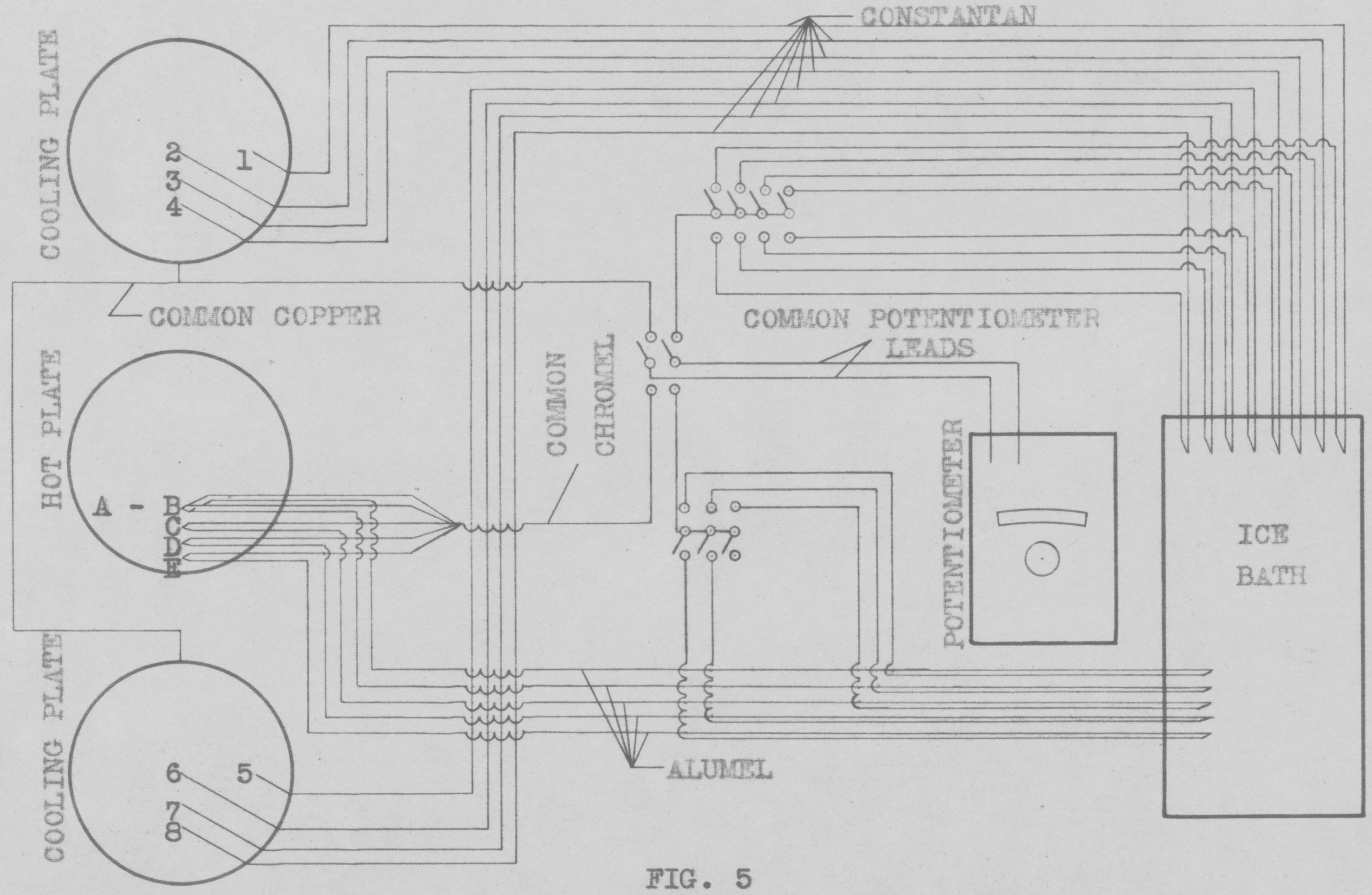

FIG. 5

THERMOCOUPLE CIRCUITS FOR
HEAT TRANSMISSIVITY APPARATUS

double-pole, double-throw switch, the center posts of which were connected to the terminals of the potentiometer, thus completing the circuit.

Potentiometer

The potentiometer used is manufactured by Leeds and Northrup Company, Philadelphia, Pa. This instrument has a scale range from 0 to 16 millivolts and an accuracy of 1/100 millivolts.

Ammeter

The ammeter employed is manufactured by the General Electric Company, Schenectady, New York. The scale range of this instrument is 2.0 amperes, and it has a guaranteed accuracy of 1-1/2 to 3 per cent of the full scale reading.

Voltmeters

These meters are of the same type with the same range of accuracy as the ammeter, and are manufactured by the same company. The meter measuring the voltage drop across the test section of the main heater has a capacity of 50 volts, which is slightly in excess of the estimated maximum value of the drop across this section, while the one used for measuring the line voltage has a scale range from 0 to 250 volts. This latter is connected to the main source (Fig. 4) both before and after the line rheostat, R_L; thus it may be used in adjusting the apparatus to maintain a constant voltage across the heating circuits.

Calibration

Voltmeters and Ammeters. Because the guaranteed accuracy of the voltmeters and the ammeter is not close, these instruments were calibrated in the Electrical Engineering Laboratory, and the calibration curves are included as Figs. 6 and 7. Since the line voltmeter is used only for adjusting the apparatus, this instrument was not calibrated.

Thermocouples. The calibration for these was taken directly from Leeds and Northrup "Standard Conversion Tables", since the accuracy of these tables is within the accuracy of the apparatus as controlled by the power readings. Moreover, Copper-Constantan couples used in a research project of the Chemical Engineering Department were calibrated and a comparison of their calibration with the one tabulated by Leeds and Northrup proved the latter raliable; the differences being entirely within the range of personal accuracy in conducting the calibration.

To facilitate the use of the Leeds and Northrup data, curves were made of temperature vs. millivolts for a reference junction temperature of 32°F., and these are included in this thesis as Figs. 8, 9, and 10.

Operation

The procedure followed in conducting tests is not difficult. Some time is required, however, to bring the apparatus to a state of steady flow, and care must be exercised in adjusting the rheostats.

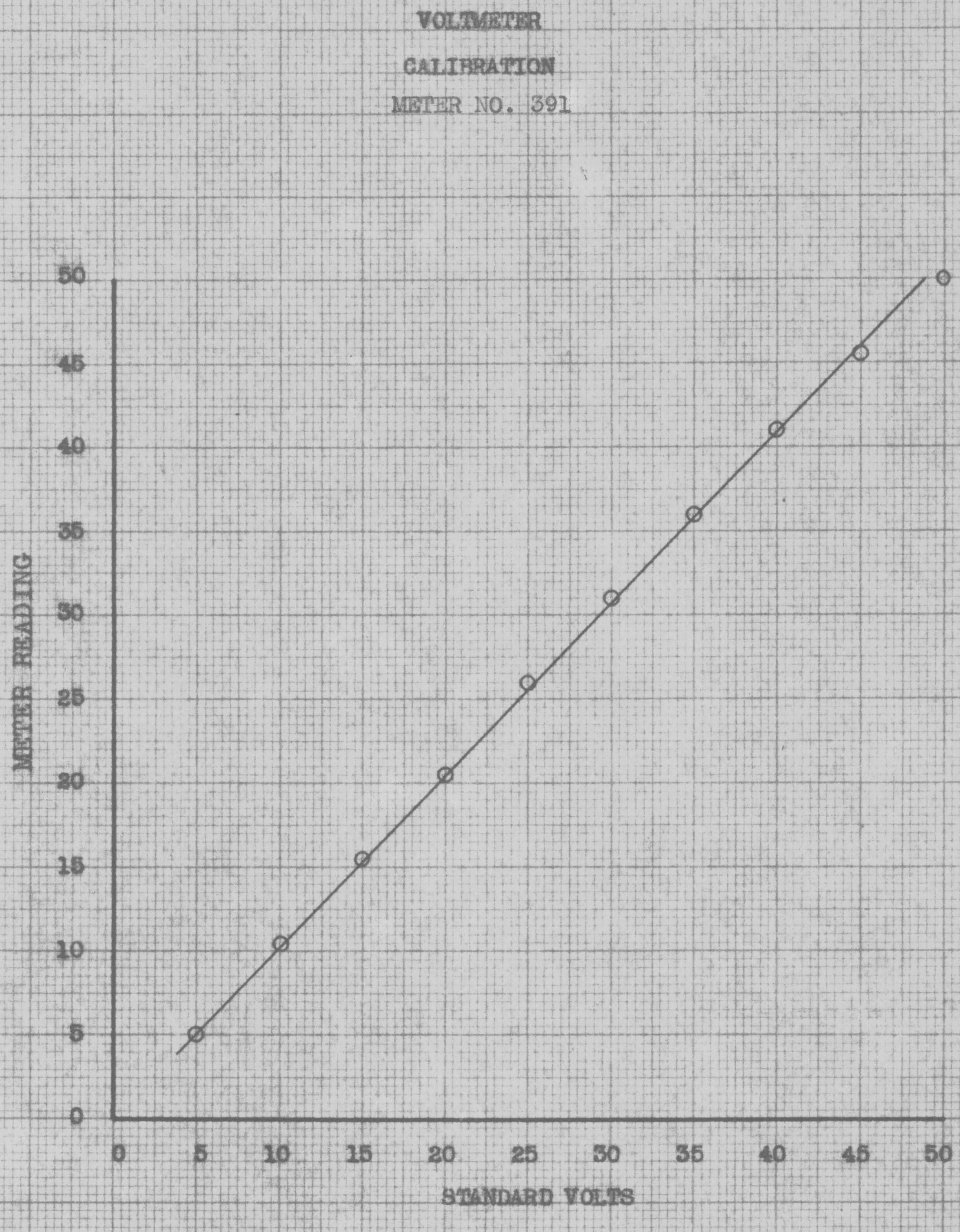
VOLTMETER
CALIBRATION
METER NO. 391
METER READING
0
5
10
15
20
25
30
35
40
45
50
STANDARD VOLTS

FIG. 6

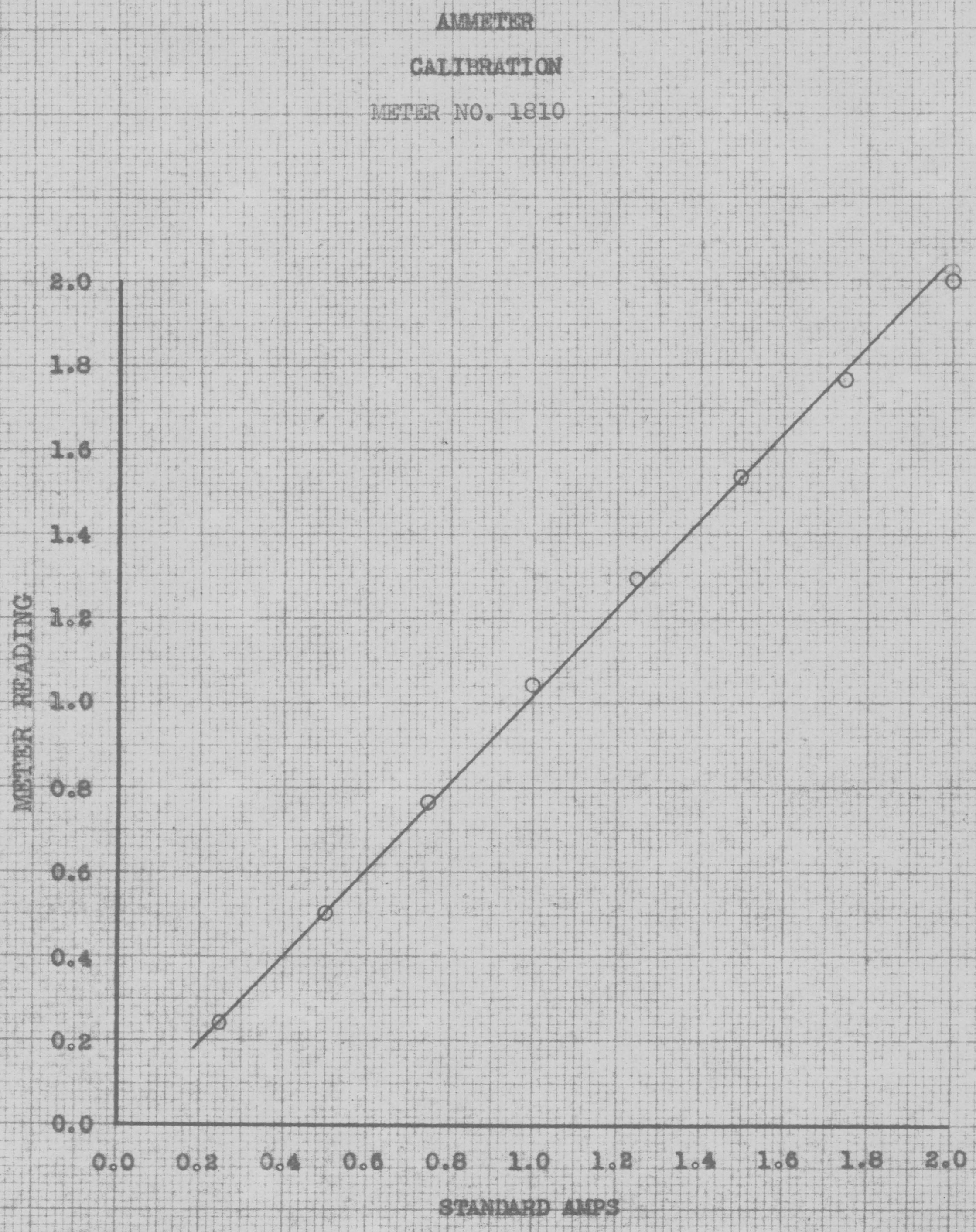
AMMETER
CALIBRATION
METER NO. 1810
METER READING
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
STANDARD AMPS

FIG. 7

CALIBRATION FOR

CHROMEL-ALUMEL THERMOCOUPLE

FROM

L. & N. STANDARD CONVERSION TABLES

(REFERENCE JUNCTION 32° F)

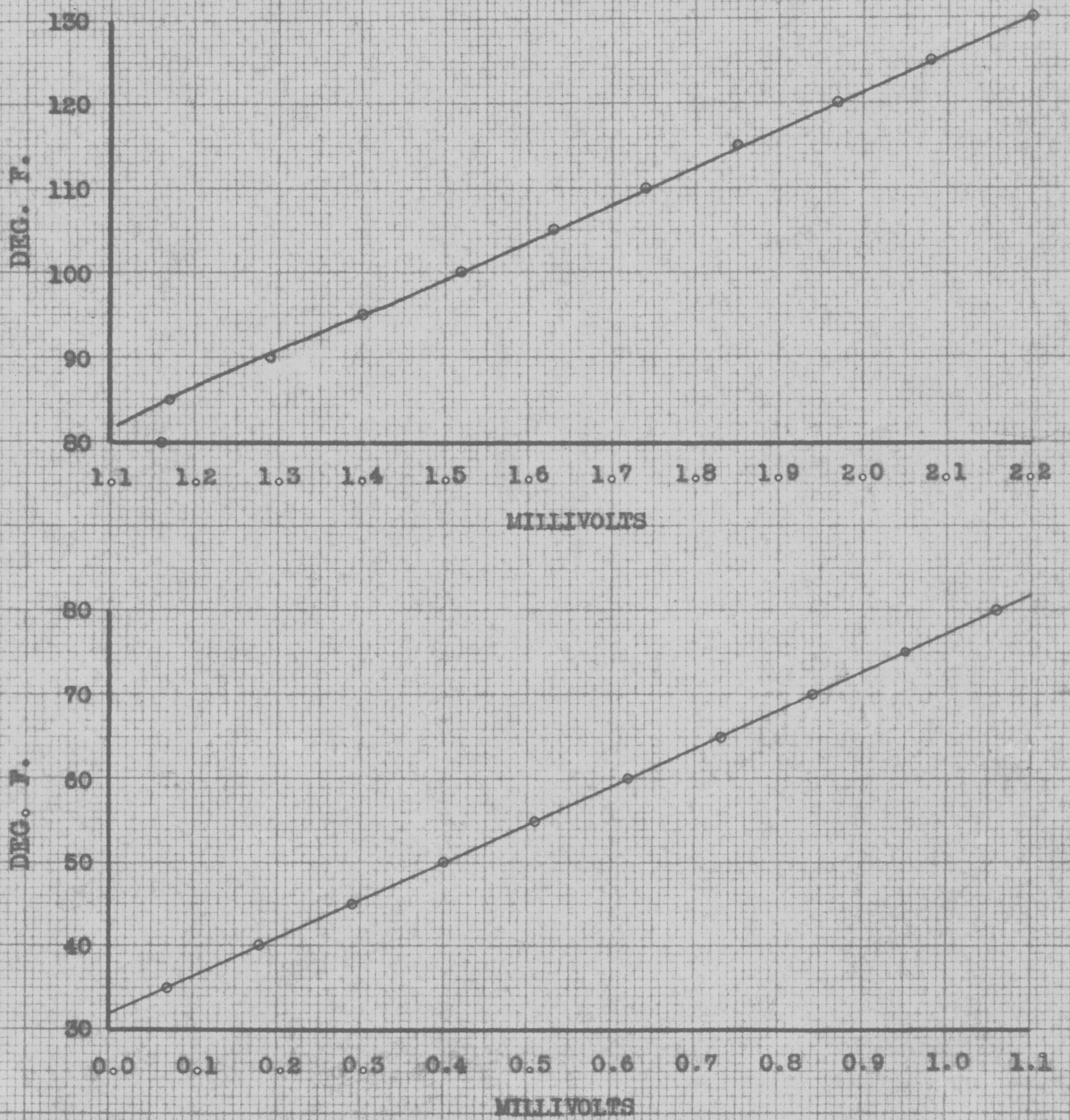

FIG. 8

CALIBRATION FOR
CHROMEL-ALUMEL THERMOCOUPLE
FROM
L. & N. STANDARD CONVERSION TABLES
(REFERENCE JUNCTION 32° F)

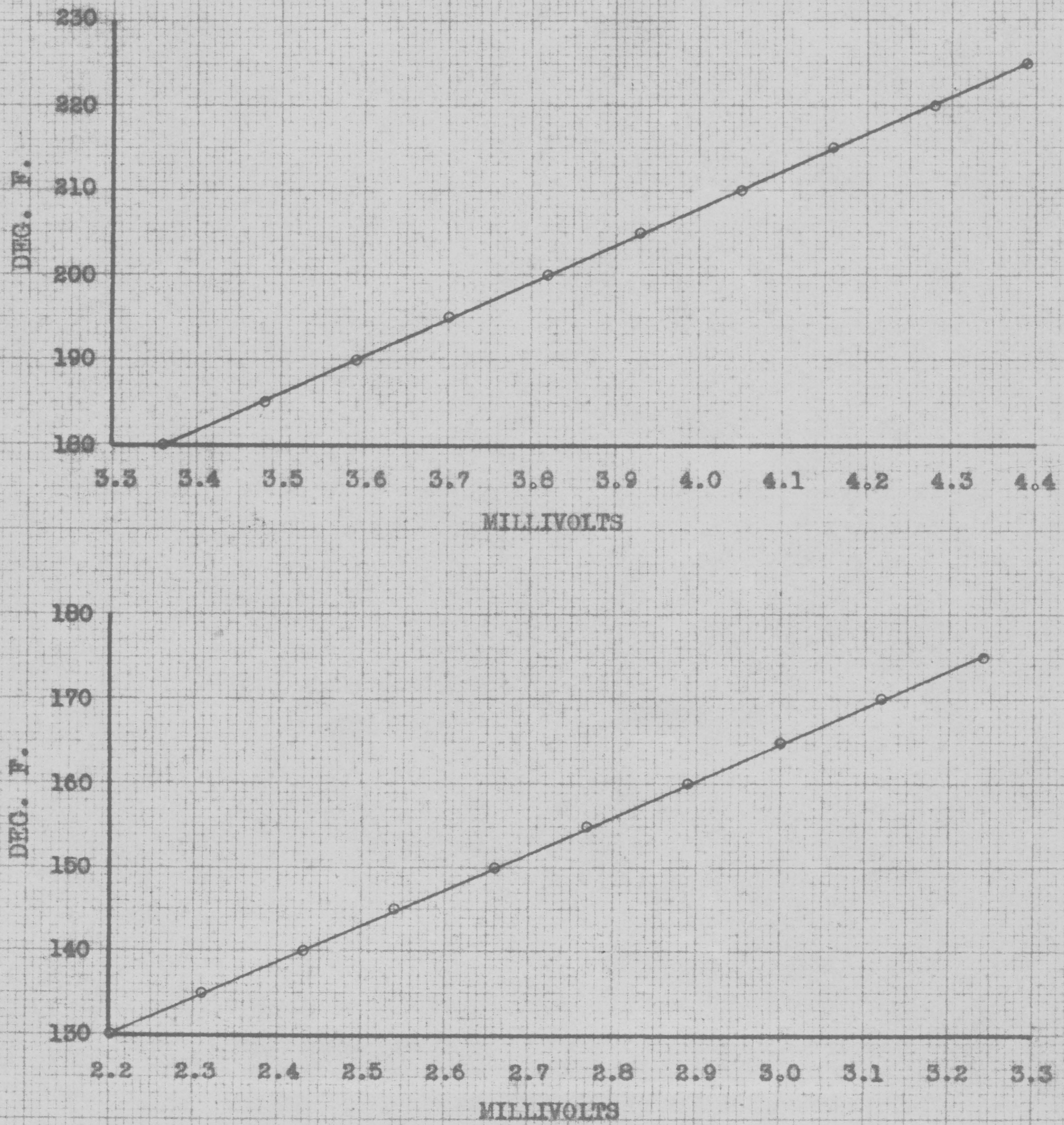

FIG. 9

CALIBRATION FOR

COPPER-CONSTANTAN THERMOCOUPLE

FROM

L. & N. STANDARD CONVERSION TABLES

(REFERENCE JUNCTION 32° F)

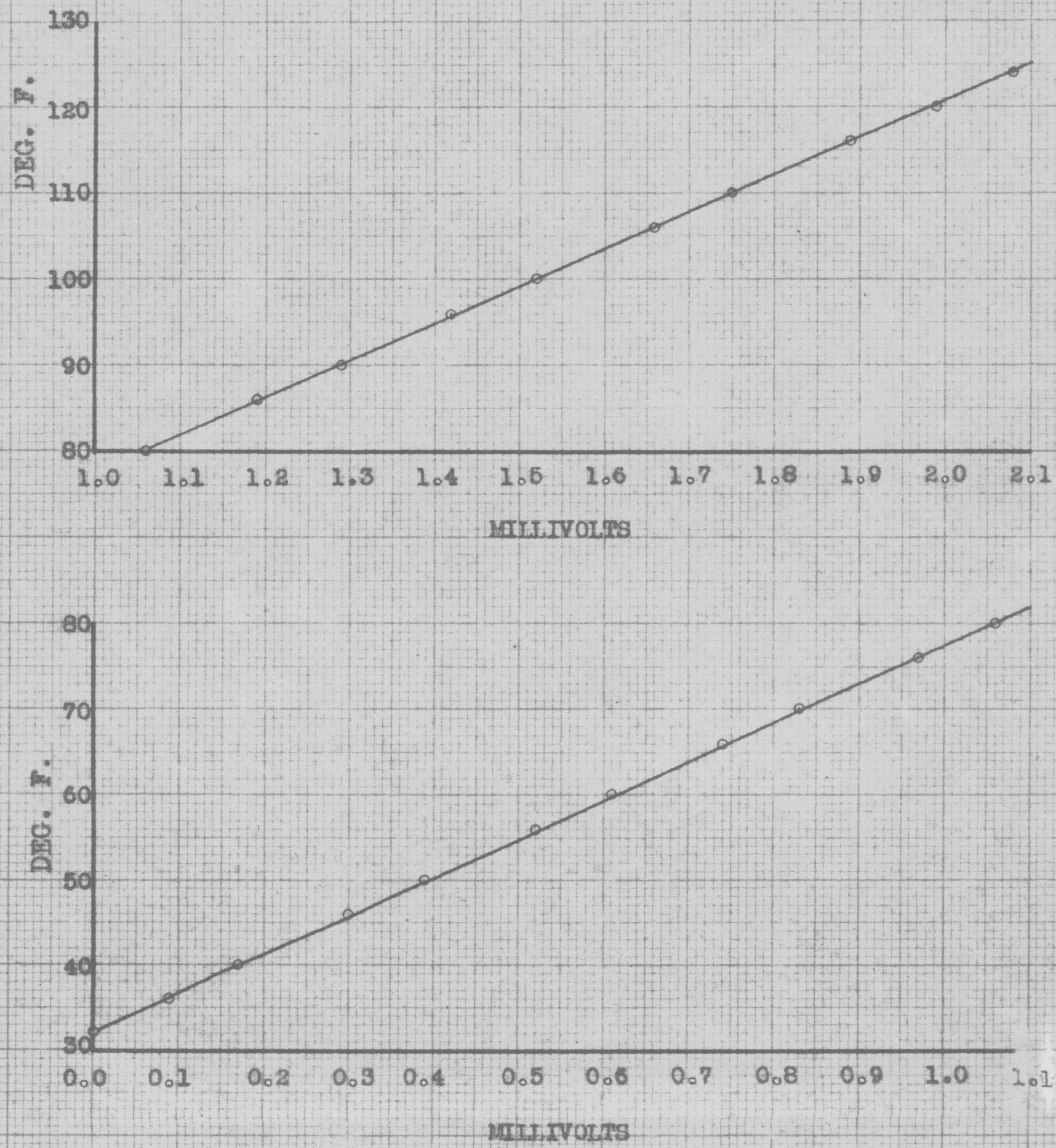

FIG. 10

In preparation for a test, two identical samples of insulating material are prepared as explained under the "Review of Literature". These are placed in the apparatus, one on each side of the alundum hot plate, as in Fig. 11; the enclosing panel is bolted in place, and the test started.

The alundum hot plate is allowed to heat up fairly rapidly, within the current capacity of the rheostats to a temperature slightly higher than that desired for equilibrium. During this period, no attempt is made to establish an equilibrium condition. The temperatures on the surfaces of the guard rings, however, should be kept somewhere near that of the test section, and preferrably slightly below it.

When the increase in temperature of the surface of the test section becomes small, the current to the main heater is reduced slightly by adjusting the main heater rheostat, and the current in the guard rings slightly increased. After several minor adjustments, a perfect balance may be obtained, i.e., the temperatures of all five thermocouples will be the same. In general, the temperature of the outer guard ring as indicated by thermocouple "E" will be slightly less than that of the others because of edge leakage.

When steady flow has been established, i.e., when there is no change in the temperature gradient as indicated by constant thermocouple readings for both hot and cold plates, the test is started and continued for a one hour period. Readings are taken of the amperage drawn by the main heater, the voltage drop across the test

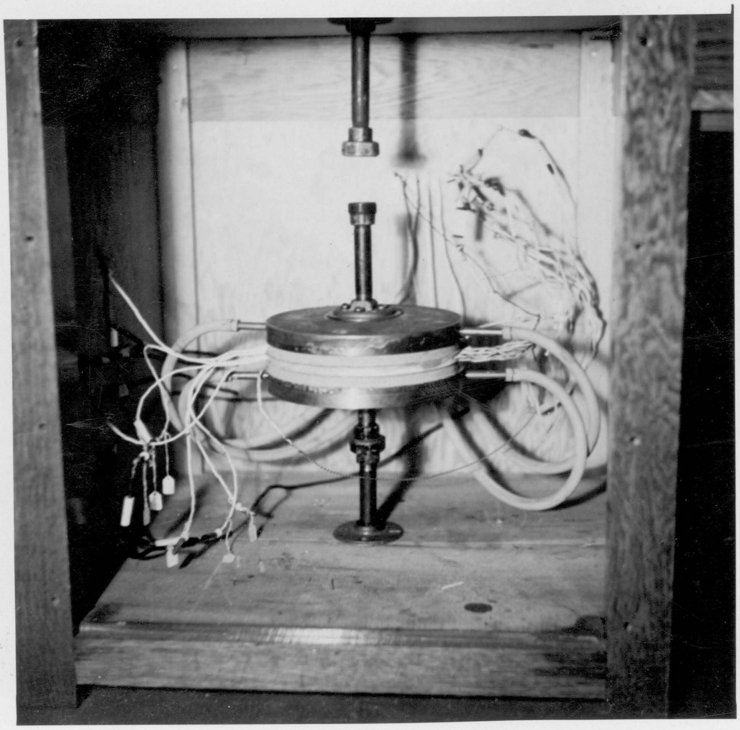

Fig. 11 - Samples and Plate Assembled

in Apparatus Ready for Test.

Fig. 12 - Apparatus Completely

Assembled for Test

section and of the potentiometer for thermocouples "A", "B", "C", "D", "E", "2", "3", "6", and "7", at fifteen minute intervals throughout the test period.

Results

The results of tests made with this apparatus are shown in Tables 1 to 5, inclusive.

Discussion of Results

After the apparatus had been assembled, a series of preliminary tests were made the purpose of which was to check the installation with respect to the circuits. In all of these preliminary tests, the temperatures of the cold plate surfaces remained constant. For this reason, in making subsequent tests only couples "2" and "3", and "6" and "7" were read. Tests were then run on samples of 3/4-in. Celotex sheathing, 1/2-in. Gyp-Lap, and 1/2-in. Celotex lath .

Only one test was made on the 3/4-in. Celotex sheathing, the purpose of which was to determine the approximate accuracy of the apparatus. The results of this test gave a conductivity of 0.35 Btu. per hr. per sq. ft. per deg. F., which is slightly higher than the average value for this material found in reference tables. However, this type of insulation is supplied for sheathing purposes and is water-proofed on both surfaces with an asphalt compound which undoubtedly changes its conductivity and it was felt that this deviation from reference material was characteristic of the samples, rather than due to inaccuracy of the apparatus.

Table 1

TEST NO. 1

Material - 3/4 in. Celotex sheathing

TIME	POWER		THERMOCOUPLES - mv.								
	amps.	volts	A	B	C	D	E	2	3	6	7
8:15	0.62	10.0	2.97	2.99	2.97	2.97	2.97	0.61	0.61	0.61	0.61
8:30	0.62	10.0	2.97	3.00	2.99	2.99	2.98	0.59	0.59	0.59	0.59
8:45	0.62	10.0	2.97	3.00	3.00	3.00	3.00	0.60	0.60	0.60	0.60
9:00	0.62	10.0	3.01	3.01	3.01	3.01	3.00	0.60	0.60	0.60	0.60
9:15	0.62	10.0	3.05	3.10	3.05	3.05	3.04	0.60	0.60	0.60	0.60
	0.62	10.0	2.99	3.02	3.00	3.00	3.00	0.60	0.60	0.60	0.60

Average inside temperature . . . 165°F
Average outside temperature . . 59°F
Corrected amperage . . . . 0.60 amps
Corrected voltage . . . . 9.5 volts

$$k = \frac{0.60 \times 9.5 \times 3.415 \times 0.75}{0.3928 \times (165 - 59)} = 0.35 \text{ Btu/sq. ft./hr/}^{\circ}\text{F.}$$

Table 2

TEST NO. 2

Material - 1/2 in. Gyp-Lap

TIME	POWER		THERMOCOUPLES - mv.								
	amps.	volts	A	B	C	D	E	2	3	6	7
8:15	1.20	20.0	2.42	2.50	2.23	2.20	2.16				
9:30	1.14	19.0	2.35	2.38	2.38	2.12	2.10				
10:30	1.01	16.9	2.00	2.01	1.98	1.98	1.98				
10:45	1.00	16.6	1.98	1.98	1.98	1.98	1.99	0.70	0.70	0.70	0.70
11:00	1.00	16.5	1.98	2.00	1.97	1.99	2.00	0.70	0.70	0.70	0.70
11:15	1.00	16.5	1.98	2.00	1.98	1.99	2.00	0.70	0.70	0.70	0.70
11:30	1.00	16.5	1.98	2.00	1.98	1.99	2.00	0.70	0.70	0.70	0.70
11:45	1.00	16.5	1.98	2.00	1.98	1.98	2.00	0.71	0.71	0.71	0.71
Average	1.00	16.5	1.98	2.00	1.98	1.99	2.00	0.70	0.70	0.70	0.70

Average inside temperature . . . 121°F
Average outside temperature . . 64°F
Corrected amperage . . . . 0.95 amps
Corrected voltage . . . . 16.0 volts

$$k = \frac{0.95 \times 16.0 \times 3.415 \times 0.5}{0.3928 \times (121 - 64)} = 1.16 \text{ Btu/sq. ft./hr/}^{\circ}\text{F.}$$

Table 3

TEST NO. 3

Material - 1/2 in. Gyp-Lap

TIME	POWER		THERMOCOUPLES - mv.								
	amps.	volts	A	B	C	D	E	2	3	6	7
8:30	1.25	20.9	3.19	3.22	3.30	3.52	3.62				
9:30	1.44	24.1	3.32	3.41	3.36	3.42	3.50				
10:30	1.42	23.9	3.10	3.20	3.05	3.12	3.15				
10:45	1.40	23.5	3.08	3.15	3.05	3.12	3.15				
11:00	1.40	23.5	3.05	3.12	3.05	3.12	3.16	0.59	0.59	0.60	0.60
11:15	1.39	23.2	3.02	3.10	3.02	3.10	3.12	0.59	0.59	0.60	0.60
11:30	1.40	23.5	3.02	3.10	3.02	3.10	3.12	0.59	0.59	0.60	0.60
11:45	1.40	23.5	3.02	3.11	3.02	3.11	3.15	0.58	0.58	0.59	0.59
12:00	1.40	23.5	3.02	3.10	3.02	3.10	3.13	0.58	0.58	0.59	0.59
Average	1.40	23.4	3.03	3.11	3.03	3.11	3.14	0.59	0.59	0.60	0.60

Average inside temperature . . . 168°F
Average outside temperature . . 59°F
Corrected amperage . . . . 1.39 amps
Corrected voltage . . . . 22.8 volts

$$k = \frac{1.39 \times 22.8 \times 3.415 \times 0.5}{0.3928 \times (168 - 59)} = 1.16 \text{ Btu/sq. ft./hr/}^{\circ}\text{F.}$$

Table 4

TEST NO. 4

Material - 1/2 in. Celotex lath

TIME	POWER		THERMOCOUPLES - mv.								
	amps.	volts	A	B	C	D	E	2	3	6	7
5:00	0.75	12.2	3.15	3.16	3.16	3.15	3.15				
5:15	0.75	12.1	3.11	3.12	3.12	3.12	3.12				
5:30	0.75	12.2	3.09	3.09	3.09	3.09	3.09				
7:20	0.73	12.0	3.00	3.00	3.00	3.00	3.00	0.99	0.99	0.78	0.78
7:35	0.72	12.0	3.00	3.00	3.00	3.01	3.00	1.01	1.01	0.79	0.79
7:50	0.73	12.0	3.01	3.01	3.01	3.00	3.01	1.11	1.11	0.79	0.79
8:05	0.72	12.0	3.01	3.01	3.01	3.01	3.01	1.21	1.21	0.79	0.79
8:20	0.73	12.0	3.02	3.02	3.02	3.02	3.02	0.89	0.89	0.80	0.80
Average	0.73	12.0	3.01	3.01	3.01	3.01	3.01	1.04	1.04	0.79	0.79

Average inside temperature . . . $165^{\circ}F$
Average outside temperature . . $74^{\circ}F$
Corrected amperage . . . . 0.702 amps
Corrected voltage . . . . 11.5 volts

$$k = \frac{0.702 \times 11.5 \times 3.415 \times 0.5}{0.3928 \times (165 - 74)} = 0.33 \text{ Btu/sq. ft./hr/}^{\circ}\text{F.}$$

Table 5

TEST NO. 5

Material - 1/2 in. Celotex lath

TIME	POWER amps.	POWER volts	A	B	C	D	E	2	3	6	7
9:00	0.50	8.2	2.33	2.33	2.30	2.30	2.28				
9:45	0.50	8.2	2.10	2.10	2.10	2.10	2.10				
10:00	0.50	8.2	2.02	2.02	2.02	2.02	2.02	0.78	0.78	0.90	0.90
10:15	0.51	8.2	2.00	2.00	2.00	2.00	2.00	0.78	0.77	0.96	0.96
10:30	0.51	8.2	2.00	2.00	2.00	2.01	2.00	0.77	0.78	0.99	0.99
10:45	0.51	8.2	2.01	2.01	2.01	2.00	2.01	0.77	0.77	1.02	1.02
11:00	0.51	8.2	2.01	2.01	2.01	2.01	2.01	0.77	0.77	1.08	1.08
Average	0.51	8.2	2.01	2.01	2.01	2.01	2.01	0.77	0.77	0.99	0.99

THERMOCOUPLES - mv. (columns A through 7)

Average inside temperature . . . 122°F
Average outside temperature . . 72°F
Corrected amperage . . . . 0.495 amps.
Corrected voltage . . . . 7.7 volts

$$k = \frac{0.495 \times 7.7 \times 3.415 \times 0.5}{0.3928 \times (122 - 72)} = 0.32 \text{ Btu/sq. ft./hr/}^{\circ}\text{F.}$$

in

Samples of Gyp-Lap were then obtained and tested at two different temperature gradients. Both of these tests, at mean temperature differences of 57°F. and 109°F., respectively, gave a value of k of 1.16. It is thought that this exact duplication was the direct result of not drying the samples prior to making the tests. This lack of drying caused the value of k obtained in the first test to be slightly higher than the true value for this material by virtue of the latent heat absorbed. The second test was run immediately following the first, and the effect of latent heat absorption in this test is thus minimized.

Between the first and second of these tests, the samples were interchanged, so that any idiosyncracies of the apparatus might be detected. When duplicate results were obtained, after this interchange of samples, it was felt that the accuracy of the apparatus was definitely established.

As an additional check upon the installation, however, two tests were run using samples of 1/2-in. Celotex lath. The results of these tests gave conductivities of 0.32 and 0.33 at temperature gradients of 50°F. and 91°F., respectively.

With these additional results, it was felt that the apparatus was unquestionably properly installed, and that the object of this thesis had been obtained; particularly in view of the fact that the samples had not been dried before testing, this being impossible because a drying oven was not available sufficiently large to accomodate the 13 in. x 13 in samples.

As a final check upon the accuracy of the installation, however, these 13 in. x 13 in. samples have been forwarded to the Pennsylvania State College Experiment Station, where they are to be tested in a 12 in. x 12 in. hot plate.

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