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CORRELATION
OF ELECTRICAL AND THERMAL
PROPERTIES OF BUILDING BRICK

by

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for the Degree of

DOCTOR OF PHILOSOPHY

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Approved:

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I. INTRODUCTION

A. Purpose of Investigation

Although ceramic materials are used quite extensively in electrical insulation and construction, comparatively little is known of their electrical properties. Nor has the manner in which these properties vary with respect to certain of the other physical characteristics of the material been investigated very extensively. It is the purpose of this work to study a few of the direct-current properties of ceramic materials and to show that a relationship exists between the electrical and physical properties.

B. Scope

Obviously measurements and attempted correlations of electrical and physical properties might be made almost indefinitely. For that reason those properties have been chosen which were considered most important, most liable to correlation, and which lent themselves most readily to measurement with the equipment at hand.

The measurements and correlations which have been made are: (1) the direct-current electrical conductivity; (2) the thermal conductivity at relatively low mean temperatures; (3) the porosity; and (4) the relation between the electrical and thermal conductivities based on the porosity of the material.

In addition studies were also made of the current-voltage relations and the current-time relations and the manner in which they were affected by the porosity of the material.

II. REVIEW OF LITERATURE

A. Discussion of Theories

1. Electrical conductivity

a. Factors influencing electrical conductivity in dielectrics. Any material, no matter how high its electrical insulating powers, is not absolutely impervious to the flow of current. The degree of current conduction may, in non-homogeneous, non-metallic materials, depend upon a number of things. These include the number of free electrons, the degree of ionization, the electrolytic action, the temperature, the impressed voltage, and the dimensions of the specimen. The latter three are conditions which may be controlled generally by external means. The first three, however, represent three distinct types of electrical conduction, any or all of which may be present to a greater or lesser extent depending upon the material, the voltage gradient impressed, and certain other external conditions such as temperature.

The type of conduction generally considered is electronic conduction. In that case the current flows by virtue of the movement of negatively charged free electrons from points of low potential toward points of higher potential. If these charges move with a uniform velocity, the current is said to be steady. By free electron is meant any electron which is not rigidly attached to any atom or molecule as a part of its structure. Electronic conduction characterizes, generally, the metallic elements although the other types of conductivity may be present in varying degrees.

Thus the conductivity of a material might first be considered as depending upon the number of free electrons in the material.

Inasmuch as the non-metallic materials have relatively few free electrons and yet in many cases exhibit an appreciable electrical conductivity, other types of conductivity must be investigated as possibly contributing to the flow of current.

The second type of conductivity to be considered is that in which the carriers of charge are ionized particles produced and caused to move by the voltage gradient impressed on the specimen. It is this type of conduction which is thought to predominate in solid dielectrics.

The current flow here depends upon a number of things. First, the voltage gradient has a great deal of influence upon the degree of ionization and hence upon the current flow. If the manner of variation of current with voltage be considered as approximately the same for solids as for gases, the general current-voltage curve for gases, for a constant external source of ionization, may be assumed to be qualitatively correct. The first portion of the curve represents the current flowing as a result of the impressed voltage sweeping away those few ions which have been produced by the external ionizing source and are already present in the medium. The flat portion of the curve represents the situation obtained when all the ions are drawn to the electrodes as rapidly as they are produced. This constant current, saturation current, exists until the voltage gradient applied is increased to a sufficiently high value to cause one or both of two things to occur.

First, additional ions may be produced by collision. That is, the high velocity energy or kinetic energy attained by the ions as a result of the increased voltage gradient may become great enough to knock one or more electrons from a neutral molecule or atom. The ions thus produced are then themselves subjected to the high accelerating gradient and by virtue of their kinetic energy begin to produce still other ions by collision. This phenomenon increases more rapidly with increasing voltage. Hence, since the current is a function of both the number and velocity of the charge carriers, the current also increases rapidly with increasing voltage. Second, the voltage gradient may be made high enough to cause the internal strains in the molecules to become so great that the molecule is torn apart and additional ions thus produced. The probability, however, is that the latter does not occur until the voltage gradient is very much higher than that necessary to produce ionization by collision; hence this case may be omitted from consideration.

In addition to the effect of the voltage gradient upon the degree of ionization, the temperature also has a decided effect. In a solid material the effects are several and in some instances tend to neutralize each other. The primary effect of temperature is to increase the mobility of both the positive and the negative ions. The increased temperature also causes the material in question to become somewhat more viscous; that is, the frictional forces opposing the motion of the ions are to a certain extent reduced. Both these effects naturally allow ions to be moved more rapidly with the same applied voltage. A third condition which exists argues for the reduction of current with increased temperature, as is the case for metals. The increased temperature causes a more rapid oscillation of the molecules in the material. This oscillation may become so rapid as to interfere with the moving charges before they have attained sufficient velocity to produce ionization by collision.

The net result of these three temperature effects is, in some cases, to actually produce a conductivity-temperature curve showing a maximum. In general, however, the conductivity of metals is an inverse function of temperature and that of non-metals is a direct function.

The last condition which requires consideration relative to the degree of ionization is the size of the ionization chamber.

In order that ionization by collision occur it is necessary not only to have a voltage gradient large enough to produce the required velocity of the ions, but it is also necessary to have the continuous paths long enough to permit the velocity of the ion to attain a value high enough to produce another ion by collision with an atom or a molecule (38, p. 23). This condition is of importance in dealing with dielectrics in which there are air pores or air films. However, in the case of clay products the majority of the pore spaces may be assumed to be large enough to avoid the possibility of having a path too short for the ion to attain the necessary ionizing velocity.

The third type of conduction, electrolytic, need be mentioned only briefly in connection with this study. The absence of moisture or liquid of any sort eliminates almost entirely the possibility of conduction by this means. Essentially electrolytic conduction resembles ionic conduction. It is evidenced by the transfer of matter to the electrodes.

b. Anomalous properties of dielectrics. The so-called anomalous properties of dielectrics refer to those phenomena which actually occur in dielectrics but which are not explainable on the basis of the theory of perfect dielectrics.

Foremost among the anomalous properties is the phenomenon of dielectric absorption. It is a well-known fact that a certain amount of time is required for the complete charging — or discharging — of a condenser and that the length of time depends upon the nature of the particular dielectric concerned. In general it can be said that upon sudden application of the voltage a very large current flows which more or less rapidly dies down to the steady-state current, that current which flows by virtue of the leakage conductance of the dielectric.

The phenomenon of dielectric absorption was recognized in the earliest days of electrostatic experiment. From that time to the present various theories have been proposed to account for the dielectric absorption. Recently the phenomenon has been considered more than merely an interesting problem and has been investigated commercially. Inasmuch as an appreciable current may flow for a finite period of time even in a material which has essentially no steady-state conductivity, the final or steady-state conductivity may be of little importance. Hence the value of apparent conductivity after a given time of voltage application has been chosen arbitrarily in some instances to represent the actual conductivity of the specimen. In general this time is taken as one minute (31). The phenomenon is important in the design of alternating current equipment in which the reversal of voltage occurs so rapidly that the decaying current does not have sufficient time after an application of voltage in one direction to decrease much from its high initial value before the voltage reversal occurs and the high initial current flows in the other direction. This cycle of voltage causes the magnitude of the current to oscillate between the initial value of current and some lower value. Hence it is not always the final value of conductivity which is important or effective but some higher apparent value.

The theories proposed to explain the phenomenon are in the main divided into two classes. Maxwell's Theory, in which he assumed no new hypotheses beyond the fundamental laws of electricity, is the basis of one class and is also representative of that class. The second class includes those theories which attempt an explanation on the basis of new hypotheses concerning the electrical behaviour of matter.

Maxwell's theory (27, p. 376) is based solely upon two electrical properties of matter, electrical conductivity and dielectric constant. The assumption is made that no dielectric is absolutely homogeneous. In other words, any dielectric is made up of at least two component materials and may be replaced by layers of each material. The theory may thus be thought of as applying to all dielectrics or combinations of dielectrics. It may best be explained, therefore, by considering a parallel-plate condenser having two dielectrics in series. Both the electrical conductivity and the dielectric constant of the materials are, in the general case, different. If a voltage is suddenly applied to the condenser, the voltage gradient across each of the two dielectrics at the first instant may be shown to vary inversely as their dielectric constants (33, p. 32).

As a result of this unequal voltage distribution and as a result also of the unequal electrical conductivities, the currents tending to flow in the two layers of the dielectric are not the same. Therefore a charge collects at the surface of separation. This charge continues to build up until the potential gradients gradually assume values determined by the individual conductivities such that the currents in the two media are the same. The current flowing after steady-state conditions are obtained is called the conduction current. That flowing previous to steady-state is the sum of the conduction current and the absorption or anomalous current.

There is slight experimental verification for this theory. Its greatest appeal lies in the fact that it introduces no new ideas. It is certainly not the complete explanation, however, since it predicts dielectric absorption in all non-homogeneous dielectrics or in multi-layered dielectrics, a condition which is not in every instance true. Maxwell, himself, admitted that the theory did not satisfy all cases. He says (27, p. 381):

> This investigation shows that a dielectric composed of strata of different kinds may exhibit the phenomena known as electric absorption and residual discharge, although none of the substances of which it is made exhibit these phenomena when alone . . . It by no means follows that every substance which exhibits this phenomenon is so composed, for it may indicate a new kind of electric polarization of which a homogeneous substance may be capable, and this in some cases may perhaps resemble electrochemical polarization much more than dielectric polarization.

Maxwell proposed an additional theory or qualification which may be considered in the second class. He pictured an elastic ether pervading all space and matter. The electric field was assumed to displace or strain the medium, the displacement being opposed by the elastic forces.

The latter were considered as being different when the ether was in the presence of molecules of different kinds to explain the diverse action of the various dielectrics. That this idea is erroneous is obvious with the present knowledge.

Among the first to attempt to explain the action of dielectrics based upon observed results was Helmholz, in 1870 (19). He proposed that the molecules be considered as containing charged particles which were drawn out of their equilibrium positions by the electric field, the rate of change of the position decreasing with time as a result of the increasing elastic restraining forces in the molecule. This theory accounts for the rapid decrease in current from the high initial value. Recent studies substantiate this theory insofar as they indicate the displacement of the electron within the atom resulting in an electric doublet.

Helmholtz's theory, however, has been found to hold only for dielectric materials such as gases and some liquids in which the time necessary for complete absorption is very small. Test results on all materials show the large initial current and the exponential type of decrease with time, but in the case of many solids and liquids the time of absorption approaches as much as several hours or even days, a very long time compared to the minute portion of a second predicted by this theory. Although the absorption phenomenon may in part be due to this cause, evidently some other theory must be introduced to complete the picture for all dielectrics. Maxwell approached this idea when he assumed that his elastic ether had different restraining forces in the presence of different dielectric media.

Houllevigue (20) developed a theory in which he attributed the phenomenon of absorption to the viscosity of the material in the dielectric. He assumed from Maxwell an elastic ether in which the molecules were suspended and attached by some elastic connection. Under the influence of an electric field the ether was displaced in the direction of the field until elastic equilibrium was obtained. In the case of perfect dielectrics this was an instantaneous effect. For dielectrics exhibiting absorption the molecules were assumed to yield under tension, their mean position displaced, and the displacement of the ether increased further by the molecular displacement. Thus the theory as applied to an imperfect dielectric divides the displacement into two parts: first, an instantaneous displacement of the ether occuring until the elastic forces between the ether and the molecules are in equilibrium, and second, an additional gradual yielding of the molecules under tension caused by the first displacement. This theory introduces the laws of viscocity in which the displacement current depends not only upon the displacement itself but upon the rapidity with which it takes place. In other words, there is introduced a frictional reaction proportional to the velocity of movement. Thus far, with the exception of the original conception of molecules suspended in the ether, the theory seems to approach a similarity to physical conditions. An additional point in its favor is the prediction of heating resulting from the frictional losses. This heating is very decidedly noticeable with alternating stresses. With the exception of the viscosity influence, however, no explanation may be found for the difference between the phenomena in different dielectrics or the difference between ideal and imperfect dielectrics.

Pellat (34 and 35) also refused to make any direct explanation of the cause of polarization. He merely attempted to prove experimentally that dielectrics when subjected to an electric force show an initial instantaneous polarization or displacement in addition to a polarization which changes with time. He proposed the law that the latter or variable part of the polarization tends to a final value which is proportional to the applied electric force and that its rate of change is always proportional to the amount by which it differs from its final value. The result is a negative exponential variation.

Von Schweidler (44) extended Pellat's proposal with the aim of supplying a picture of the underlying mechanism. His theory traces the cause of absorption to high frequency oscillations of the molecular charges. Inasmuch as a purely exponential form of the current-time curve is seldom observed, he assumed the presence of several types of molecules which oscillate with different degrees of damping, thus introducing a series of such exponential terms, resulting in a close approximation to experimental results.

Décombe (8) went further and assumed that the movement of charge was within the atom and that the rate of displacement of this charge from its equilibrium position was the cause of the absorption current. To account for the slow rate of decay of this current in some materials he assumed a varying viscosity within the atom.

At this point it is well to state that though there are a few theories based upon various conditions of conductivity which result from an irreversible charging current, these should not be confused with those concerning the reversible current, that is, a charging current which is observed in the opposite direction upon removal of the electric field. The irreversible current is generally associated with liquid, though it exists also in some solid dielectrics; it is considered to be the result of the removal of certain free ions from the dielectric. None of the theories are very outspoken on the subject.

Probably the most reasonable and applicable theory is the qualitative theory of Debye (6 and 7). His theory assumes that there are different types of molecules insofar as they may be electrically symmetrical or non-symmetrical with respect to the internal charges. In other words, materials may be divided into two classes, non-polar and polar. The non-polar substances are those which contain molecules which are chemically symmetrical, having the centers of positive and negative charge which coincide so long as the material remains electrically unstressed. Polar substances contain molecules which are chemically assymmetrical; the centers of positive and negative charge are permanently displaced forming a "permanent dipole".

When a constant electrical stress is suddenly applied to those substances which contain the so-called non-polar molecules, they exhibit a short-time polarization or absorption current resulting from the internal straining of the positive and negative charge centers from their common equilibrium position. Upon the removal of the stress the discharge current is noted by virtue of the movement of the charges in returning to their original positions. All substances exhibit this type of absorption current, though it may be, and often is, overshadowed by other types of charge movement, as in the case of metals.

If, on the other hand, a constant voltage is suddenly applied to a polar substance, the absorption current may or may not be noticeable over a long period of time. When the electric dipole is subjected to an electric stress the tendency is for it to rotate into alignment with the electric field, after which a further displacement occurs due to the straining of the charges within the molecule as explained in the instance of non-polar molecules. The rapidity with which the motion takes place is dependent upon the magnitude of the electric field, the electric moment of the dipole, and the freedom which the dipole has to turn. The reason for the first of these is obvious. The greater the accelerating force, the greater is the velocity of the charges. The electric moment corresponds to a couple in the mechanical analogy. The two displaced charges represent the forces, when the field is applied, and the distance between them represents the moment arm of the couple. Thus the greater the distance between the charges and the greater the magnitude of the charges, the greater is the twisting moment applied to the dipole for a given value of impressed voltage. The freedom to turn depends upon the viscosity of the material. For example, in a perfectly rigid material the frictional forces resisting the turning are so great that no rotation is possible. On the other hand the internal frictional resistance to rotation in most gases and some liquids is relatively low. Hence, in the latter materials the motion of the charges is rapid resulting in a high initial current which rapidly dies out. The perfectly rigid material exhibits no polarization current with the exception of that obtained from the displacement of the charges within the molecule itself, a phenomenon which corresponds to the first type of polarization.

Upon removal of the voltage from the polar substance, the molecules resume their random orientation again by virtue of the constant motion or vibration of the molecules. The rapidity with which this random orientation is obtained again depends upon the frictional forces in the material.

Debye's theory may be summarized by saying that there are two types of polarization. All materials exhibit the first type, a rapidly dying out absorption current which occurs as a result of the electrical straining of the charges within the molecules. Other materials, those made up of polar molecules, exhibit an added polarization of a magnitude depending upon the degree of assymmetry of the charge centers in the molecule, the magnitude of the charges, and the viscosity of the material.

This theory may be applied to cases in which the absorption current is not represented by a single negative exponential curve but is made up of several such curves by assuming that the material is made up of different molecules whose electrical moments differ.

The theory of Debye seems best to explain all the phenomena associated with absorption current. It explains also the so-called dielectric hysteresis observed in dielectrics under alternating stress. Since the polar molecules are rotated by the electric field they tend to follow any reversals or changes in that field. However, since there are frictional forces acting to hinder such rotation, there is a decided lag in many cases, resulting in a current-voltage loop similar to the magnetic hysteresis loop. Hence there is a heat loss caused by the frictional resistance of the material to the motion of the molecules, just as in a magnetic material there is a heat loss due to the resistance of the material to the motion of the elemental magnets tending to rotate into the direction of the magnetic field.

A brief discussion of the physical arrangement of polar and non-polar molecules has been given by Morgan (28 and 29).

2. Thermal conductivity

There are three methods commonly recognized by which heat may be conveyed from one region to another (36, p. 601).

The first of these is radiation. It is by means of radiation that heat energy is transferred from stellar bodies or from lamps. Inasmuch as it occurs through space or through a vacuum it is considered as wholly independent of the presence of matter. It may readily be distinguished from the other two by the enormous rapidity with which it advances.

The remaining two modes of heat transfer are dependent upon the presence of matter. Convection characterises the transfer of heat by the material with which it is associated. It is this type which mainly establishes the uniformity of temperature in liquids and plays the most important role in the distribution of heat throughout rooms and buildings.

The third type of heat transfer is known as conduction. Heat carried in this manner does not depend upon any visible motion of matter.

However, it will be shown that matter is nevertheless essential.

In porous materials heat transfer by convection does not, in general, occur since the pore spaces are not sufficiently large for convection currents to be set up.

Radiation may or may not occur depending upon the temperature and the size of the pores. Experiment indicates that radiation is not appreciable until the size of the pores become large or until the temperature becomes relatively high (39, p. 568). This appears reasonable in view of the fact that the radiant heat energy is a direct function of both the temperature and the size of the radiating surface.

The third type of heat transfer, conduction, occurs in all materials. The propagation of heat by this means is a comparatively slow process, and the heat, in travelling through a body in this manner, increases the temperature of the intermediate points and remains partly lodged in them until a steady condition of heat flow is reached.

In order that heat be transferred by this latter means some sort of carrier or some type of heat-energy transfer is necessary.

Drude made the assumption (11) that in metals the carriers of heat were the free electrons. His theory is based on the fact that molecules in the hotter portion of a gas, being free to move, tend to diffuse to the cooler portion. The free electrons being those particles in a metal which are relatively free to move are assumed to act in the same manner. Thus a difference of thermal potential when applied to a metal results in the movement of electrons away from the warm face and toward the cool face. The greater the thermal potential difference, the greater is the rate of diffusion of the electrons.

Lorentz (26, p. 266) followed a similar assumption with respect to the type of carriers. His theory differs from Drude's, however, in the manner in which the thermal conductivity is computed from the free electron theory. The main difference is in the fact that Drude assumed a uniform distribution of the electron velocities whereas Lorentz used Maxwell's distribution law.

With the coming of wave mechanics a new type of electronic distribution was introduced. A theory by Sommerfeld (40) involved the use of this new distribution. However, the assumption was still made that the free electrons were the heat carriers. The Sommerfeld theory differs only in the manner of approach used in determining the thermal conductivity from the electronic characteristics and velocities.

All these theories satisfactorily explain the thermoelectric effect upon the basis of unequal transfer of electrons along the two arms of the thermocouple by virtue of the different thermal conductivities of the two metals. This disarrangement of the charges disturbs the electrical equilibrium and a small electrical potential is built up, the magnitude of which indicates the relative temperature difference between the ends of the thermocouple.

The theories appear further justified by the following experiment: If a metal bar is subjected to a difference of electrical potential a current flows by virtue of the movement of free electrons. If the temperatures are measured at various points along the bar, the temperature is found to vary in a uniform manner from one end to the other.

However, all materials are not metallic. Hence such a theory may not entirely describe the action in these materials. As was mentioned in connection with gases, the carriers are molecules or those particles relatively free to move. Similarly they may be those molecules or ions in a non-metallic solid which are free to move and diffuse into the cooler region of the material. It appears reasonable to attribute the relatively poorer thermal conductivity of non-metals to the fact that the number of free carriers are fewer or more restrained allowing heat to be transferred less readily.

Another conception of the manner in which heat is conducted (36, p. 602) introduces the idea of vibrating molecules or other particles. If the end of a bar of some material is heated by being placed near a hot radiating surface, the waves of radiated heat energy are received by the end of the bar and are used in setting up a vibration in a thin layer of molecules at the end of the bar. This layer at first absorbs the waves almost entirely and protects those behind from the disturbance. Soon, however, the molecules in the first layer have been set in active vibration and themselves become active centers of disturbance. This disturbance may be transmitted to the other molecules either by direct contact or by radiation. The heat energy is thus propagated along the bar by a process of successive absorption and radiation.

Another way of considering the vibration type of heat conduction is to suppose that the first layer of molecules has been forced into resonant vibration by the absorption of the radiated heat energy. As soon as this condition has been reached this layer of molecules offers no resistance, except that energy necessary to keep the molecules vibrating, to the passage of the radiated heat-energy waves into the next layer. Thus the radiated wave progresses through the material by setting the molecules into resonant vibration. Each layer of molecules absorbs just sufficient of the energy of the wave to keep it vibrating. Thus the transfer and attenuation of the heat wave is explained.

In any case the transfer of heat by conduction is certainly dependent upon particles of matter whether they move throughout the material or whether they merely vibrate locally. In addition it is quite probable that those free carriers considered in one type of analysis are the same as those which are considered as vibrating and transmitting heat energy by vibration in the other analysis. This appears reasonable since, in the latter analysis, the rate of heat flow is greater in those materials in which the molecules or particles are most readily set in motion. As the free carriers of the first analysis are less restrained than other particles they will naturally respond more quickly to the vibration disturbance. Thus either analysis is based fundamentally upon the freedom of the particles to move in some manner or other.

The term thermal conductivity is used to indicate the rate at which heat is conducted through a material. It may be defined as the amount of heat flowing in one unit of time perpendicularly through a sample one unit square and of one unit in thickness in the direction of heat flow for each degree of temperature difference on the two faces. Mathematically the relation may be expressed as

$$K = \frac{Q\,d}{t\,A\,\theta}\ , \quad \theta = \theta_1 - \theta_2 \qquad \text{(Eq. 1)}$$

Where Q is the total heat transferred, t is the time, A is the area of the face of the material, d is the thickness of the material, θ is the temperature difference of the two faces, and K is the thermal conductivity. The units in which K is expressed depend upon the units in which the other quantities are measured.

Little can be said regarding the effect of a variation of mean temperature upon the thermal conductivity except that experimental evidence is such as to indicate that the effect is small and that the temperature coefficient of thermal conductivity may be either positive or negative even for metals.

3. Correlation of electrical and thermal conductivity

Forbes (13), in his experiments on conductivity in 1852, first noted that the orders of the thermal and electrical conductivities of metals were the same. He observed that those metals which were the best conductors of electricity were also the best conductors of heat.

A few years later Wiedemann and Franz (47) from their experiments on metals, pushed the analogy further and concluded that not only were the orders of the two conductivities the same but that their ratio was essentially a constant. Considerable work has been done in an attempt to prove or disprove the theory. The more recent measurements are in general agreement that the approximate constancy of the ratio is valid for pure metals.

For alloys or non-metals the proportionality relationship has not been found to hold in every case although the order of the two conductivities is still generally the same.

The theoretical treatments by Drude (11), Lorentz (26), and others predict a different value for the constant ratio but agree on the order of magnitude of the constant. The difference arises, of course, from their different manner of treatment of the problem. The constant obtained from Drude's simpler theory agrees with experimental results quite well. Drude, however, as has been mentioned, failed to take into account Maxwell's velocity distribution. Lorentz, who used this distribution, obtained theoretically a more rigorous proof but one which agrees less well with experimental results although his constant is still of the same order of magnitude.

These theories are all based on the fact that both heat and electricity are conducted by the free electrons in the metals. The electrical conductivity is calculated by assuming that the current flow is the result of the number of free electrons, the charge on each electron, and the mean velocity of the electrons. It is in this last assumption that the main differences occur in the theories.

The thermal conductivity is obtained from the kinetic theory of gases by assuming that the electrons act as gas molecules, their number and velocity determining the value of the conductivity.

The ratio of the relations thus obtained gives a constant. Variations in the constant are evidently the result of some factors which are not taken account of in the theories as derived.

It is interesting to note that the theories give the ratio as a direct function of the absolute temperature, a fact which is substantiated experimentally by the manner in which the electrical resistivity of metals varies directly with the temperature and the comparatively total lack of any such variation in the thermal conductivity with temperature.

In the case of non-metals and some metallic alloys the thermal conductivity is considered as broken into two components (21, p. 76), one of which obey the Wiedemann-Franz Law. The other is attributed to the non-metallic or non-homogeneous qualities of the material. This latter portion of the conductivity is the more important in materials whose thermal conductivities are low. Experiments indicate that as a general rule the Wiedemann-Franz ratio is higher for materials whose conductivities are relatively low (21, p. 91). The reason for this is that the non-metallic portion of the conductivities becomes more important as the metallic character and hence the electrical conductivity becomes smaller.

B. Test Methods and Equipment

There are a number of different types of apparatus which have been used in making measurements similar to those made in this study, and, in most cases, different testing techniques associated with each. This section is devoted to a brief description of those types of equipment and to the objections and advantages connected with their use in the present study.

1. Electrical conductivity

Gilchrist and Klinefelter (14) carried on experimental work with porcelain mixes to determine the effect of different ingredients upon dielectric strength. The material was molded into a cup and placed in a shallow mercury bath to form one electrode. The other electrode was formed by covering the bottom of the cup with a thin layer of mercury. The dielectric strength was determined by applying a sixty-cycle voltage at the rate of three or four kilovolts per second until breakdown. A similar method might conceivably be used for direct current measurements of electrical conductivity using a sensitive galvanometer as the current measuring device. For the materials used in this study, however, the objections were several. In the first place the specimens were already supplied in a definite shape and form. Thus the cup idea was out of the question. The use of mercury contact on such porous materials as were tested would have given very inaccurate results due to the great amount of absorption which would have taken place resulting in semi-conducting paths of mercury through the material. An additional feature which made the equipment impractical for conductivity tests was the fact that no means of eliminating surface leakage from the measurements was included.

Whitehead and Marvin (46) measured the direct-current conductivity of certain waxes and oils by means of a D'Arsonval galvanometer having a sensitivity of $4x10^{-10}$ amperes per centimeter. The voltage was applied by a bank of storage batteries. The test sample was placed between the plates of a condenser; the plates were approximately sixty centimeters in diameter. To prevent surface leakage one of the plates had a narrow guard ring around it. The entire apparatus was enclosed in a container and placed in an electrically heated oil bath for the purpose of temperature control.

The adoption of this method of measurement to the determination of the conductivity of porous ceramic materials would necessitate several changes. In the first place the feasibility of using test specimens of the dimensions suggested is questionable. Then, with the smaller, thicker samples the voltage applied would necessarily have to be greater. The increased voltage would result in a leakage which would probably eliminate the possibility of using the oil bath as a means of temperature control.

Whitehead and Marvin also measured the absorption current for waxes and oils. The equipment was essentially the same except for the current recording device. The galvanometer consisted of a strong electromagnet having a quartz fiber under tension in the air gap. The current variations resulted in a movement of the fiber, the shadow of which was thrown on a sensitized film moving at a constant rate. The trace of the shadow indicated the variation of the current with time. In the case in which the absorption current continues over a relatively long period of time such a precise piece of current-measuring equipment is unnecessary.

Benedict (1) measured the leakage current and charging current for condensers having dielectrics of such substances as mica, glass, paraffin, varnish, cloth, and so forth. His equipment consisted of thin sheets of the dielectric fitted with lead foil electrodes. A number of the specimens were connected in parallel and clamped together. It will be noted that here again no attempt was made to eliminate surface leakage. The conduction current was measured on a galvanometer having a sensitivity of $7\text{x}10^{-10}$ amperes per millimeter. As such thin specimens were used it was both possible and necessary to use low voltages.

The use of the above equipment in this study is outlawed on several points. First, as mentioned, no provision was made to prevent surface leakage. Then, the size of the specimens used was unsuitable for the case at hand. Last, the assumption of the uniformity of specimens automatically made by connecting several in parallel can certainly not be even approximately justified for most ceramic conductivity specimens.

The charging current was measured by a special amplifying device and an oscillograph. The timing was done by means of an intricate piece of equipment in which the switching was done by a rapidly moving projectile fired from a gun.

The fine timing apparatus is unnecessary in tests on materials in which the absorption current persists over longer periods of time.

Haworth (18) measured the conductivity and dielectric hysteresis of glazed porcelain discs about twenty centimeters in diameter and about one-half centimeter thick. He connected two plates in parallel and, using tinfoil electrodes, applied a direct voltage of four thousand volts by means of storage cells. His current measuring apparatus was mainly a highly sensitive galvanometer (0.5×10^{-10} amperes per millimeter at a distance of two meters).

The humidity was kept as low as possible by placing the specimen in an air tight vessel with a drying agent. An oil bath around the vessel was used to control the temperature.

The method used by Haworth takes no account of the surface leakage as is necessary for accurate measurements. In addition his method assumed that the specimens were identical, an assumption which, as has been mentioned, is not completely justified.

The dimensions of the test specimens were such that relatively low voltages could be used on them for the conductivity measurements. The construction of the air-tight vessel was permitted by the low voltages used. The sizes of the specimens used in the present study were such as to necessitate the use of high voltage resulting in leakage which would prevent the use of the temperature control method used by Haworth.

Additional experimental work on electrical conductivity and its related subjects has been done by Mouline (30) and others. However, the equipment described above is representative of the majority of the features incorporated into the different types of apparatus.

In very few of the investigations is any attempt made to do more than present the results and in fewer cases is any relation shown between the electrical properties of the material and other physical properties.

2. Thermal conductivity

There are a number of methods which have been used to measure thermal conductivity. The older methods involve the use of steam heat and the measurement of the rate at which the cooling water at the cold plate is warmed. Others, somewhat more recent, use electric heaters with no guard rings. In some instances an attempted correction is made for the non-linear or lateral flow of heat around the edges of the heater. The shape of specimens also differ with different methods of test and with different investigators. One method makes use of a cylindrical sample with the heat applied along the central axis. Another method, and the one which adapts itself most readily to the majority of test materials, is the flat specimen. The heat is applied to one face by either steam or electrical means. Guard rings may or may not be used.

Despretz (9 and 10) was about the first to make observations on the thermal conductivity of metals. His experiments, however, give only qualitative results. He measured the temperature at different points along similarly shaped bars of different materials heated at one end by the same source. The lower gradient indicated the high conductivity.

Péclet (32) caused steam to be blown against one face of the specimen. Ice was placed on the other face. The rate at which the ice melted indicated the rate of heat flow through the material. The temperatures of the two faces were the temperatures of the steam and ice. The thermal conductivity was calculated from these measurements.

Forbes (13) measured the thermal gradient in metals by immersing one end of the metal rod in a bath of molten lead held at a constant temperature. The bar used in the test was so long that the temperature at the other end was not sensibly raised during the eight- or ten-hour experiment. The temperatures were measured by means of thermometers placed in small holes along the length of the rod.

His equipment was adopted by Callendar and Nicolson in 1898 (12) to determine thermal conductivity. They kept one end of the bar in a bath of steam and the other in a calorimeter through which cooling water was run. To prevent surface radiation they covered the bar with a material of low conductivity. Temperature measurements were made as before. After steady temperature conditions were obtained the rate at which the heat was carried away by the cooling water in the calorimeter was measured and the thermal conductivity was calculated.

The methods just described are fairly accurate so long as the material is of high conductivity. For materials of lower conductivity somemeans is needed to prevent the measurement of the lateral heat flow that occurs. Berget (2) used a method called the wall method in which he contrived to measure the melting ice over the center portion of the cold face of the test sample. The region outside the center, nearer the edges where the lateral flow occurs, was also in contact with the ice but the rate of melting was not measured and not included in the calculations.

The effects of lateral heat flow were thus eliminated from the calculated value of the thermal conductivity.

Callendar and Nicolson (3) used the cylinder method in which the center hole was heated by steam and the rate of heat flow obtained by measuring the amount of condensed steam in a given time.

Lees (24) used a modification of the wall method. He used a central, electrically heated plate with an identical specimen on each side. The heat supplied was measured by a wattmeter. The temperatures of the faces were obtained from thermocouple readings. The heat loss through the air at the edges by conduction and radiation was estimated on the basis of surface emission.

Lees also made tests on insulators and metal rods (22 and 23). In the latter case one end of the rod was wound with an insulated heating element wire. The heat flow was measured electrically and the temperatures were measured by platinum thermocouples.

More recent investigators have used modifications of either the cylinder method or the wall method for determining the thermal conductivity of materials in which the conductivity is low.

Clement (5) investigated the thermal conductivity of fire clay at high temperatures by means of the cylinder method.

Carman and Nelson (4) used a similar method in the determination of the thermal conductivity of concrete.

In order to measure the thermal conductivity of walls, concretes, and plasters Griffiths (15, 16, 17) used the wall-type method both with and without guard rings. In the latter case he corrected for the lateral leakage by estimating the amount of heat which escaped through the cork which was placed around the edges of the samples to reduce the lateral flow to a minimum. He used the idea of identical specimens to eliminate the unknown loss of heat from the side of the hot plate away from the sample. The heat was supplied electrically and the temperatures were measured by thermocouples.

Van Dusen (43) also made use of the guard ring method for obtaining the thermal conductivity of a large number of materials all having low values of conductivity.

Willard and Lichty (48) used the wall method with two identical samples in their experiments on the conductivity of walls. No guard ring was included in their equipment.

The apparatus used in the present study was patterned after those of the guard ring type used by Griffiths and Van Dusen.

3. Correlation of electrical and thermal conductivity

Nearly all the investigators of thermal conductivity have at some time either obtained or borrowed values of electrical conductivity in order to prove or to disprove the validity of the conclusions reached by Lorentz, Wiedemann and Franz, and others regarding the relationship between the thermal and electrical conductivity. Most of these comparisons have been made on metallic materials and appear to agree with the theory that the ratio of the two conductivities is essentially constant for a given temperature.

Griffiths (15) compares the Lorentz constant for several alloys at different temperatures. His results indicate a very close agreement with theory. Schofield (37) made similar measurements on pure metals.

Other experiments agree more or less closely depending upon the purity of the materials and the accuracy of the measurements.

4. Porosity

The term porosity refers to the amount of pore space existing in a material. It may be expressed in several ways (39, p. 99), as the percent by volume, as the percent by weight, or as the percent absorption.

The first of these is obtained by expressing the volume of voids as a percentage of the total volume of the specimen. Since there are sealed pores present the actual volume of the voids can only be determined by finely pulverizing the material and comparing the net volume of the powder to that of the specimen when whole. The powder must, of course, be so fine that no pores remain still sealed. The work and time involved in obtaining the powdered condition is prohibitive in many instances. Another objection to this method is the fact that the material must be completely destroyed for the determination. Still another objection arises in the manner of measurement of the net volume of the powder. The latter is done by the method usually employed in measuring the voids in concrete aggregate. In this instance, however, the particles are so fine that to make use of this type of measurement is rather difficult.

The porosity when specified as the percent by weight is the difference between the specific density of the material when powdered and when whole expressed as the percentage of the specific density of the specimen when whole. Inasmuch as the material must necessarily be powdered the same objections arise here as in the preceeding method.

The two methods just described give the true porosity. A third method may be used in which the results are approximate though comparable.

The porosity when measured as the percent absorption by weight is the difference between the weights of the specimen when dry and when it has absorbed as much water as possible expressed as the percentage of the dry weight.

Since there are closed pores which no water enters this method, of course, yields only approximate results. However, if the assumption is made that the same percentage of pore space in different specimens is sealed, the results obtained may be considered as giving proportional values of the porosity. Hence the method may be considered as sufficiently accurate for the purpose of comparing the properties of materials on the basis of porosity.

III. ANALYSIS

In the proceeding section is a discussion of the factors influencing the conductivities of simple homogeneous materials. The present investigation, however, involves the study of ceramic products which are made up of several elements and two distinct types of material. For that reason this section has been included to assemble and apply the theories of electrical and thermal conductivity for homogeneous materials to those which are not homogeneous and to show the manner in which these properties might be expected to vary with different materials and different relative porosities.

A. Electrical Conductivity

1. Factors influencing electrical conductivity in non-homogeneous dielectrics

Consider first a combination of two materials A and B having uniform cross-section but different electrical resistivities placed in a series circuit, as shown in Fig. 1. The resistance of the system, assuming a constant, uni-directional impressed voltage, may be calculated from the formula

$$R = R_aL_a + R_bL_b \qquad \text{(Eq. 2)}$$

where R is the total resistance, R_a and R_b are the resistances per unit length of A and B, respectively, and L_a and L_b are the lengths of A and B, respectively, in the direction of current flow.

Conductors in Series

Figure 1

Dielectrics in Series

Figure 2

Since L is the sum of L_a and L_b, where L is the total length of the combination, the resistance equation (Eq. 1) may be written

$$R = R_a(L_a) + R_b(L - L_a) \qquad \text{(Eq. 3)}$$

or

$$R = L_a(R_a - R_b) + LR_b \qquad \text{(Eq. 4)}$$

This is a linear equation in which R and L_a may be considered as the variables. Thus, if R_a is assumed larger than R_b, the resistance of the combination increases linearly with the length of material A so long as the total length, L, remains the same.

Electrical conductivity may be expressed by the equation

$$C = \frac{L}{AR} \qquad \text{(Eq. 5)}$$

where C is the conductivity, L is the total length, A is the cross-sectional area, and R is the total resistance as obtained from Eq. 4. As both A and L are constants the conductivity is an inverse function of the total resistance and hence an inverse function of the length L_a of material A.

If a porous material be chosen in which the pore spaces and the solid are assumed to be effectively segregated into two distinct layers and placed side by side a similar situation may be imagined.

As the resistance of air is greater than that of any solid material, the air may be thought of as representing material A and the solid as representing material B.

The overall dimension of the pore spaces in the direction of current flow is thus called L_a and that of the solid L_b. The electronic conductivity may be shown then, as for metals, to be inversely proportional to the length L_a so long as L remains constant.

The fictitious arrangement of segregated components of the material may be considered, however, only in the case of pore spaces which are statistically uniform in both distribution and shape. In the materials used such a statistical assumption may be made. In addition it must be mentioned that although the materials are no longer metals the inverse relation between conductivity and the length of the current path through one material is still valid for electronic conductivities.

The length L_a is a measure of the porosity of the material by volume. Thus the conductivity which a porous material exhibits by virtue of the flow of free electrons is inversely proportional to the percent porosity by volume of the material.

However, electronic conduction does not in general contribute greatly to the conductivity of dielectrics. The phenomenon of ionic conduction is much more prevalent. In the case of conduction of electricity by ions the same analysis, while perhaps approximately true, can not be applied exactly since there is a non-linear relation between voltage and current. The resistance per unit length may not be considered as a constant as was done in the case of electronic conduction.

The analysis in this case may best be made by considering the action of the voltage gradient immediately after the voltage is applied to the specimen (33, p. 32).

Assume a parallel plate condenser with two dielectrics of different dielectric constants placed in series between the plates, as shown in Fig. 2. The flux concentration at the edges of the plates may be neglected so far as the analysis is concerned.

Let

C_1 = the capacity of the condenser formed by the upper plate, dielectric one, and the boundary surface between the two dielectrics.

C_2 = the capacity of the condenser formed by the lower plate, dielectric two, and the boundary surface between the two dielectrics.

C = the total capacity of the system.

x_1 = the thickness of dielectric one.

x_2 = the thickness of dielectric two.

x = the total thickness of the two dielectrics.

e_1 = the voltage across dielectric one.

e_2 = the voltage across dielectric two.

e = the total voltage across the condenser.

k_1 = the dielectric constant of dielectric one

k_2 = the dielectric constant of dielectric two.

A = the area of one condenser plate.

g_1 = the voltage gradient across dielectric one.

g_2 = the voltage gradient across dielectric two.

g = the apparent voltage gradient across the entire condenser.

Q_1 = the charge on dielectric one.

Q_2 = the charge on dielectric two.

Q = the total charge on the condenser.

For the parallel plate condenser formed by the upper plate, dielectric one, and the dielectric boundary surface

$$C_1 = \frac{k_1 A}{x_1} \qquad \text{(Eq. 6)}$$

and for the similar condenser formed by the lower plate and the second dielectric

$$C_2 = \frac{k_2 A}{x_2} \qquad \text{(Eq. 7)}$$

The expression involving the charge on the first condenser may be written

$$Q_1 = C_1 e_1 \qquad \text{(Eq. 8)}$$

from which

$$Q_1 = \frac{k_1 A}{x_1} e_1 \qquad \text{(Eq. 9)}$$

Similarly

$$Q_2 = C_2 e_2 = \frac{k_2 A}{x_2} e_2 \qquad \text{(Eq. 10)}$$

But in a series condenser circuit

$$Q_1 = Q_2 = Q \qquad \text{(Eq. 11)}$$

Hence

$$e_1 = \frac{k_2 x_1}{k_1 x_2} e_2 \qquad \text{(Eq. 12)}$$

or, since $e_1 + e_2 = e$

$$e = e_2 + \frac{k_2}{k_1} \frac{x_1}{x_2} e_2 \qquad \text{(Eq. 13)}$$

$$e_2 = \frac{e}{1 + \frac{k_2 x_1}{k_1 x_2}} \qquad \text{(Eq. 14)}$$

Similarly

$$e_1 = \frac{e}{1 + \frac{k_1\ x_2}{k_2\ x_1}} \qquad \text{(Eq. 15)}$$

The voltage gradients are then

$$\mathcal{E}_1 = \frac{e_1}{x_1} = \frac{e}{x_1(1 + \frac{k_1 x_2}{k_2 x_1})} \qquad \text{(Eq. 16)}$$

$$\mathcal{E}_2 = \frac{e_2}{x_2} = \frac{e}{x_2(1 + \frac{k_2\ x_1}{k_1\ x_2})} \qquad \text{(Eq. 17)}$$

If one of the dielectrics, number one, is air, k_1 becomes equal to one and the equations may be rewritten

$$\mathcal{E}_1 = \frac{e}{x_1(1 + \frac{x_2}{k_2 x_1})} = \frac{e}{x_1 + \frac{x_2}{k_2}} \qquad \text{(Eq. 18)}$$

and

$$\mathcal{E}_2 = \frac{e}{x_2(1 + \frac{x_1 k_2}{x_2})} = \frac{e}{x_2 + x_1 k_2} \qquad \text{(Eq. 19)}$$

The apparent voltage gradient across the system is given by

$$\mathcal{E} = \frac{e}{x_1 + x_2} = \frac{e}{x} \qquad \text{(Eq. 20)}$$

Therefore, unless k_2 is also equal to unity, it is quite evident that the apparent initial voltage gradient across the system is merely an average value and in no way represents the true state of electrical stress existing in the separate materials. The true initial gradients are dependent upon the relative magnitudes of x_1 and x_2 and, of course, upon the value of k_2.

If the porous test material is again considered as being divided into the two distinct layers containing the air spaces and the solid, respectively, the above analysis may be applied. Let dielectric one represent the air, inasmuch as that dielectric has already been assumed to have a dielectric constant of unity, and dielectric two represent the solid matter. Again, x_1 is an approximate measure of the percent porosity by volume of the material. Hence it is evident that, given a constant value of k_2 other than unity, the percent porosity influences very greatly the voltage gradient across each portion of the material. Fig. 3 indicates graphically the inverse manner in which the voltage gradients vary with the porosity. One hundred percent on the abscissa represents a value of x_1 equal to one and x_2 equal to zero, whereas zero percent indicates that x_1 equals zero and that x_2 equals one. The curves are all drawn for a unit impressed voltage and for dielectric constants varying from one to five.

The final values of the voltage gradients across the two component parts of the material must be such that they will produce a uniform current flow throughout the material. The initial impressed gradient is not, in general, of such a nature. In a combination of two metals the gradient is initially uniform. The current through the lower resistance metal is thus higher at first than that through the higher resistance metal. However, this condition of unequal current flow can not exist in a series circuit.

In order for the current flow through the two metals to be the same

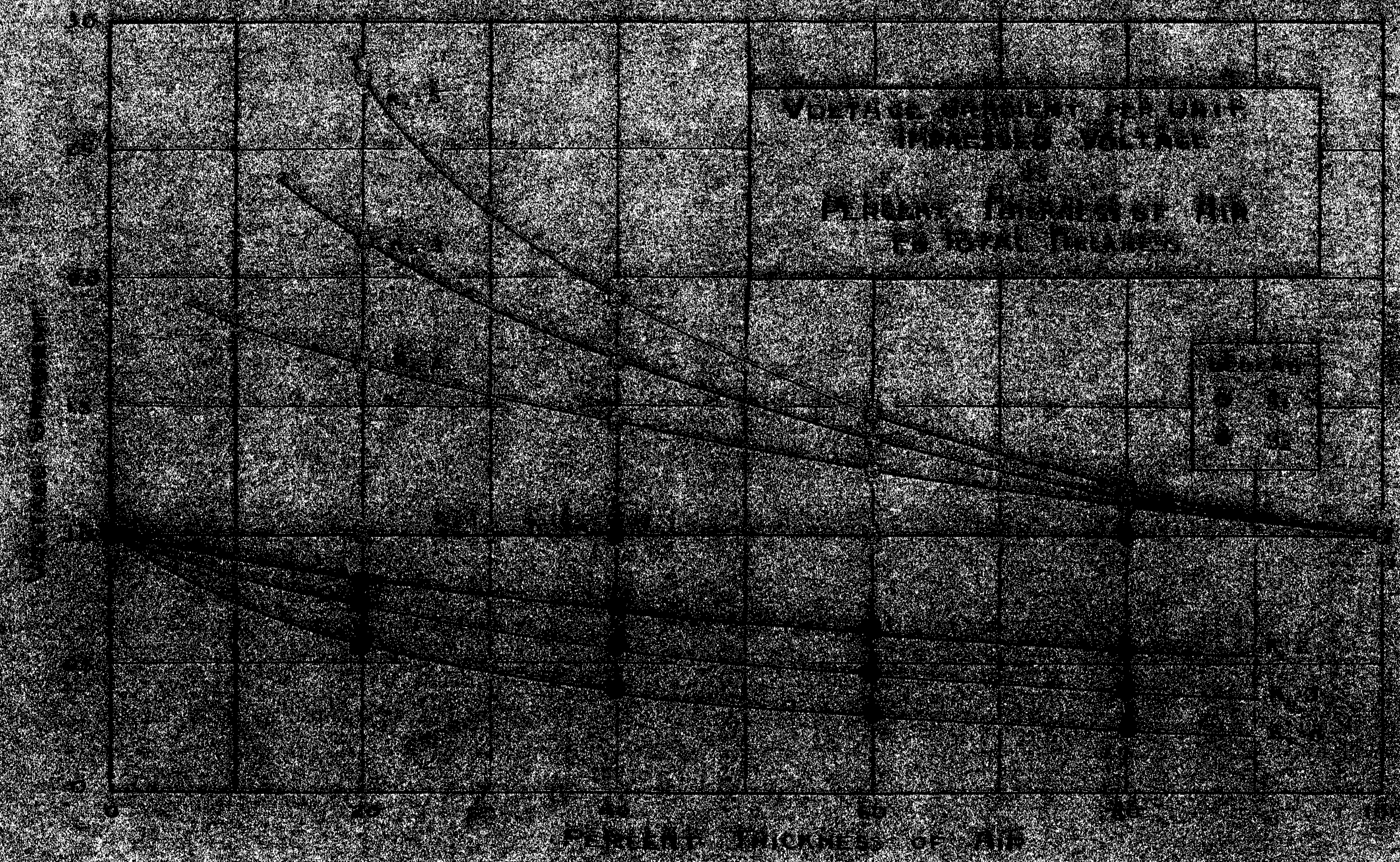

VOLTAGE GRADIENT PER UNIT IMPRESSED VOLTAGE
vs
PERCENT THICKNESS OF AIR
TO TOTAL THICKNESS
3.0
2.5
2.0
1.5
1.0
0
20
40
60
80
100
PERCENT THICKNESS OF AIR

Figure 3

either the voltage gradient on the portion of the system having the lower resistance must decrease or that on the portion having the higher resistance must increase or both changes must occur. Hence excess charges are deposited on the boundary surface between the two metals until a sufficient charge is built up to establish an equilibrium between the voltage gradients and the conductivities of each portion of the system such that a constant uniform current flows in the circuit. This building up of charge in the case of electronic conduction occurs so rapidly in metallic systems as to generally escape observation.

The same analysis may be applied also to the electronic conductivity of non-metallic systems.

The voltage gradient adjustment just mentioned does not affect the final value of the electronic conductivity or the electronic conduction current in either metals or non-metals since the relationship between conductivity and porosity was based upon the constancy of the values of the resistivities of each material, a condition which is obtained for electronic conduction inasmuch as the electronic current-voltage relations are linear.

It will be shown that the voltage gradient adjustment does, however, affect the ionic conductivity.

If the material is again considered to be arranged in such a way that the solid and air are separated into two layers, the initial current will be less for increasing lengths of air path, that is, for increasing porosities, since the voltage gradients are less, as evidenced by Fig. 3.

The magnitude of this current will depend largely upon the motion of ions and, further, upon the motion of ions in that material for which ionic conduction is greatest for the existing initial voltage gradient in that material. Thus the initial ionic conduction current is also an inverse function of the porosity.

To establish a uniform flow of current the voltage gradient on the material for which the conduction is greatest must decrease and that on the other material must increase. This is accomplished in a manner similar to that described for electronic conduction with the exception that ionic charges are deposited upon the dielectric boundary rather than electronic charges.

If the current and voltage were assumed to vary linearly, the final conduction current would have the same type of variation with porosity as that obtained for electronic conduction. However, with the voltages used in this study the gradients were sufficiently high to produce ions by collision and thus to cause a very rapid non-linear increase of current with voltage.

The effect of this non-linear variation on the conductivity of the system may be shown as follows:

The assumptions are first made that the current-voltage curves for the two materials, air and solid, are similar in shape and that the gradient in the air being greater than that in the solid tends to produce a greater current flow than does the initial gradient in the solid. In this case the voltage gradient on the aid must necessarily be reduced and that on the solid must be increased in order to establish uniform current flow in the series system. Since the current-voltage curves in the voltage range used are in the general shape of higher order curves, resembling parabolas open upward rather than straight lines, any change in the voltage and consequently in the current tends to change the resistance of that portion of the system.

An inspection of the equation of the resistance of a series circuit

$$R = L_a(R_a - R_b) + LR_b \qquad \text{(Eq. 21)}$$

or

$$R = L_aR_a + L_bR_b \qquad \text{(Eq. 22)}$$

readily indicates that such a change in the component resistances, except in special cases, changes the total resistance and hence the conductivity of the system.

Two cases illustrate the manner in which the conductivity relation of such a system differs from the purely inverse relation found in the electronic case where the component resistances per unit length were constant. Since the voltage gradient across the air decreases, the current through that portion of the substance also decreases. The resistance R_a is thus increased by virtue of the curvature of the current-voltage curve. Likewise the resistance R_b is decreased by the increase in voltage gradient across the solid.

For very low porosities L_a is very small compared to L_b. Hence the product L_aR_a may be considered as relatively unimportant compared to the product L_bR_b. Thus with a decreased value of R_b the result is a decreased total resistance and a consequent increase in the conductivity. For high porosities the situation is reversed and the result is a decreased conductivity. It is apparent, therefore, that the relation between ionic conductivity and porosity is represented by a steeper curve than that obtained for the purely electronic case.

Thus it appears that the ionic conductivity of a combination of materials such as was used in this study decreases with increasing porosity, and that the variation is more pronounced than would be obtained if the resistances remained constant as in the case of electronic conductivity. In other words, the conductivity varies as an inverse function of the porosity raised to some power greater than one.

The total conductivity is the direct summation of the two conductivities of the material, electronic and ionic. However, since the electronic conduction is present in only small quantities, the manner in which the ionic conductivity varies may be considered as representing the manner of variation of the total conductivity.

It must be understood, however, that the discussion is based upon the fundamental assumption that the different voltage gradients in the air and the solid cause more ionization in the air than in the solid. If the reverse is true, then the manner of variation is also reversed and the conductivity-porosity curve for ionic conduction will decrease less rapidly than the inverse first power relation between conductivity and porosity. If, in addition, the normal conductivity of air is greater than that of the solid, the conductivity-porosity curve will rise with increasing porosities. That the original assumptions are correct is verified by the experimental results presented in the next section.

The assumption has also been made in comparing the brick on the basis of their ionic conductivities that the air in the pore spaces was all at atmospheric pressure or at some other constant pressure. Since some of the pores are closed this is probably not true. However, for the purpose of analysis it appears reasonable to suppose that the effects of those pore spaces containing air under pressure and those undoubtedly existing in which there is a partial vacuum are sufficiently well balanced that the net effect resembles the situation which would be obtained with atmospheric pressure in all the pores.

It should be mentioned here also that the analysis has been based upon the percent porosity by volume whereas the test results were plotted as a function of the percent absorption by weight. The reason for this is readily justified on the basis of the similarity between the two measures of porosity. Each indicates the relative volume of pores present. The analysis is much simpler to carry through for the volume of pores while the measurements of porosity were much more readily made by the absorption method.

2. Anomalous properties of dielectrics

The theory of Debye concerning the anomalous properties of dielectrics appears to explain most completely the phenomenon of dielectric absorption. It is his theory which is used in this discussion in predicting the manner in which the current might be expected to vary with time for materials of the type used for test purposes.

Briefly, again, Debye's theory is based upon the assumption that molecules may be classed as non-polar and polar. Each type contributes to the absorption current, though in different degrees. Non-polar molecules differ from polar molecules in that the latter contain centers of positive and negative charge which do not coincide. The absorption current produced by the non-polar molecules is the direct result of the strain motion of the electrons within the atom. Polar molecules exhibit absorption by virtue of the rotation of the dipoles formed by the assymmetrical arrangement of the charge centers.

When an electric field is applied to a material containing non-polar molecules the result is a displacement of the electrons from their natural orbits. Internal stresses developed during this action limit the degree of displacement. The absorption current is proportional both to the velocity of these electrons in the direction of the field and to their number. The time required for the change of position is so small, in the order of 10^{-10} seconds (31), that this type of polarization is generally not considered.

Polar molecules are seen, therefore, to be responsible, in general, for the entire measurable absorption current in materials made of a single solid substance. The effect of several component substances on the absorption current will be taken up later.

Since the polar molecules are originally oriented in a random position with respect to any given axis, they may be considered statistically as having the line joining the centers of positive and negative charge effectively perpendicular to the direction of the applied field at the instant of voltage application. Upon sudden application of the electric field each dipole is subjected to a twisting moment by virtue of the assymmetrical arrangement of the charges and the force exerted by the field. The twisting moment or electric moment on each molecule causes that molecule to start to rotate into alignment with the field. As the molecule rotates two conditions arise which result in a decreased velocity of rotation and hence in a decreased current. First, the turning of the dipole shortens the effective moment arm, decreases the twisting moment, the velocity, and consequently the current. Second, as the dipole turns the velocity of the dipole charges in the direction of the field is a continually decreasing component of the actual linear velocity of the charges. Thus, since the measured current depends only upon the charge velocity in the direction of the field, this current is considerably reduced as the molecule rotates. The effect of the double tendency to decrease the current is to produce a current-time relation in which the current first decreases rapidly with time and then less rapidly as the absorption current approaches zero.

The fact that polar molecules are subject to the same type of internal displacement as non-polar molecules need not be considered since, as mentioned, the time involved in the movement is so short as to be relatively negligible in comparison with the longer times required for the rotation of the dipoles.

The difference in the amount of polarization observed in different materials may be explained on the basis of the magnitude of the electric moment or the degree of assymmetry, the number of dipoles, and the frictional resistance to the rotation of the molecules. The first of these depends upon the type of material. Polar molecules in different materials do not necessarily have the same degree of assymmetry. Also the number of dipoles may vary for different samples, depending both upon the material and the density. The frictional restraint depends upon the viscosity of the material. For denser materials the friction resistance results in a slow rotation of the polar molecules with a consequent long-time absorption current. On the other hand light materials might be expected to exhibit a relatively rapidly decreasing absorption current.

The test specimens used in this study were brick having approximately equal volumes but different porosities. If the molecules of the material are assumed to be polar, an absorption current should appear upon application of the voltage. In addition the absorption current through more porous brick, or the less dense brick, might be expected to decay faster since the frictional forces are slightly less. As the rotation is more rapid in such brick, however, the initial current might be expected to be larger. On the other hand the porous brick contains fewer polar molecules, a fact which would tend to reduce this initial current. Which of these factors predominates is questionable. However, it appears reasonable to suppose that the measurable initial absorption current might be greater for the denser brick inasmuch as the current in the porous brick reaches its maximum and decays considerably before measurements of current can be made. Thus, for the range of time over which the absorption current is readily measurable, the dense brick should exhibit a large initial current and one which dies out comparatively slowly.

The absorption current due to any polar molecules in the air need not be considered since the time necessary for their complete alignment with the electric field is so small as to be negligible.

An additional contribution to the absorption current for materials of more than one substance is undoubtedly present by virtue of the voltage gradient adjustment referred to earlier. The motion of the charges which are eventually deposited upon the boundary surface between the materials, solid and air in this case, results in an initial current which is measured along with the polar absorption current. The shape of the component of the current-time curve produced by the charge motion involved in the gradient adjustment is that of a negative exponential curve.

Although the magnitude of the initial current is greater for lower porosities, since the current in this case is a direct function of the individual conductivities of the materials, no reasons are apparent to indicate the manner in which a change in the porosity might affect the rate at which this component absorption current should decay.

The absorption current found by some investigators is best represented by a series of several negative exponential terms (45, p. 25). It appears probable that this series is partially the result of the two types of absorption which may be present and partially the result of the presence of more than one type of polar molecule in the sample, as is the case in most non-homogeneous substances.

B. Thermal Conductivity

The relation giving the total thermal conductivity of a combination of materials each having different values of individual conductivity has been found by experiment to follow the same general law as that for the conductivity of a series of metals.

On the assumption that the free electrons or ions transfer the heat the proof or analysis is analogous to that given for the case of conduction of electricity by free electrons.

Hence the conductivity of a series combination of two materials may be shown to vary inversely as the first power of the length of the heat flow path through that material having the lower thermal conductivity. If the two materials are a solid and air, as in this study, in which the actual conductivity of the air is the smaller, the thermal conductivity varies inversely as the percent porosity by volume. The conductivity-porosity curve which results has the shape of a hyperbola.

If the transmission of heat through the material or combination of materials is considered to be the result of thermal agitation and collision, as explained in the preceding section, the analysis may be made similarly with one assumption. The ions, electrons, or molecules which were supposed to be actually transporting the heat under the first theory may be considered to be the ones which are set in vibration and which transmit the heat by setting in vibration by contact or radiation the adjacent particles as assumed in the vibration theory of heat conduction.

In either event the experimental evidence is generally such as to justify the use of the same relation, direct addition of the resistances for a series circuit.

The fact that porous materials were used in the study may introduce an additional type of conduction. Radiation may occur in the pores. However, this is not generally appreciable until temperatures in the neighborhood of 1150 degrees centigrade are reached or until the diameter of the pores approaches 0.1 millimeters (39, p. 568).

Nevertheless radiation does occur in gradually increasing amounts as the porosity is increased; for materials of low conductivity heat transfer by radiation is relatively more apparent at somewhat lower porosities. Since the materials used were very porous the observed conductivity-porosity curve may be slightly flatter than the hyperbolic relation found for the true conductivity. For very large porosities in which the radiation has become large, the increase in heat transfer by radiation may exceed the decrease in heat transfer by true conduction and result in an observed apparent conductivity which is actually larger for large porosities. It must be remembered that for low temperatures the contribution of radiation to heat transfer is generally very slight and may not even be present. However, the following discussions are based upon the assumption that it does occur to a certain degree by virtue of the pore size.

Thus, the heat transfer through porous materials may not be entirely the result of conduction but a combination of conduction and radiation. It is, of course, impossible to separate experimentally these two types of heat flow in a porous material, just as the separation of electronic and ionic conduction of electricity is impossible in such materials. Thus the measured thermal conductivity may not be the true conductivity but only the apparent conductivity. Nevertheless the measurements justify themselves as illustrating the true action of the material in question under given conditions.

C. Correlation of Electrical and Thermal Conductivity

According to the theories of Drude (11), Lorentz (26), Sommerfeld (40), and others the ratio of thermal to electrical conductivity for a given temperature should be a constant. The Wiedemann-Franz constant gives experimental evidence that this relation is approximately true for pure metals and some alloys. However, other investigators have found that the constant relation does not generally apply for non-metals. The reason given is that a "non-metallic" type of conductivity exists. No attempt is made to either define non-metallic conductivity or to show how it might be expected to affect the ratio.

In porous materials this non-metallic type of conductivity exists in both the electrical and thermal cases. Therefore, in order to study the manner of variation of the ratio with porosity, both the electrical and thermal conductivities as they would be measured have been analyzed with respect to the effect of porosity upon each.

If only the true conductivities were present the ratio should appear as a constant in every case as indicated by the simple hyperbolic relationships obtained between the conductivities and the porosity. The introduction of ionic conduction to the electrical conductivity brings in the factor of the non-linear variation current and voltage in the range of ionization by collision which makes the conductivity-porosity curve steeper. The effect upon the ratio of thermal to electrical conductivity is an increase for increasing porosities. Neither the amount nor the rate of this increase can be determined analytically with the information at hand relative to the materials. Thus the non-metallic component of electrical conductivity has a very decided effect upon the constancy of the ratio.

The non-metallic type of thermal conductivity, if it occurs, takes the form of radiation. As already shown this results in a flatter conductivity-porosity curve than might be expected with only the true conductivity present. The ratio of thermal to electrical conductivity is therefore still further increased for increasing values of porosity by the increasing contribution of heat transfer by radiation to the apparent conductivity at higher porosities.

Thus the non-metallic conductivities referred to by previous investigators are, in this case, seen to be ionic conductivity on the one hand and heat radiation on the other. Both cause the ratio of conductivities to vary in the same sense although the amount of this variation can not be predicted.

IV. INVESTIGATION

A. Experimental

1. Plan of investigation

a. Measurement of electrical conductivity. The electrical conductivity of all the test specimens was obtained at the same temperature, 47 degrees Centigrade (± 1°C.), and at zero humidity. Since the true conductivity was the property desired, a constant, uni-directional voltage was applied.

Continuous readings of current and time were made from the time at which the current was first measurable to the time at which the current became steady. Calculations of conductivity were made as described in the section on calculations. The final conductivity-porosity relation was expressed graphically in the form of curves.

In order to determine the effect of voltage upon current flow, a number of the samples were subjected to various voltages after having been completely polarized by a long-time exposure to the test voltage. These tests were made at the same temperature and humidity as the conductivity tests.

A curve of electrical conductivity as a function of porosity was also plotted for the conductivity as calculated from current measurements made after a one-minute application of the voltage and after steady-state conditions had been reached. Assuming all the error to be in the galvanometer readings the curves were drawn on a statistical basis in such a manner as to reduce the total variation in all these readings to zero.

Curves of current against time were also drawn and the current-voltage relations similarly shown for a representative set of specimens.

b. Measurement of thermal conductivity. Since the fundamental objective of this study was the comparison of the thermal and the electrical conductivities, the thermal conductivity of each specimen was measured with no moisture present in the samples and at an average mean temperature of about 47 degrees Centigrade. The thermal conductivity was calculated as described in the section on calculations.

Curves of thermal conductivity as a function of the porosity were drawn in a manner similar to those for the electrical conductivity.

c. Correlation of electrical and thermal conductivity. The correlation of the electrical to the thermal conductivity was indicated graphically by curves in which the ratios of the conductivities were plotted against values of porosity. The data for computing these ratios were obtained both from the actual conductivities of the materials as observed and from points picked off the thermal conductivity- and the electrical conductivity-porosity curves.

d. Measurement of porosity. Porosity measurements were made by determining the amount of water the specimen would absorb expressed as the percent by weight.

2. Apparatus

Measurements of dielectric conduction have, in general, been made on thin specimens of large cross-sectional area, and, in a number of cases, several specimens have been assumed to be identical and have been connected in parallel for the purpose of increasing the current. Inasmuch as the test samples used in this study were relatively thick and of small cross-section, the equipment used in making the measurements could not to a very great extent be patterned after that designed by previous investigators. A further limitation to the extent to which such equipment could be adopted as a whole was introduced by the fact that no two specimens could in this case be assumed to be anywhere near identical with respect to their conductivities.

The apparatus as built was designed to conform to the dimensional requirements of the test samples, and at the same time to incorporate such desirable features of the equipment of other investigators as was deemed both feasible and possible,

a. Electrical conductivity testing cabinet. Since both temperature and moisture have such a decided effect upon the electrical properties of most materials, a large container was built in which the temperature could be controlled and held constant and in which the humidity could be kept essentially at zero. This container was a wooden cabinet made of three-ply material. The dimensions were approximately 60 by 70 by 215 centimeters long. The cabinet was mounted on a table as indicated in Fig. 4 and hinged at one end to permit raising the cabinet. The front of the cabinet was provided with a glass-panelled door held in place by wing nuts. The door was used for inserting and removing test samples.

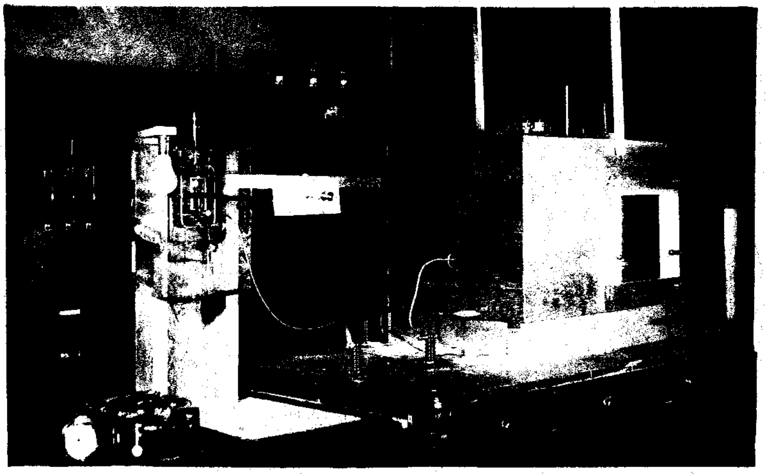


Figure 4. Electrical Conductivity Measuring Equipment.

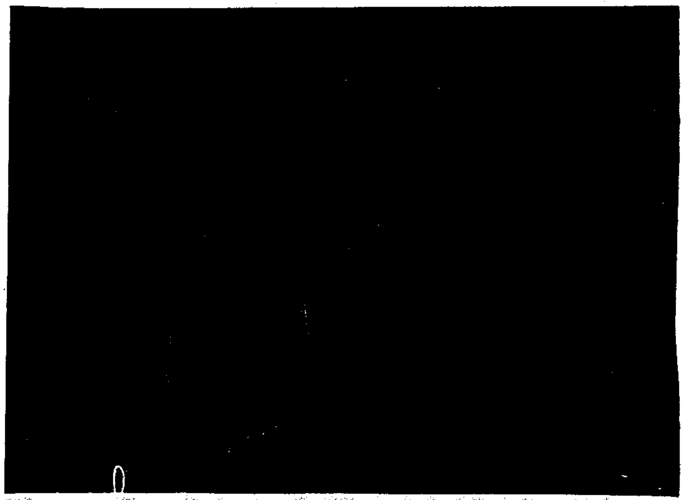


Figure 5. Internal View of Electrical Conductivity Testing Cabinet.

In order to maintain constant temperature in the cabinet a nine-hundred-watt lamp bank controlled by a bi-metal thermostat and a relay was used. The thermostat was adjustable to such an extent that a fairly wide range of temperatures was obtainable. The instrument was sufficiently sensitive to maintain the cabinet temperature within about one degree Centigrade of any desired mean value of temperature. That is, the temperature differential of the system was two degrees.

The low humidity was obtained by keeping anhydrous calcium chloride in the cabinet continuously. This served quite well as a drying agent as was evidenced by the fact no change was noted in the conductivity even after periods of several hours.

The voltage was applied to the test samples by means of two electrodes placed in the testing cabinet. These electrodes were of two types. The positive, or high-voltage, electrode was an aluminum disc 0.3 centimeters thick and 24 centimeters in diameter. The negative, or zero potential, contact consisted of two parts. The electrode itself was a brass disc 3.5 centimeters in diameter. Surrounding this was a guard ring of aluminum having overall dimensions of 15 by 30 centimeters. The two electrodes and the guard ring were each mounted on separate insulators. The small electrode and the guard ring were fixed rigidly while the high voltage electrode was fitted with a pressure adjustment screw and a socket joint, the former to allow the insertion of test specimens and the latter to enable the electrode to fit itself exactly to the plane surface of the test sample, thus adjusting for any poor alignment of the electrodes and for any non-parallelism in the two faces of the samples. Fig. 5 shows the arrangement of the electrodes with a sample in place.

Guard rings were considered essential for two reasons. As the guard ring was maintained at essentially the same potential as the low voltage electrode it eliminated any tendency for the lines of current flow between the small electrode and the center of the large electrode to be other than parallel. This permitted the simple linear equation for conductivity to be used in the calculations. In addition the guard ring prevented the measurement of current leakage around the edges or along the surface of the test sample. For test specimens of low resistance either of these considerations might well be neglected since the low conductivity of the air path and the low conductivity of the surface path would be too small by comparison to necessitate the use of the guard ring. However, the materials used here were of such high resistance as to make the conductance of the three possible paths comparable. If no guard ring were used current would flow both through and around the sample and be measured. With the guard ring in place any current flowing around the brick flowed from the high voltage electrode to the guard ring and thence to ground and did not reach the center electrode to which the current measuring galvanometer was connected.

With the high voltage used it was necessary to screen the low-voltage leads from the influence of the high-voltage side. The screens were, of course, grounded. Figs. 4 and 5 show the arrangement of the screens. The one inside the cabinet prevented any air leakage from the high-voltage electrode or its leads to the galvanometer leads. The screen above the box was for the purpose of preventing a similar leakage from the high-voltage leads to the galvanometer leads.

Fig. 6 is a diagram showing the schematic arrangement of the equipment.

b. High-voltage Kenotron set. The uni-directional voltage applied to the test samples for the purpose of determining their electrical conductivities was supplied by a 50,000-volt Kenotron set.

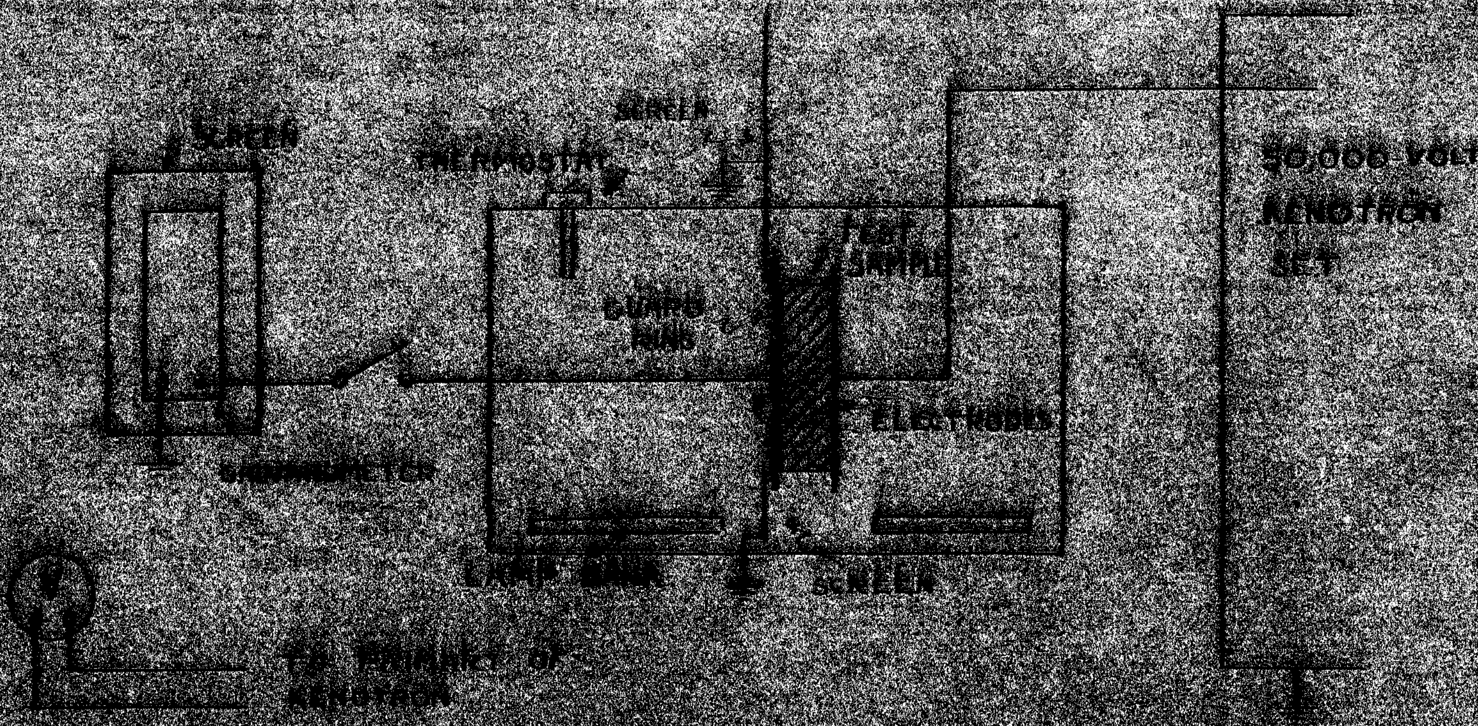
The equipment consisted essentially of a 220- to 100,000-volt transformer with a center tap and two 25-watt Kenotron tubes, one on each side of the center tap of the transformer, to provide a full-wave rectification.

The voltage to the primary of the transformer was supplied from a sine wave set.

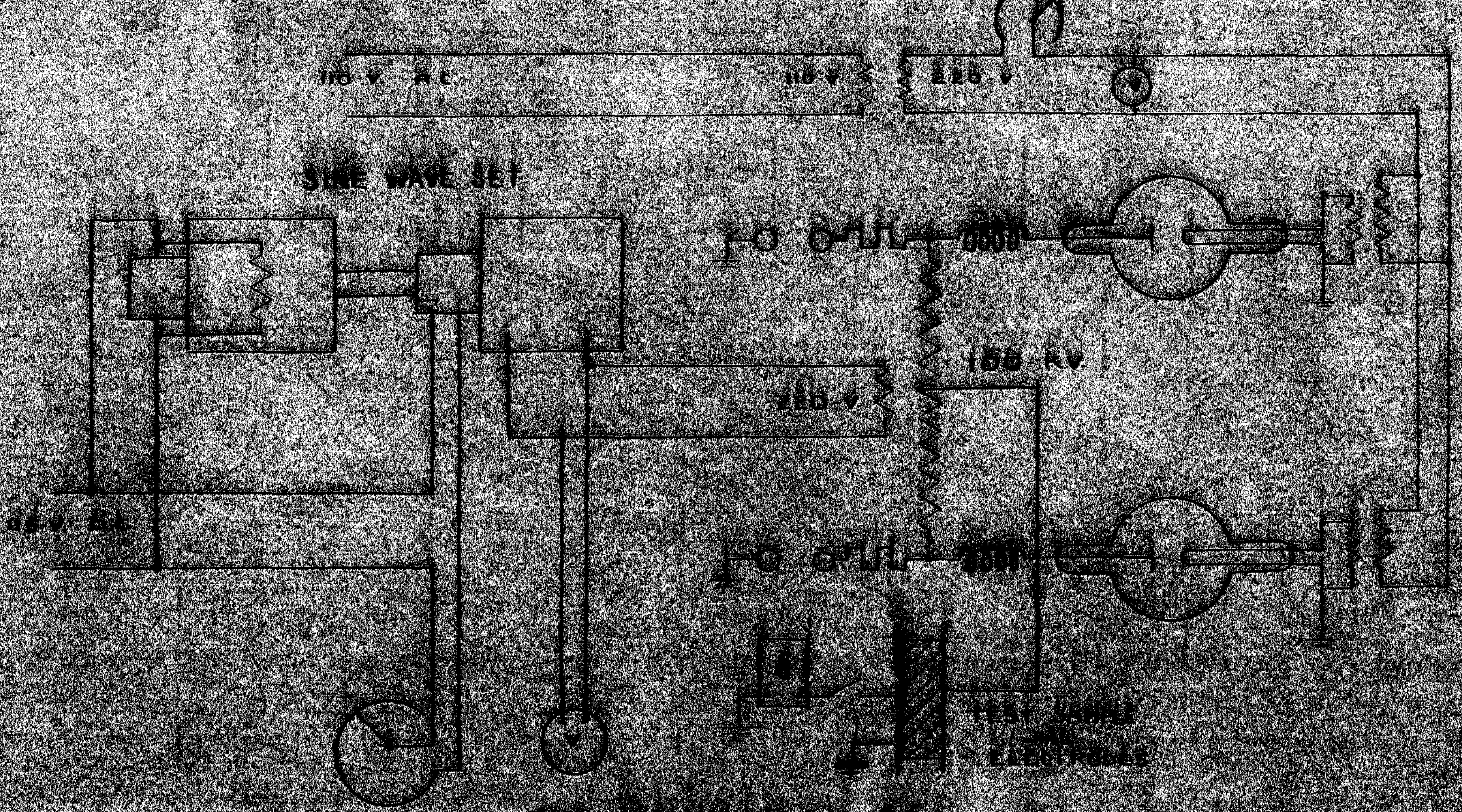
The output voltage of the Kenotron set was controlled by means of the voltage applied to the field of the sine wave set.

A schematic diagram of the apparatus showing the manner in which it was connected to the electrodes and measuring equipment is evident in Fig. 7.

c. Instruments used in making measurements of electrical conductivity. The measurements of current flow were made by means of a Leeds and Northrup wall-type ballistic galvanometer, laboratory number 533. The sensitivity of the meter was determined by the voltage-resistance method described in the Appendix. An average of twenty measurements



DIAGRAMMATIC SKETCH OF ELECTRICAL CONDUCTIVITY
MEASURING EQUIPMENT
FIGURE 6



KENOTRON SET
FIGURE 7

indicated a sensitivity of 6.179×10^{-9} amperes per millimeter deflection at a distance of one meter.

To prevent the measurement of leakage currents through the air from the high voltage leads to the galvanometer the instrument was surrounded by a grounded screen as is evident in Fig. 4.

Voltage measurements were not made directly on the high-voltage side of the Kenotron set. Instead, the voltage output of the sine wave set, or the primary voltage of the Kenotron, set was measured and the value of the voltage applied to the test specimen obtained by applying the transformation ratio, 226. The instrument used in making the voltage measurements was a General Electric voltmeter, laboratory number 1130. The meter had two scales, 0 to 150 volts and 0 to 300 volts.

Time measurements were made with an Eastman stop clock.

d. Thermal conductivity testing cabinet. Measurements of thermal conductivity were made with the samples held between "electrodes" which were suspended in a wooden testing cabinet. The dimensions of the testing cabinet were approximately 60 by 36 by 5½ centimeters high. A door in the front of the cabinet allowed the samples to be inserted or removed from the apparatus. An external view of the testing cabinet is shown in Fig. 8. The reasons for using an enclosed testing cabinet were much the same as those presented for the use of an electrical conductivity testing cabinet. As moisture definitely affects the thermal conductivity of materials the American Society of Heating and Ventilating Engineers has set up a tentative code (41) which states that the thermal conductivity of materials shall be determined in the dry state. For this reason

Figure 8. External View of Thermal Conductivity Testing Cabinet.

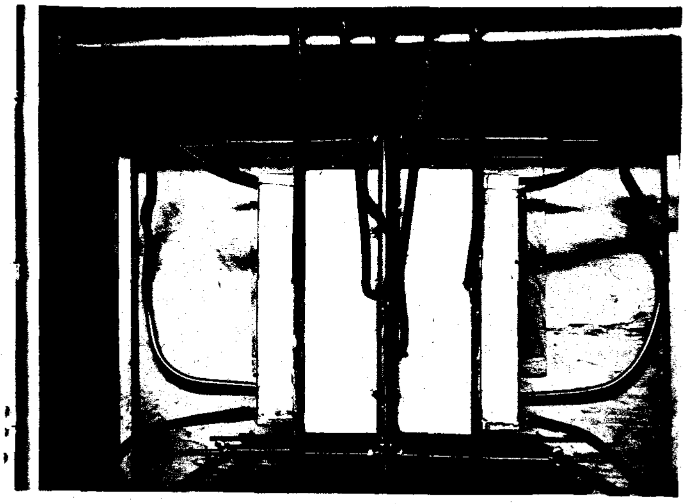


Figure 11. Internal View of Thermal Conductivity Testing Cabinet.

and since the effect of the empty pore spaces upon the conductivity was to be studied, the cabinet was built to assist in maintaining dry conditions. As in the electrical testing cabinet a drying agent, anhydrous calcium chloride, was kept in the cabinet continuously. The electrodes referred to above consisted of a hot plate and two cold plates to supply the thermal difference of potential for the test specimen and cause the heat flow.

The cold plates each consisted of a 0.3-centimeter brass plate 15 by 30 centimeters in area. To each plate was soldered a galvanized sheet steel tank 13 by 23 by 2.5 centimeters deep. A short piece of small copper tubing was soldered into each end of each tank for making connections to the water circulating system.

The hot plate was fundamentally an electric heater. The heating element was made of number 30 nichrome wire wound on a 15-by 30-centimeter micanite plate. The wires of the element were spaced 0.6 centimeters apart and covered an area of 4.57 by 14.47 centimeters. The total resistance of the element was 47 ohms at 25 degrees Centigrade.

Surrounding this element was a guard ring also wound with number 30 nichrome wire with a 0.6-centimeter spacing. The outside dimensions of the guard ring were 12.5 by 22.5 centimeters. Two symmetrical halves of the guard ring element were connected in parallel making the resistance of the element approximately 33 ohms. The purpose of the guard ring was to prevent the lateral flow of heat from the center portion of the heating element through the sample to the edges. In other words, the heat flow through the central portion of the sample was constrained to a linear flow from the hot to the cold plates. Here again the linear flow allowed the use of the linear equation for calculating conductivity.

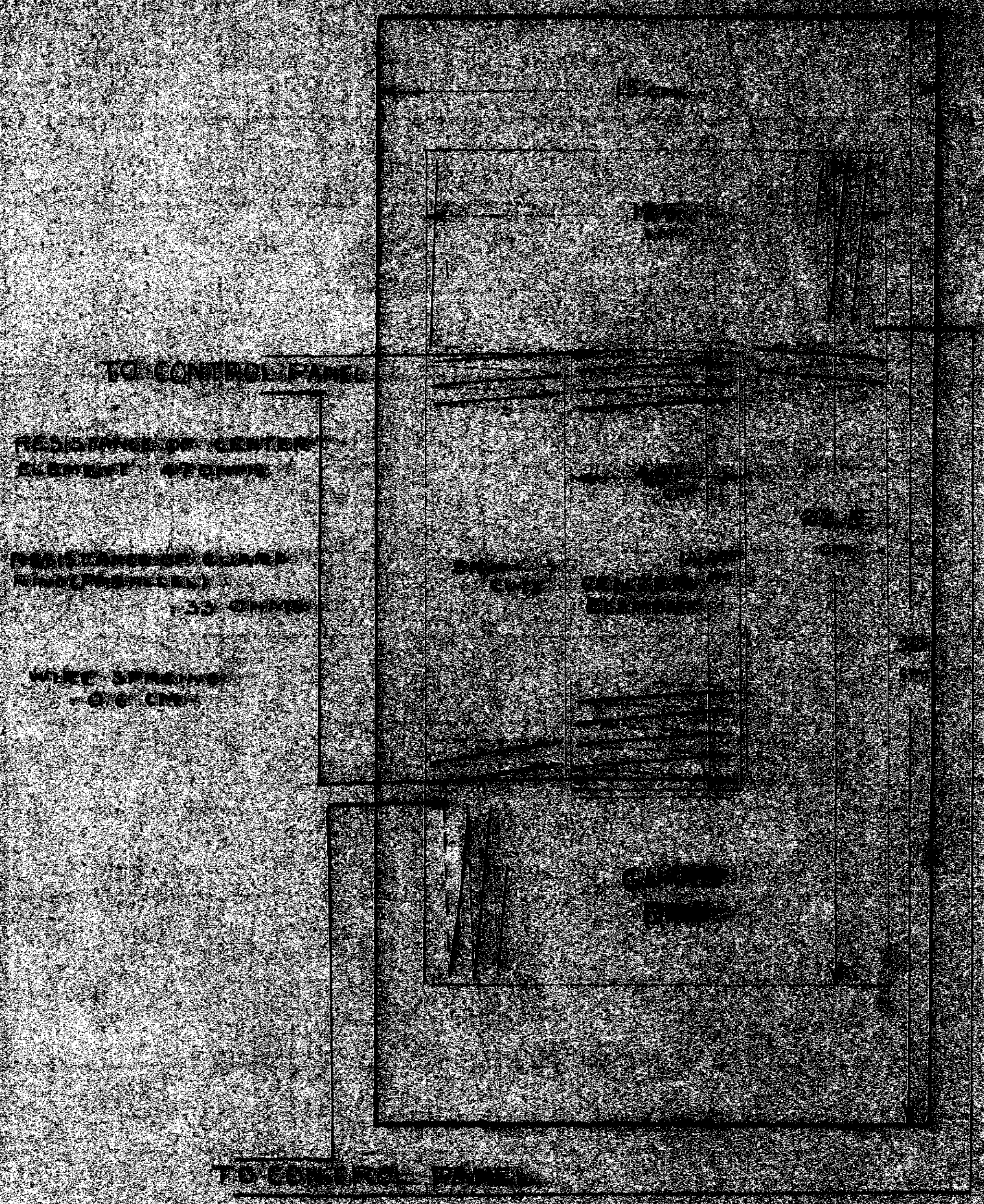
Fig. 9 shows the arrangement of the heater and guard ring on the micanite plate. The combined element was placed between two other micanite plates and this unit in turn placed between two 0.3-centimeter fiber plates. This entire element was bolted rigidly together. Narrow saw cuts were made between the center element and the guard ring to more effectively insulate thermally the heater from the guard ring.

The hot plate and the cold plates were mounted by running four long threaded rods through the corners of each of the plates and suspending the entire unit by wires from the top of the testing cabinet to reduce heat leakage. Pressure adjustments on the test samples were made by means of wing nuts.

Approximate constant temperature conditions were maintained by holding the mean temperature of the hot and cold plates at a relatively fixed value.

In order to facilitate the placing of the thermocouples for temperature measurements and still maintain a flat contact surface between the sample and the hot and cold plates, thin fiber plates were also placed against the cold plates. Narrow, shallow slots were cut in all four fiber plates in the desired positions to accomodate the thermocouples.

An assembled view of the electrodes is shown in Fig. 10. Fig. 11 is a photograph of the interior of the testing cabinet showing the hot



Schematic Diagram of [illegible]
Heating Element
Figure [illegible]

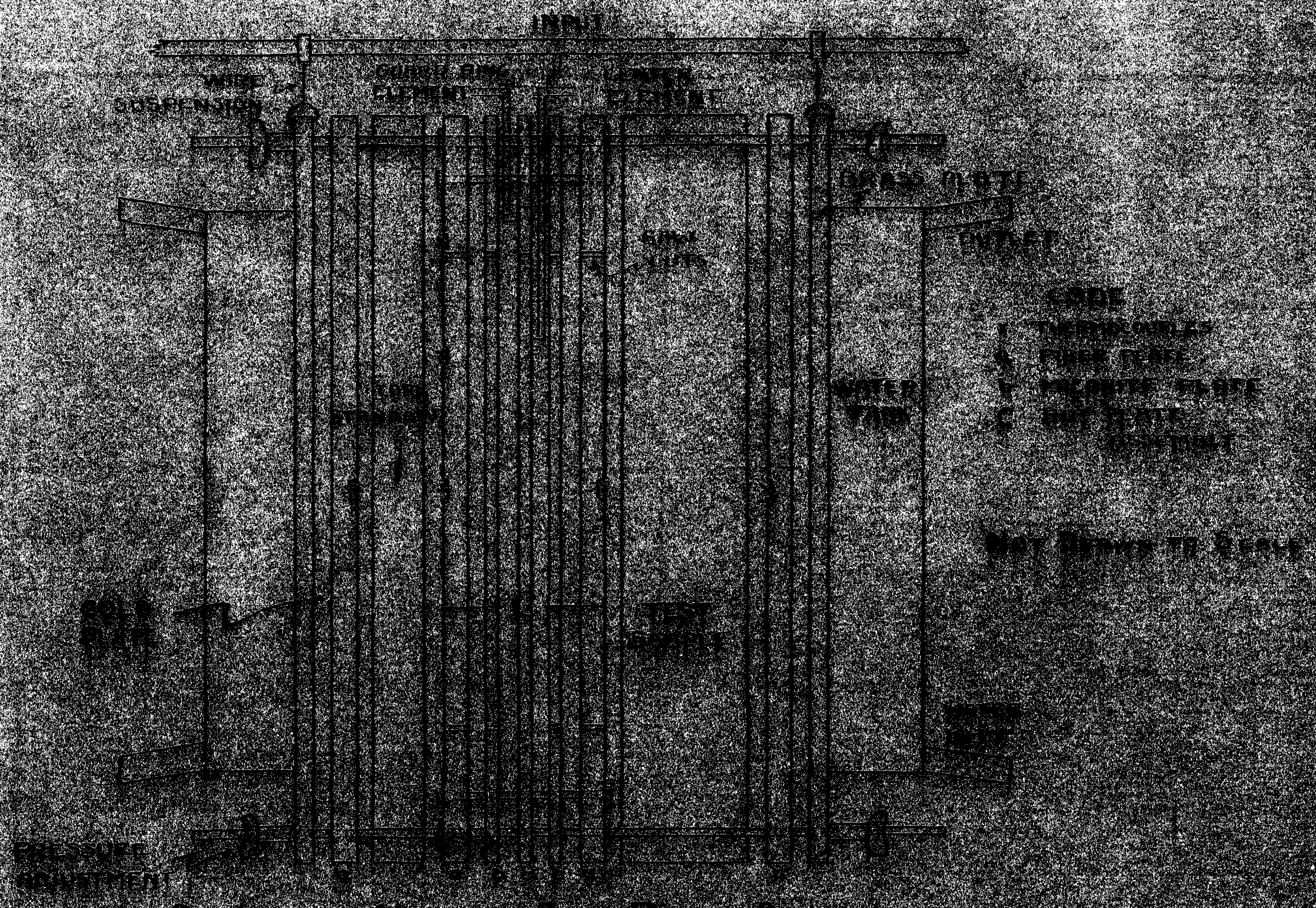


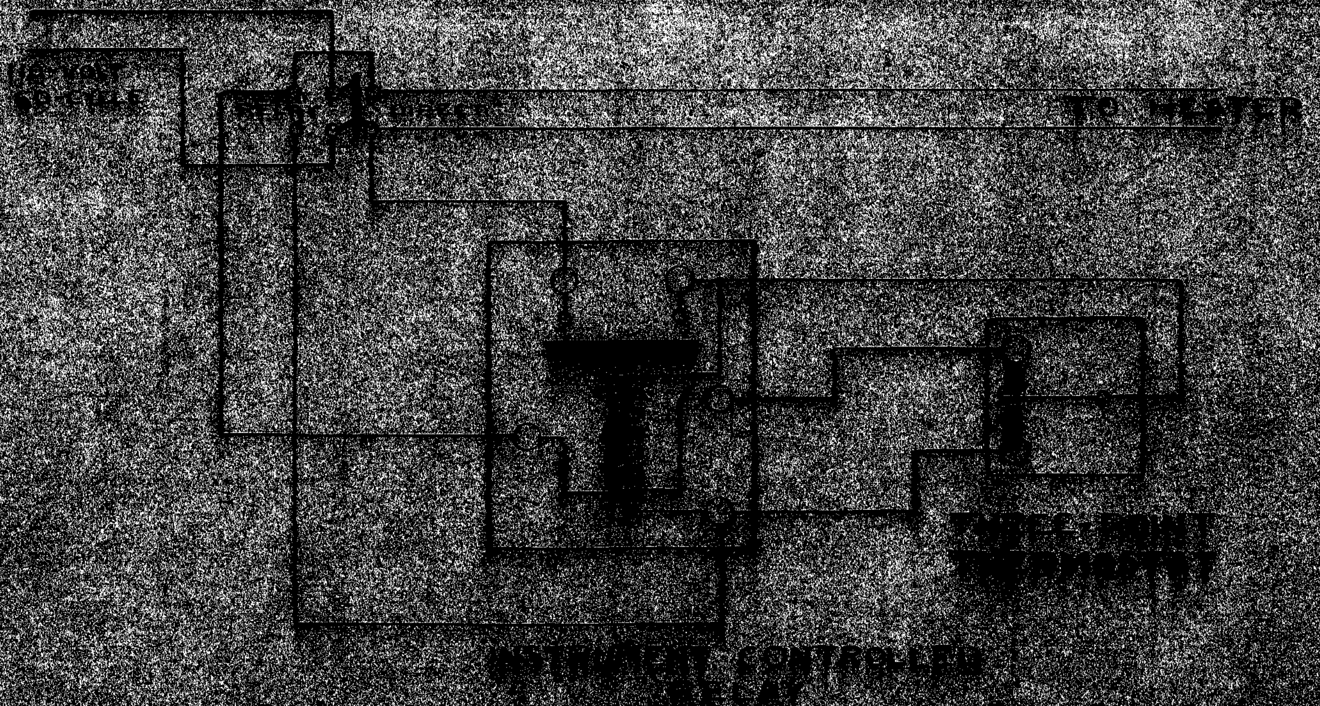
DIAGRAM OF HOT AND COLD PLATE ASSEMBLY
FIGURE 10

and cold plates, the water circulating system connections, the sample, and the thermocouples.

e. Temperature control equipment for the cold plates. The maintenance of a cold surface on the test specimen in opposition to the higher temperature of the hot plate was for the purposes of setting up the required thermal potential to control the rate of heat flow through the sample. In addition to merely having a cold surface, itwas considered desirable to have a fairly constant temperature over a period of several hours, for the duration of the test, in order that the heat flow conditions might become sufficiently stabilized to allow the conductivity measurements to be made.

The temperature was held approximately constant by means of a constant-temperature water circulating system. A tank of plywood was lined with galvanized sheet steel and soldered to make it water-tight. The dimensions of the tank were 64 by 50 by 30 centimeters deep. An overflow valve was placed at the 25-centimeter level. Sufficient cold tap water was allowed to run continuously into the box to maintain the temperature at about 23 degrees Centigrade, which was several degrees below that chosen for the cold plate temperature. The temperature of the water in the tank was then boosted by an immersed heater of nichrome wire, capable of dissipating about 800 watts at 110 volts, controlled by a bi-metal thermostat and relay. Fig. 12 is a diagram of the control circuit.

The water was circulated through copper tubing to the cold plates



TEMPERATURE CONTROL CIRCUIT
FIGURE 12

by means of a small centrifugal pump driven by a capacitor motor. Although this system was not maintained at an absolutely constant temperature, on account of weather conditions it did maintain a steady temperature for considerably longer than was necessary for the completion of one test and was therefore satisfactory.

The general arrangement of the water circulating system is evident in Fig. 13.

f. Temperature control equipment for the hot plate. The heat input to the hot plate heater element and the guard ring element were controlled by means of potentiometers and variable series resistances. The circuit is shown in Fig. 14. The subscripts G and C in the figure refer to the guard ring and center element, respectively.

g. Thermocouples. Temperature measurements were made with thermocouples. Couples of number 16 gauge iron and constantin wire were used since they gave straight line calibration curves up to several hundred degrees, well beyond the maximum temperatures used in the study. The ends of the two wires were welded together. The leads were about five feet long.

The cold junction consisted of a small plywood tank lined with galvanized sheet steel through which cold tap water was constantly circulated. Generally the cold junction temperature of thermocouples is held at zero degrees Centigrade. In this case, however, the thermocouples were calibrated at several temperatures to allow for any change in the temperature of the tap water. Equations for the calibration

Circulating System for Constant Temperature Water

Figure 13

CONTROL AND MEASURING CIRCUIT
FOR HOT PLATE TESTER
FIGURE 11

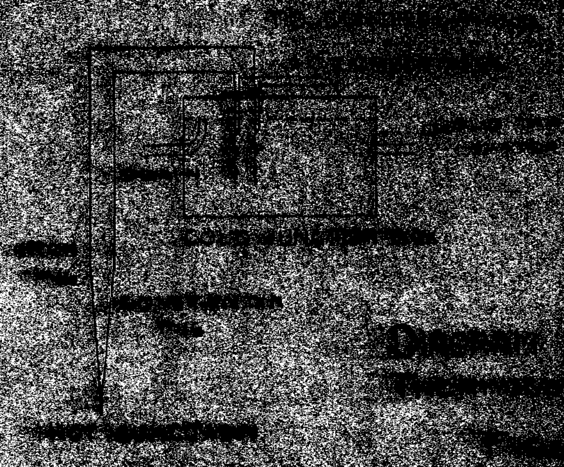
curves of each thermocouple were obtained for each cold junction temperature and curves relating the constants of these equations to the cold junction temperature were drawn. The method used in calibrating the couples and in arriving at the constants of the equations is described in the Appendix.

The cold junction box and the thermocouples are evident in the upper portion of Fig. 8. Fig. 15 shows a sketch of the cold junction connection.

To enable readings to be taken more rapidly and very nearly simultaneously a switching panel, Fig. 16, was constructed. The calibrations were all made with this panel in position.

h. Instruments used in making measurements of thermal conductivity. Readings of thermocouple voltage were made with a Leeds and Northrup suspension-type galvanometer, laboratory number 1184. The normal sensitivity of the instrument was about 0.015 microamperes per millimeter deflection at 18 centimeters. In order to adjust the full scale deflection of the instrument to indicate the maximum desired reading, an external resistance of 4500 ohms was inserted in series with the internal resistance of 1122 ohms. A 60-centimeter scale was fixed at a distance of 70 centimeters from the galvanometer to permit a more exact reading to be taken.

The reading was indicated by a line shadow thrown on the scale by the reflected light from a mirror fixed to the galvanometer suspension shining through a lens upon which was a vertical hair line. The light was furnished by a 6-volt lamp.



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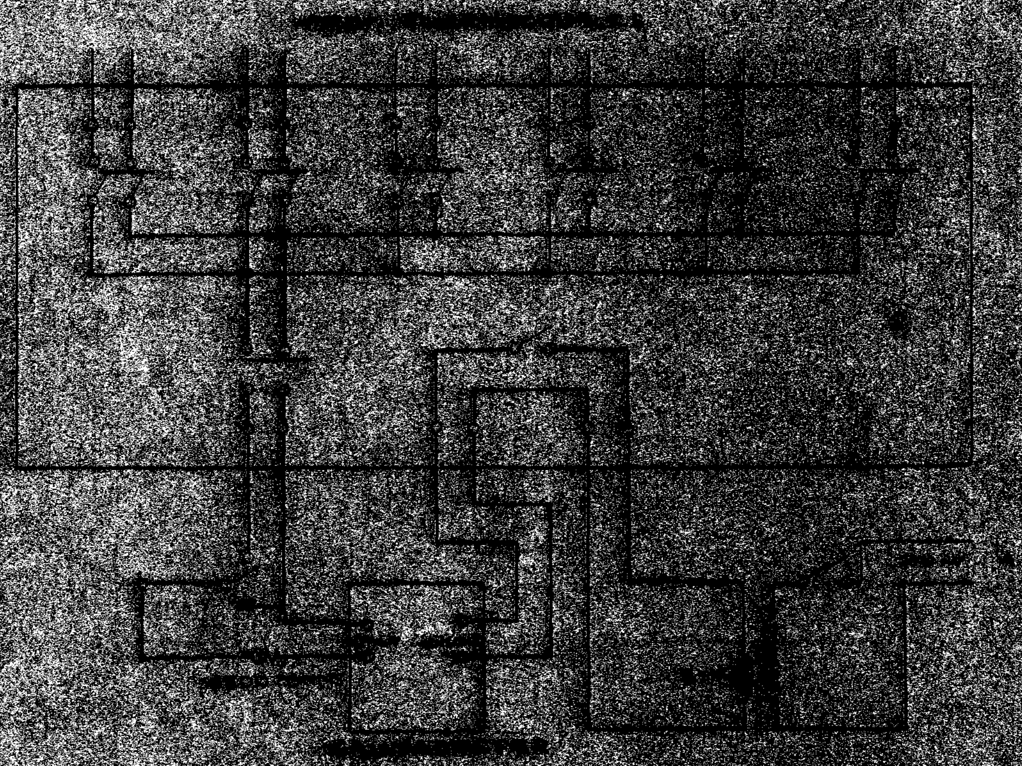


[illegible]

Input measurements to the hot plate were made by reading the current and voltage in both the center element and the guard ring element circuits.

The meter used for measuring the voltage across the guard ring element was a Weston, A. C. voltmeter, laboratory number 62, having 0–to 60– and 0– to 120–volt scales. The resistances for each full scale reading were 1013.7 and 2027.4 ohms, respectively. Measurements of the current in the guard ring circuit were made with a Weston, A. C. ammeter, laboratory number 708. The meter had two scales, 0 to 0.5 and 0 to 1.0 amperes. The 0– to 60–volt scale on the voltmeter and the 0– to 1.0–ampere scale on the ammeter were used in the test.

The meter used in the measurement of the center element voltage was a Weston, A. C. voltmeter, laboratory number 470, with scales of 0 to 7.5 and 0 to 15.0 volts and internal resistances of 92 and 184 ohms for the two scales, respectively. The ammeter used for current measurement was a Weston, A. C. ammeter, laboratory number 750, with scales of 0 to 0.25 and 0 to 0.50 amperes. The 0– to 15–volt scale on the voltmeter and the 0– to 0.50–ampere scale on the ammeter were used.

i. Drying oven. The apparatus for removing all the moisture from the samples before testing them consisted of a small electric oven insulated with asbestos board. The inside dimensions of the oven were approximately 20 by 20 by 30 centimeters deep. A bi–metal thermostat and relay were used for regulating the temperature to approximately 125 degrees Centigrade, a temperature sufficiently high to remove the moisture and yet low enough to eliminate the possibility of any chemical or structural changes taking place in the specimen. The oven was capable of dissipating about 800 watts at 115 volts.

j. Test materials. As the correlation between the electrical and thermal condictivities in this study was fundamentally based upon the percent porosity, test specimens identical in every respect except for porosity were used. The A. P. Green Firebrick Company, of Mexico, Missouri, furnished a number of brick having the desired qualities. The brick were their type G-25 and were found to have a wide range of porosities.

A few building brick manufactured by the Ava Brick Company were used to make the correlation of conductivities in the low porosity range. The two types of brick also served to show the effect of different materials upon the correlation.

The cork standard for the thermal measurements was furnished by the United States Bureau of Standards (42).

3. Test procedure

a. Measurement of electrical conductivity. In order to determine accurately the true conductivity of the materials, it was necessary to drive off all moisture from each test specimen. The brick sample was placed in the drying oven, the temperature of which was adjusted to approximately 125 degrees Centigrade. This temperature was chosen as being satisfactory since the water would be readily driven off above 100 degrees and no chemical changes or vitrification would occur at such a relatively low value of temperature. To ascertain the time required for the complete elimination of all the water, the test sample was weighed before baking. As the moisture was driven off the weight of the brick decreased. When the brick had reached a constant weight all the moisture was assumed to have been evaporated. The time necessary for this, for the fire brick, was found to be about two or three hours. In general, however, the brick specimen was allowed to remain in the oven for a period of about six hours to insure complete drying.

The dry brick was then placed in the electrical conductivity testing cabinet and clamped between the electrodes by means of the screw adjustment on the high voltage side. The temperature in the cabinet was maintained continuously at 47 degrees Centigrade (± 1°C.). The air in the cabinet was kept free from moisture by using a drying agent, anhydrous calcium chloride, which was kept in the cabinet at all times. Contact with the metal electrodes allowed the more rapid dissipation of heat from the brick and only a short time was required for the brick to cool to approximately the temperature of the interior of the testing cabinet.

When the temperature conditions had become fairly constant the galvanometer zero was set and the instrument connected to the circuit. The voltage was applied suddenly by closing the field circuit of the sine wave set supplying the primary of the Kenotron set.

In order that the voltage applied be the desired voltage it was necessary to have previously adjusted the field rheostat of the sine wave set to give the proper value of voltage and also to have the Kenotron tubes warmed up. The primary voltage used on the set was 110.7 volts giving a voltage across the sample of 25,000 volts.

Simultaneously with the closing of the field switch, the stop clock was started. The galvanometer deflection was noted and both it and the time recorded as soon as the maximum reading of the galvanometer occured, or, if the galvanometer went off the scale, the time was recorded as soon as a reading could be taken. Galvanometer readings were taken then at appropriate time intervals thereafter depending upon the rapidity with which the current was changing.

After the current became relatively smaller the galvanometer readings were estimated to the nearest tenth of a millimeter. The steady-state current was assumed to have been reached when the galvanometer reading did not change over a period of ten minutes.

After the current flow had become steady the voltage was removed and the zero of the galvanometer checked.

The data for the current-voltage relations were taken immediately after the conductivity test by observing the galvanometer deflections for various values of impressed voltage. The lower limit of the range of voltages used was determined by the amount of observed deflection. The upper limit was determined by the voltage at which an arc occurred around the surface of the brick between the high-voltage electrode and the guard ring. The voltage at which the latter occurred depended, of course, upon the surface conductivity of the brick.

Before any quantitative tests were made the effect of electrode pressure upon the conductivity was investigated. No difference could be detected in the conductivity for even the extreme values of electrode pressure. Neither was any difference in the conductivity noted when tinfoil, aluminum foil, or other common types of contact were used. Therefore no attempt was made to clamp the samples with a uniform pressure. The clamp was merely adjusted until the electrodes were holding the sample sufficiently tight that it could not readily be pulled out by hand.

Before removing the test sample after the test the sine wave switch and the galvanometer circuit were opened. The condenser formed by the two electrodes and the brick was then discharged by shorting.

The brick could not be used again immediately for a check test for several reasons, the main one being that it was partially polarized and therefore would not give the same current-time relation. The depolarized or random orientation of the polar molecules was obtained by rebaking the brick and allowing the molecules to adjust themselves to their random positions.

b. Measurement of thermal conductivity. Before any accurate determination of the thermal conductivities of the brick could be made it was necessary to adjust the equipment to indicate the temperature properly. This was done as indicated in the Appendix by using two pieces of standard cork board rather than one standard and a test specimen.

After the apparatus had been adjusted properly the measurements of the conductivities were made without disturbing the positions of the thermocouples in contact with the cork board which was to be used as the permanent standard. Occasional rechecks were made on the settings, however, to eliminate the possibility of slippage as a source of error in the measurements.

The thermal conductivities of the brick were measured in the following manner:

The test brick was placed in the oven to be dried and baked until it had reached a constant weight. To avoid the necessity of continual weighing and reweighing a time of six hours was chosen to be more than sufficient for the moisture to be all driven out and the constant weight reached.

The dried brick was then placed in the testing cabinet between the hot plate and the cold plate on the right (Figs. 10 and 11). After the thermocouples to measure the temperatures of the hot and cold faces were inserted in the grooves provided in the fiber contact plates, the brick was firmly clamped between the plates by means of the wing nuts.

The next step was the adjustment of the hot and cold plate temperatures.

Inasmuch as the temperature of the cold plates was held approximately constant by the water circulating through the tanks no further attention was paid to the temperature adjustments of the cold plates.

To adjust the temperatures of the hot plate the potentiometer and series resistor in both the guard ring and center element circuits were set to give an input which was estimated to be that required by each element to result in equal temperatures in the center element and in the guard ring element at the inner edge of that element. Care was taken not to exceed the current-carrying capacity of the elements.

After sufficient time had elapsed for the thermal conditions to become steady, generally about three hours, temperature readings were taken by observing the galvanometer deflections for each thermocouple. The deflections were read to one-half of a millimeter. Simultaneous readings of the cold junction temperature were also taken.

It might be well to mention at this point that steady thermal conditions were assumed to have been obtained when the thermocouple temperature readings remained constant for an hour. This length of time is not included in the three-hour time mentioned above.

In general the first readings of the thermocouple temperatures indicated that the temperatures of the guard ring and the center element were unequal. Inasmuch as the purpose of the guard ring was to constrain the lines of heat flow through the center portion of the sample to straight, parallel lines, and since this condition could not be obtained without an equality of the guard ring and center element temperatures, a further adjustment was necessary. The input to either the guard ring element or the center element was changed, depending upon the approximate value of the desired mean temperature, by varying the setting of the potentiometer or series resistor in that circuit. After steady-state conditions had once more been reached the temperature readings were again taken. This process was continued until the temperatures indicated by the guard ring and center element thermocouples were the same.

After the temperatures had been equalized, readings of current and voltage were taken to determine the input to the heater or center element.

The calculations were made as indicated in the section on calculations.

c. Measurement of porosity. The porosity of each of the specimens was measured by the absorption test.

The brick was weighed and placed in the oven and dried. When the moisture had all been removed from the brick, that is, when the weight of the specimen had become constant, the brick was removed from the oven and weighed again. This weight was called the dry weight. After the brick had cooled it was immersed in water for a period of six hours. This length of time was found to be more than sufficient for the wet weight of the sample to become constant, indicating a maximum absorption.

The specimen was then removed from the water, the excess moisture wiped off the surface of the sample, and the brick weighed. This weight was called the wet weight.

The calculations of porosity were made as indicated in the section on calculations.

B. Calculations

In general the calculations were quite simple. However, in obtaining the thermal conductivity from the observed data, the method used is not readily apparent. Hence this section on calculations is included to explain the methods and procedures followed in making the computations.

1. Electrical conductivity

Inasmuch as the guard ring was used the conductivity was calculated from the measured current flow by making use of the relation

$$\sigma = \frac{Il}{Va} \qquad \text{(Eq. 23)}$$

where σ is the electrical conductivity, I is the measured current flow in amperes, V is the applied voltage in volts, l is the length of the current path, that is, the thickness of the sample, in centimeters, and a is the cross-sectional area of the current path, or the area of the small electrode in square centimeters. This equation gives σ in mhos per centimeter or mhos per centimeter cube.

Since the current was measured as a galvanometer deflection in millimeters it was necessary to convert the galvanometer reading to amperes. The galvanometer used had a sensitivity of 6.179×10^{-9} amperes per millimeter deflection at a distance of one meter. The current was thus calculated as

$$I = dk$$

or

$$I = (6.179 \times 10^{-9})k \qquad \text{(Eq. 24)}$$

where I is the current in amperes, d is the deflection of the galvanometer in millimeters, and k is the sensitivity of the galvanometer in amperes per millimeter deflection.

2. Thermal conductivity

The calculation of the thermal conductivity from the observed data was rather involved as a result of the varying cold junction temperature and the use of a corkboard standard rather than two identical specimens.

The fundamental equation used in the calculation of the thermal conductivity was

$$K = \frac{Wl}{\Theta A} \qquad \text{(Eq. 25)}$$

where K is the thermal conductivity, W is the rate of heat flow through the brick in watts, l is the length of the heat flow path in centimeters, Θ is the difference in temperature between the hot plate and the cold plate faces of the brick in degrees Centigrade, and A is the area of the center element of the heater or the cross-sectional area of the heat flow path through the center portion of the brick measured in square centimeters. This equation gives K in watts per degree Centigrade per centimeter. That is, K represents the rate of heat flow in watts through a specimen one centimeter thick and having an area of one square centimeter, for each degree difference in temperature, measured on the Centigrade scale, between the faces of the sample.

The temperature difference on the faces was determined from the thermocouple readings. The temperatures as indicated by the thermocouples was expressed as

$$T = Ax + B \qquad \text{(Eq. 26)}$$

where T is the temperature in degrees Centigrade, x is the deflection of the galvanometer in millimeters, and A and B are constants which depend upon the cold junction temperature. Fig. 17 indicates the relation existing between these constants and the cold junction temperature. Since the cold junction temperature was always read simultaneously with the galvanometer deflection, the constants were readily determined from the curves for each set of thermocouple readings and the temperature indicated by each thermocouple calculated from the above equation. The method used in arriving at the relations between the cold junction temperature and the constants A and B is explained in the Appendix.

The temperature difference was obtained by merely subtracting the temperature on the cold face from that on the hot face.

The next step was the determination of the total input to the center element. The ammeter was so connected as to read the current I' through both the element and the voltmeter as is evident in Fig. 14. In order to correct for this the voltmeter reading was divided by the resistance of the meter according to Ohm's Law. The resulting current was then subtracted from the observed current I' read from the ammeter to give the actual current I through the element. The power in watts was readily determined as the product of the voltage , V, in volts, and the current, I, in amperes.

As a standard corkboard was used on one side of the apparatus rather than two identical specimens it was impossible to make the simple assumption of equal division of heat. However, it was possible to determine the actual manner of division of power input between the

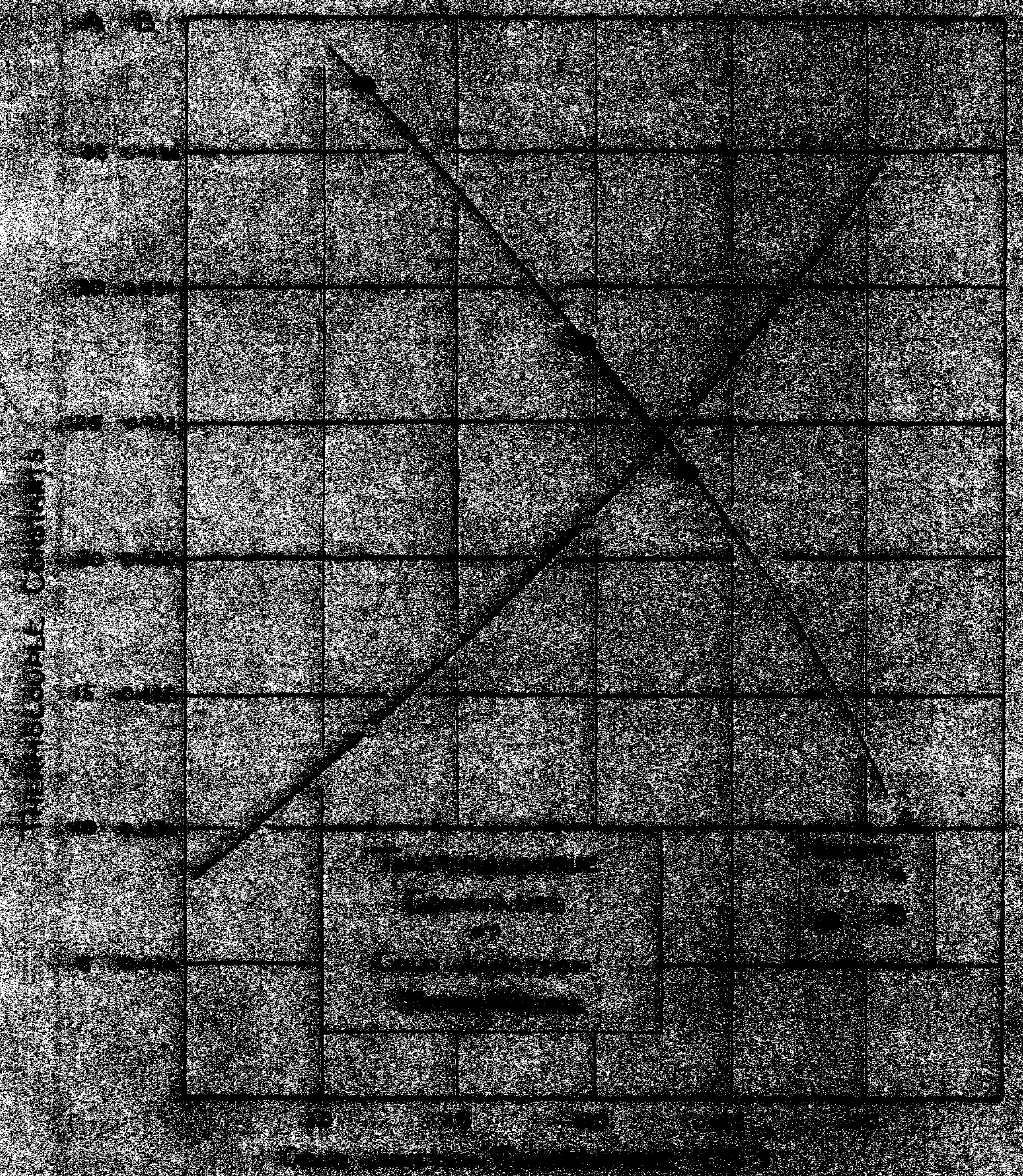

A
B
THERMOCOUPLE CONSTANTS
35
30
25
20
15
10
5
Thermocouple
Constants
vs

Figure 17

standard and the specimen.

In the following discussion the subscripts c and b are used to refer to the values of power, temperature difference, and so forth, associated with the standard cork and the test brick, respectively.

The conductivity of the standard was known as a function of the mean temperature, Fig. 18. As the mean temperature was readily obtained from the average of the temperatures of the hot and cold faces of the cork, the conductivity of the cork could be found from the figure referred to.

Also the temperature difference and the dimensions, A and d_c, of the cork were known. The equation

$$W_c = K_c \Theta_c \frac{A}{d_c} \qquad \text{(Eq. 27)}$$

was used in obtaining that portion of the power input needed to produce a thermal potential difference of Θ_c between the two faces of the standard.

When W_c had been found, W_b, the power taken to produce the thermal potential difference, Θ_b, in the brick, was found by merely subtracting W_c from W.

$$W_b = W - W_c \qquad \text{(Eq. 28)}$$

The equation

$$K_b = \frac{W_b d_b}{\Theta_b A} \qquad \text{(Eq. 29)}$$

served for calculating the thermal conductivity of the brick.

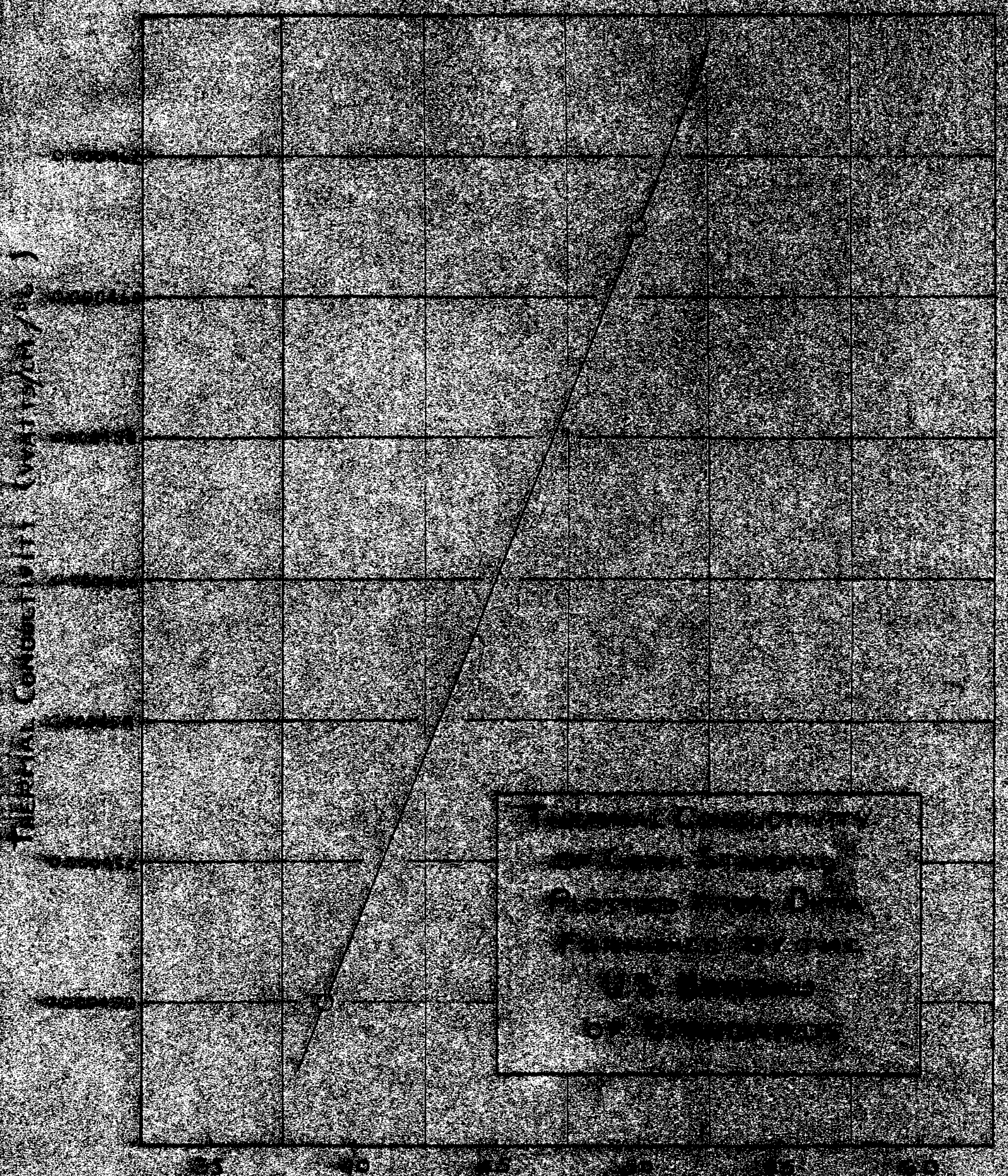

THERMAL CONDUCTIVITY (watts/cm/°K)
Thermal Conductivity
of Lead Selenide
Plotted from Data
Furnished by the
U.S. Bureau
of Standards
-35
-40
-45
-50
-55
-60

Figure 18

The same type of calculation was utilized in calibrating the equipment. One of the standards was considered as having an unknown conductivity represented by K_b.

In the event that the thermal conductivity is desired in watts per degree Fahrenheit per inch, the value as found above in watts per degree Centigrade per centimeter may be multiplied by a factor 1.411 (= 2.54 x 5/9) to give the result in the desired units.

3. Correlation of electrical and thermal conductivity.

The thermal and electrical conductivity were compared as a ratio

$$M = \frac{K}{\sigma} \qquad \text{(Eq. 31)}$$

where M is the ratio of thermal to electrical conductivity, K is the thermal conductivity in watts per degree Centigrade per centimeter and σ is electrical conductivity in mhos per centimeter cube.

The Wiedemann-Franz constant which relates the thermal and electrical conductivity of metals is found from the same ratio in which K is expressed in gram-calories per second per degree Centigrade per centimeter and σ in mhos per centimeter cube. To compare this Wiedemann-Franz constant with the results obtained in this study the Wiedemann-Franz constant may be multiplied by 4.185.

4. Porosity

The porosity was calculated as the amount of water absorption by weight expressed as a percentage of the dry weight of the sample. The equation used in making the calculations was

$$P = \frac{\text{Wet weight} - \text{Dry weight}}{\text{Dry weight}} \; 100 \qquad \text{(Eq. 30)}$$

where P is the percent absorption by weight.

C. Presentation of Results

1. Preliminary results

a. Measurement of electrical conductivity. Two qualitative investigations were made to determine the effect of certain variations upon the electrical conductivity of the brick.

First, the difference in conductivity for various electrode pressures was found to be negligible so long as the pressure was sufficient to hold the brick firmly in place.

Second, inasmuch as the contact between the brick and the electrodes was not uniform but consisted of a group of point contacts, two attempts were made to improve this condition. For the first of these a pasty mixture of carbon-black and linseed oil was used and for the second several layers of aluminum foil were placed between the brick and the electrodes. Neither of these types of contact caused any change in the measurable conductivity.

b. Measurement of thermal conductivity. A preliminary test was made to determine the effect of the plate pressure upon the thermal conductivity. The data and results for the loose plates and the tight plates are given in Table I.

TABLE I

THERMAL CONDUCTIVITY AS A FUNCTION OF PLATE PRESSURE

Test Specimen Number 6
Loose Plates

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.05	23.0	Temp.= 17.2°C.
Current (I', amps.)	0.215	0.706	A = 19.1
Corrected Current (I, amps.)	0.171		B = 0.434
Input (W, watts)	1.376		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	20.0	108.5	108.5	108.5	113.0	15.5
Temp. (°C.)	27.8	66.1	66.1	66.1	68.1	25.8
Mean Temp. (°C.)	47.0				47.0	
Temp. Difference (Θ, °C.)	38.3				42.3	
Watts Input (W.)	0.760				0.616	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001388	

Test Specimen Number 6
Tight Plates

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.05	23.0	Temp.= 17.2°C.
Current (I', amps.)	0.215	0.706	A = 19.1
Corrected Current (I, amps.)	0.171		B = 0.434
Input (W, watts)	1.376		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	20.0	108.5	108.5	108.5	113.5	15.5
Temp. (°C.)	27.8	66.1	66.1	66.1	68.3	25.8
Mean Temp. (°C.)	47.0				47.1	
Temp. Difference (Θ, °C.)	38.3				42.5	
Watts Input (W.)	0.760				0.616	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001382	

c. Miscellaneous data. Since conductivity is the property desired it was necessary to know the dimensions of the sample with respect to the center electrode. Table II gives the thickness of each brick in centimeters. In the same table are also the area of the center electrode used in making the calculations of the electrical conductivity and the area of the center element of the heater plate used in making the calculations of the thermal conductivity. These areas are the ones denoted by a and A in the conductivity formulas. The thickness of the standard cork is also indicated.

TABLE II

DIMENSIONS OF TEST SPECIMENS

Specimen number	Thickness (cm.)
1	6.35
2	6.25
3	6.35
4	6.27
5	6.25
6	6.30
7	6.22
8	6.25
9	6.30
10	6.22
11	6.35
12	6.35
13	6.35
14	6.35
15	6.30
16	6.20
17	6.30
18	6.25
19	5.58
20	5.58
21	5.58
22	5.58

Area of center electrode = 9.62 sq. cm.

Area of center element of heater = 66.1 sq. cm.

Thickness of standard corkboard = 1.53 cm.

2. Measurement of electrical conductivity

The data for the variation of the electrical conductivity of the brick specimens numbers 1 to 18 as a function of the porosity are given in Table III.

The values listed in the columns, from left to right, are the sample number, the percent absorption (obtained from Table XII), the galvanometer deflection in millimeters, the computed values of current corresponding to this deflection, and the computed electrical conductivity. Values contained in the table represent the deflection, current, and conductivity after steady conditions had been reached. The voltage used in each case was 25,000 volts.

Fig. 19 illustrates graphically the variation of conductivity with percent absorption.

The values of current and apparent conductivity one minute after the application of the voltage are given in a similar table, Table IV, and illustrated graphically in Fig. 20.

The data and computed values of current as a function of time are given in Table V. Each group of data presented in this table represents a different one of the specimens, 1 to 18. The voltage again was 25,000 volts. The variation referred to is shown graphically in Fig. 21 for a selected few of the brick, namely, numbers 3, 5, 8, and 16.

Table VI contains the data and computed values of current for different voltages. Deflection-voltage data were taken on only five of the samples, numbers 2, 3, 9, 12, and 18, representing the entire range of porosity. Fig. 22 illustrates the variation of current with voltage for these samples.

Inasmuch as the remaining samples, numbers 19 to 22 were in such a low porosity range compared to the other samples and since they represented a different material, the data and curves illustrating current and conductivity variations for these specimens have been given in separate tables and figures.

Table VII corresponds to Table III. It contains data, observed and calculated, for the true or final values of the electrical conductivity of brick numbers 19 to 22 as a function of porosity. Fig. 23 illustrates this relation graphically.

In Table VIII are presented the data for the variation of the current with time for each specimen. The corresponding curves are shown in Fig. 24.

In Table IX may be found the current-voltage data for samples 19 to 22. The relationship is illustrated in Fig. 25.

TABLE III

ELECTRICAL CONDUCTIVITY

(Spec. 1 — 18)

V = 25,000 volts
Av. Temp. = 47°C.

Test Specimen Number	Percent Absorption by Weight	Galv. Defl. (mm.)	Current (10^{-9} amps.)	Conductivity (10^{-14} mhos/cm.^{3})
1	122	1.1	6.79	17.92
2	112	1.1	6.79	17.64
3	79	2.1	12.99	34.20
4	108	1.2	7.42	19.30
5	85	1.8	11.11	28.85
6	115	1.1	6.79	17.79
7	128	1.0	6.18	15.97
8	130	1.0	6.18	16.05
9	96	1.4	8.65	22.63
10	102	1.3	8.03	20.75
11	101	1.3	8.03	21.20
12	86	1.7	10.51	27.71
13	106	1.2	7.42	19.55
14	97	1.5	9.27	24.45
15	105	1.2	7.42	19.40
16	90	1.6	9.88	25.45
17	98	1.3	8.03	21.02
18	127	1.0	6.18	16.05

TABLE IV

APPARENT ELECTRICAL CONDUCTIVITY AFTER ONE MINUTE

(Spec. 1 — 18)

V = 25,000 volts
Av. Temp. = 47°C.

Test Specimen Number	Percent Absorption by Weight	Galv. Devl. (mm.)	Current (10^{-9} amps.)	Conductivity (10^{-14} mhos/cm.^{3})
1	122	2.7	16.7	44.1
2	112	3.7	22.9	59.3
3	79	75.0	463.0	1220.0
4	108	3.8	23.5	61.3
5	85	22.0	136.0	353.0
6	115	3.0	18.6	48.5
7	128	2.0	12.4	31.9
8	130	1.8	11.1	28.8
9	96	6.3	38.9	101.8
10	102	4.8	29.7	76.6
11	101	5.0	30.9	81.4
12	86	18.0	111.2	293.5
13	106	4.2	26.0	68.4
14	97	5.1	31.5	83.2
15	105	3.7	22.9	59.8
16	90	11.5	71.0	182.8
17	98	5.8	35.9	93.8
18	127	2.6	16.1	41.8

TABLE V

CURRENT — TIME RELATIONS

(Spec. 1 — 18)

V = 25,000 volts
Av. Temp. = 47°C.

Test Specimen Number 1 (122%[+])

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
7 sec.	5.1	32
30	3.1	19
1 min.	2.7	17
2	2.2	14
3	1.8	11
5	1.2	7
10	1.1	7
20	1.1	7

Test Specimen Number 2 (112%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
8 sec.	7.3	45
30	4.4	27
1 min.	3.7	23
2	3.1	19
3	2.7	17
5	2.2	14
10	1.4	9
15	1.2	7
20	1.1	7
30	1.1	7

Test Specimen Number 3 (79%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
10 sec.	124.0	766
30	89.0	550
1 min.	75.0	464
2	56.0	346
3	42.0	260
4	33.0	204
5	26.0	161
6	22.0	136
8	15.0	93
10	11.0	68
15	5.7	35
20	3.2	20
25	2.5	15
30	2.2	14
40	2.1	13
50	2.1	13

Test Specimen Number 4 (108%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
6 sec.	8.5	53
30	4.5	28
1 min.	3.8	23
2	3.3	20
3	2.6	16
4	2.3	14
5	2.0	12
7	1.7	11
10	1.5	9
15	1.3	8
20	1.2	7
30	1.2	7

[+] percent absorption

TABLE V (continued)

Test Specimen Number 5 (85%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
8 sec.	38.0	235
30	28.0	173
1 min.	22.0	136
2	15.6	96
3	12.0	74
5	8.1	50
7	6.0	37
10	4.1	25
15	2.7	17
20	1.9	12
30	1.8	11
40	1.8	11

Test Specimen Number 6 (115%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
8 sec.	5.9	36
30	3.2	20
1 min.	3.0	19
2	2.5	15
3	2.1	13
5	1.8	11
10	1.3	8
15	1.2	7
20	1.1	7
30	1.1	7

Test Specimen Number 7 (128%)

7 sec.	4.8	30
30	2.4	15
1 min.	2.0	12
2	1.7	11
3	1.4	9
5	1.1	7
10	1.0	6
20	1.0	6

Test Specimen Number 8 (130%)

7 sec.	4.5	28
30	2.1	13
1 min.	1.8	11
2	1.5	9
3	1.3	8
5	1.1	7
10	1.0	6
20	1.0	6

Test Specimen Number 9 (96%)

8 sec.	12.0	74
30	8.0	50
1 min.	6.3	39
2	4.6	28
3	3.8	23
5	2.8	17
10	2.0	12
15	1.6	10
20	1.5	9
30	1.4	9
40	1.4	9

Test Specimen Number 10 (102%)

8 sec.	9.6	59
30	5.8	36
1 min.	4.8	30
2	3.9	24
3	3.2	20
5	2.6	16
10	1.9	12
15	1.4	9
20	1.3	8
30	1.3	8

TABLE V (continued)

Test Specimen Number 11 (101%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
8 sec.	10.0	62
30	6.5	40
1 min.	5.0	31
2	4.2	26
3	3.6	22
5	2.8	17
10	2.0	12
15	1.4	9
20	1.3	8
30	1.3	8

Test Specimen Number 12 (86%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
7 sec.	34.0	210
30	22.0	136
1 min.	18.0	111
2	13.5	83
3	10.0	62
5	6.0	37
10	3.6	22
15	2.3	14
20	2.0	12
25	1.8	11
30	1.7	11
40	1.7	11

Test Specimen Number 13 (106%)

7 sec.	8.7	54
30	4.7	29
1 min.	4.2	26
2	3.6	22
3	3.0	19
5	2.4	15
10	1.8	11
15	1.3	8
20	1.2	7
30	1.2	7

Test Specimen Number 14 (97%)

8 sec.	10.5	65
30	6.2	38
1 min.	5.1	32
2	4.5	28
3	4.0	25
5	3.4	21
10	2.5	15
15	1.7	11
20	1.5	9
30	1.5	9

Test Specimen Number 15 (105%)

7 sec.	7.8	48
30	5.0	31
1 min.	3.7	23
2	2.8	17
3	2.3	14
5	1.8	11
10	1.5	9
15	1.3	8
20	1.2	7
30	1.2	7

Test Specimen Number 16 (90%)

8 sec.	21.0	130
30	15.0	93
1 min.	11.5	71
2	8.3	51
3	6.0	37
5	4.2	26
10	2.5	15
15	2.1	13
20	1.8	11
25	1.7	11
30	1.6	10
40	1.6	10

TABLE V (continued)

Test Specimen Number 17 (98%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
8 sec.	10.9	67
30	6.8	42
1 min.	5.8	36
2	5.0	31
3	4.2	26
5	3.5	22
10	2.5	15
15	1.6	10
20	1.3	8
30	1.3	8

Test Specimen Number 18 (127%)

Time	Galv. Defl. (mm.)	Current (10^{-9} amps.)
6 sec.	5.1	32
30	3.0	19
1 min.	2.6	16
2	2.2	14
3	1.7	11
5	1.2	7
10	1.0	6
20	1.0	6

TABLE VI

CURRENT — VOLTAGE RELATIONS

Av. Temp. = 47°C.

Test Specimen Number 2 (112%)

Voltage (volts)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
0	0.0	0.00
15,800	0.4	2.47
20,300	0.7	4.32
25,000	1.1	6.79
27,100	1.3	8.03
29,400	1.6	9.88
31,600	1.9	11.73
33,900	2.3	14.20
35,000	2.5	15.45

Test Specimen Number 3 (79%)

Voltage (volts)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
0	0.0	0.00
15,800	1.0	6.18
20,300	1.5	9.27
25,000	2.1	12.98
27,100	2.5	15.43
29,400	2.9	17.92
31,600	3.3	20.40
33,900	3.8	23.45
35,000	4.1	25.30

Test Specimen Number 9 (96%)

0	0.0	0.00
15,800	0.6	3.70
20,300	0.9	5.56
25,000	1.4	8.65
27,100	1.7	10.50
29,400	2.0	12.36
31,600	2.4	14.83
33,900	2.8	17.30
35,000	3.0	18.54

Test Specimen Number 12 (86%)

0	0.0	0.00
15,800	0.8	4.94
20,300	1.2	7.42
25,000	1.7	10.50
27,100	2.1	12.98
29,400	2.5	15.43
31,600	2.9	17.92
33,900	3.4	21.00
35,000	3.6	22.20

TABLE VI (continued)

Test Specimen Number 18 (127%)

Voltage (volts)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
0	0.0	0.00
15,800	0.3	1.85
20,300	0.6	3.70
25,000	1.0	6.18
27,100	1.2	7.42
29,400	1.5	9.27
31,600	1.8	11.11
33,900	2.1	12.98
35,000	2.3	14.20

TABLE VII

ELECTRICAL CONDUCTIVITY

(Spec. 19 — 22)

V = 25,000 volts
Av. Temp. = 47°C.

Test Specimen Number	Percent Absorption by Weight	Galv. Defl. (mm.)	Current (10^{-9} amps.)	Conductivity (10^{-14} mhos/cm.^{3})
19	6.37	27.0	167	388
20	1.83	34.0	210	488
21	3.01	31.0	192	446
22	5.00	28.0	173	402

TABLE VIII

CURRENT — TIME RELATIONS

(Spec. 19 — 22)

V = 25,000 volts
Av. Temp. = 47°C.

Test Specimen Number 19 (6.37%)

Time (min.)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
9.5	245	1514
10	231	1429
11	208	1285
12	182	1125
13	164	1013
14	148	914
15	134	827
17	110	680
20	85	525
25	58	358
30	42	260
40	30	185
50	27	167
60	27	167

Test Specimen Number 20 (1.63%)

Time (min.)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
30.5	238	1472
31	220	1360
32	199	1230
33	181	1119
34	167	1032
35	151	932
37	128	790
40	102	630
45	73	451
50	55	340
60	39	241
70	34	210
80	34	210

Test Specimen Number 21 (3.01%)

Time (min.)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
18	254	1570
19	229	1414
20	208	1285
21	189	1170
22	171	1056
23	157	970
25	132	815
27	113	698
30	92	568
35	68	420
40	53	328
50	39	241
60	31	192
70	31	192

Test Specimen Number 22 (5.00%)

Time (min.)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
11	242	1495
12	228	1410
13	210	1297
14	191	1180
15	173	1070
16	160	988
18	133	820
21	105	649
25	76	470
30	57	352
35	45	278
40	38	235
45	33	204
50	28	173
60	28	173

TABLE IX

CURRENT — VOLTAGE RELATIONS

(Spec. 19 — 22)

Av. Temp. = 47°C.

Voltage (volts)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
Test Specimen Number 19 (6.37%)		
0	0.0	0.0
6,800	2.5	15.5
9,000	5.0	30.9
11,300	7.0	43.3
13,600	8.5	52.5
15,800	13.0	80.3
18,100	17.0	105.0
20,300	20.5	126.6
22,600	23.0	142.2
25,000	27.0	167.0
27,100	30.5	188.5
Test Specimen Number 20 (1.83%)		
0	0.0	0.0
6,800	6.0	37.1
9,000	9.0	55.6
11,300	12.5	77.3
13,600	16.5	102.0
15,800	20.0	123.6
18,100	23.5	145.3
20,300	26.5	163.9
22,600	30.5	188.5
25,000	34.0	210.0
27,100	37.0	228.5

Voltage (volts)	Galv. Defl. (mm.)	Current (10^{-9} amps.)
Test Specimen Number 21 (3.01%)		
0	0.0	0.0
6,800	4.0	24.7
9,000	7.0	43.3
11,300	10.0	61.8
13,600	13.0	80.3
15,800	17.0	105.0
18,100	21.0	129.8
20,300	24.0	148.3
22,600	27.0	167.0
25,000	31.0	191.7
27,100	35.0	216.2
Test Specimen Number 22 (5.00%)		
0	0.0	0.0
6,800	3.0	18.5
9,000	6.0	37.1
11,300	8.5	52.5
13,600	11.0	67.9
15,800	15.5	95.8
18,100	19.0	117.5
20,300	22.5	139.0
22,600	25.0	154.6
25,000	28.0	173.0
27,100	33.0	204.0

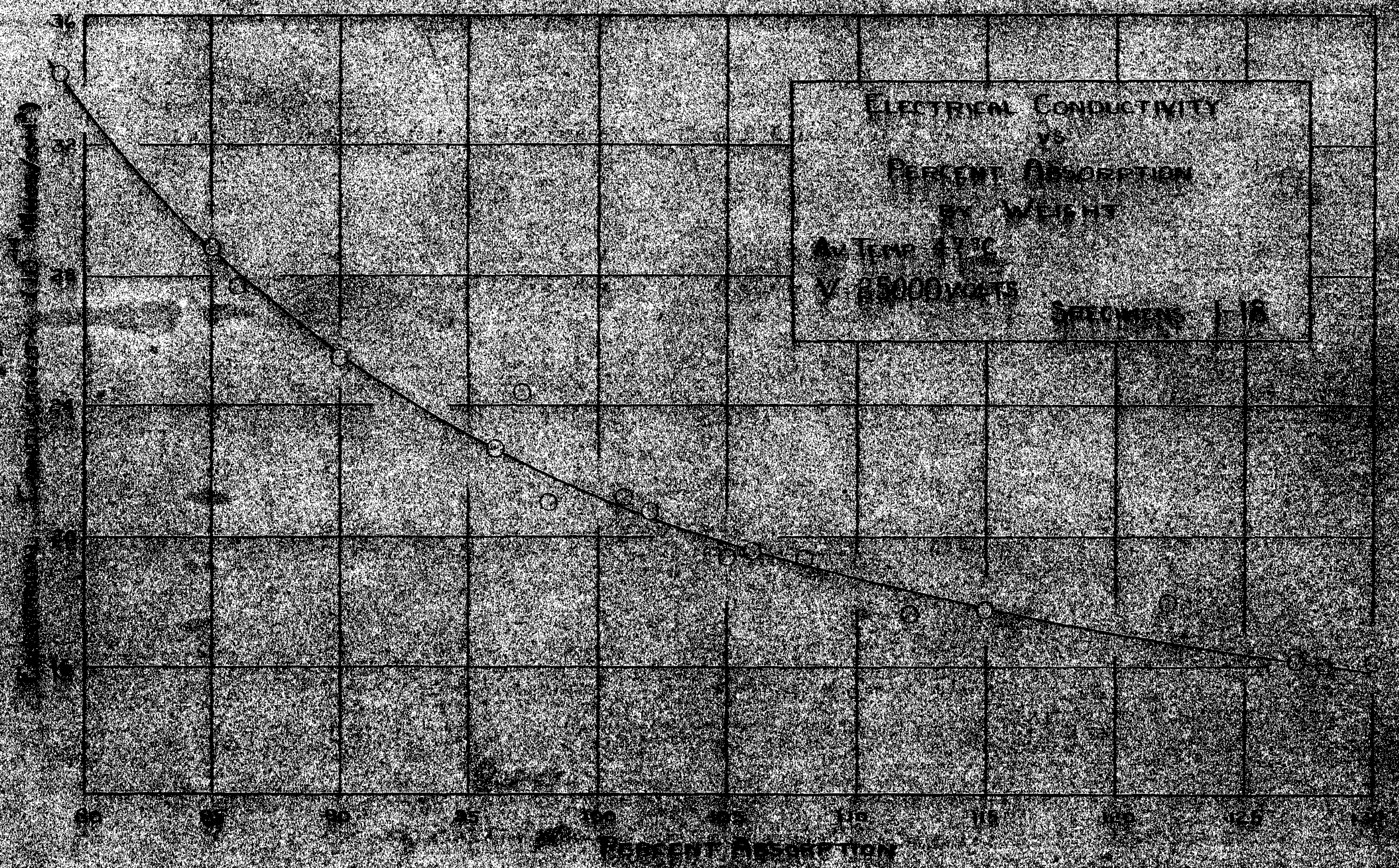
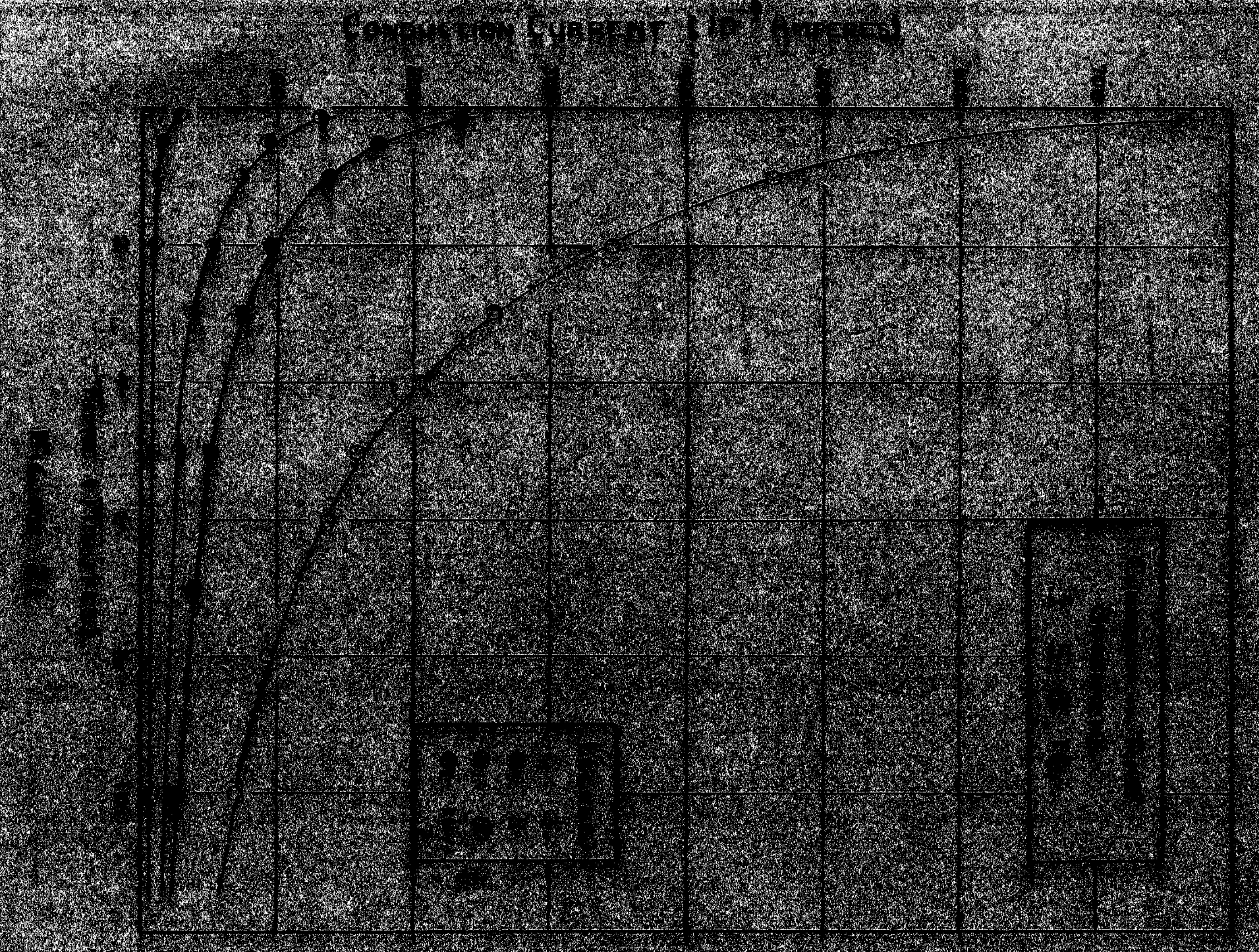

ELECTRICAL CONDUCTIVITY
VS
PERCENT ABSORPTION
BY WEIGHT
AV. TEMP. 41°C
V: 25000 VOLTS
SPECIMENS 1-18
36
32
28
24
20
16
80
85
90
95
100
105
110
115
120
125
130
PERCENT ABSORPTION

FIGURE 19

Figure 29


Conduction Current ([illegible] Amperes)

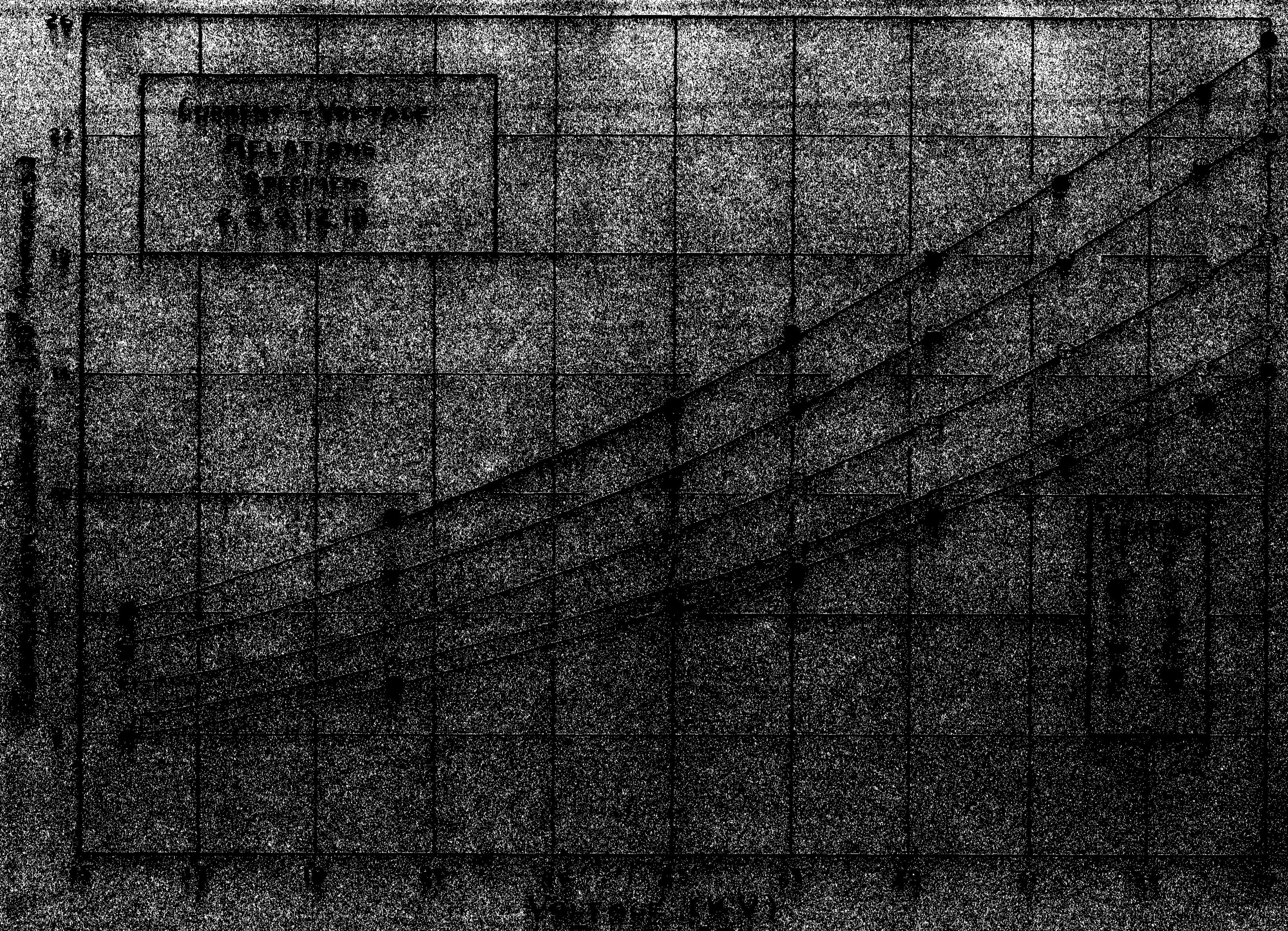
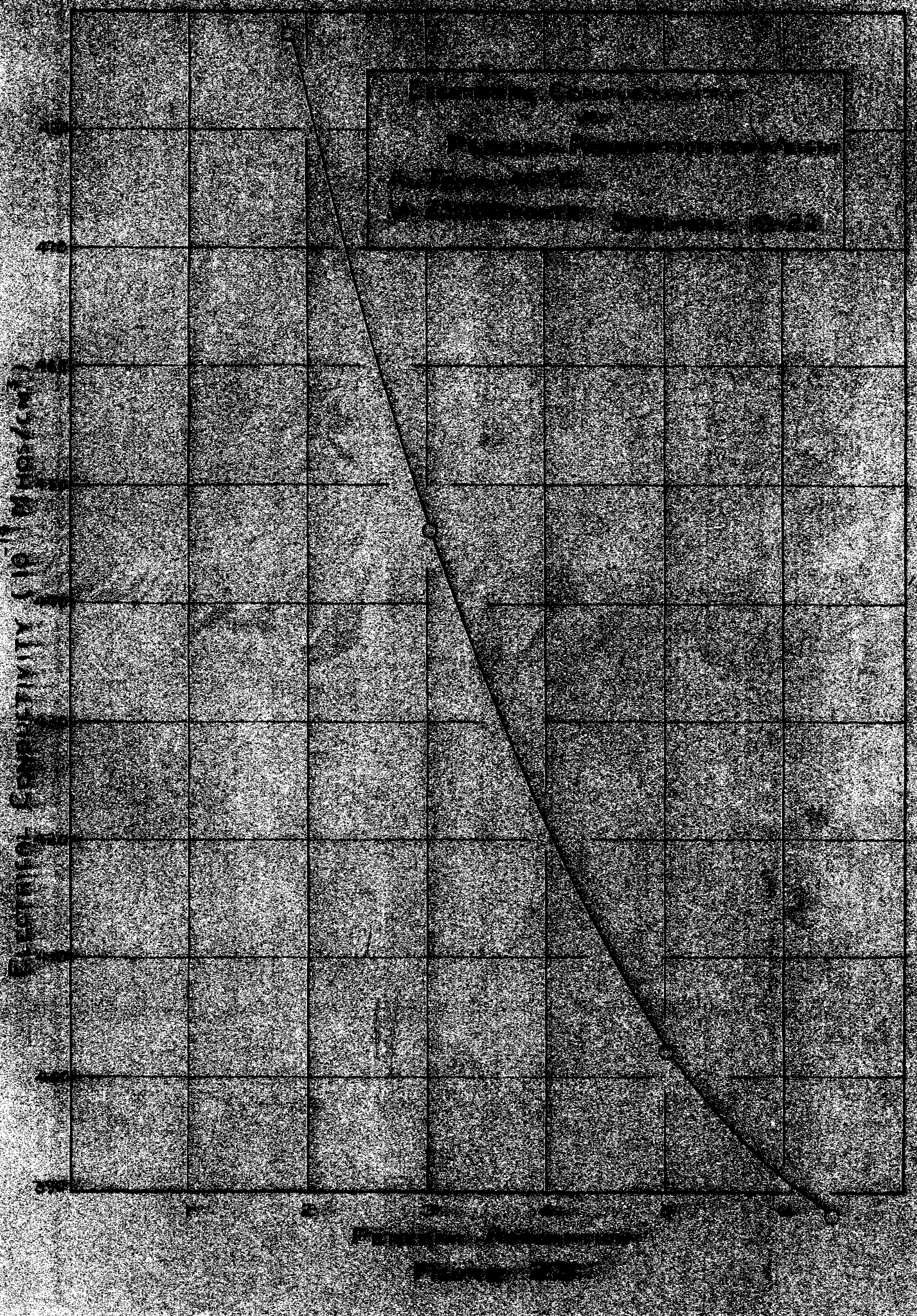


FIGURE 28


Electrical Conductivity (10^{-11} Mhos/cm)

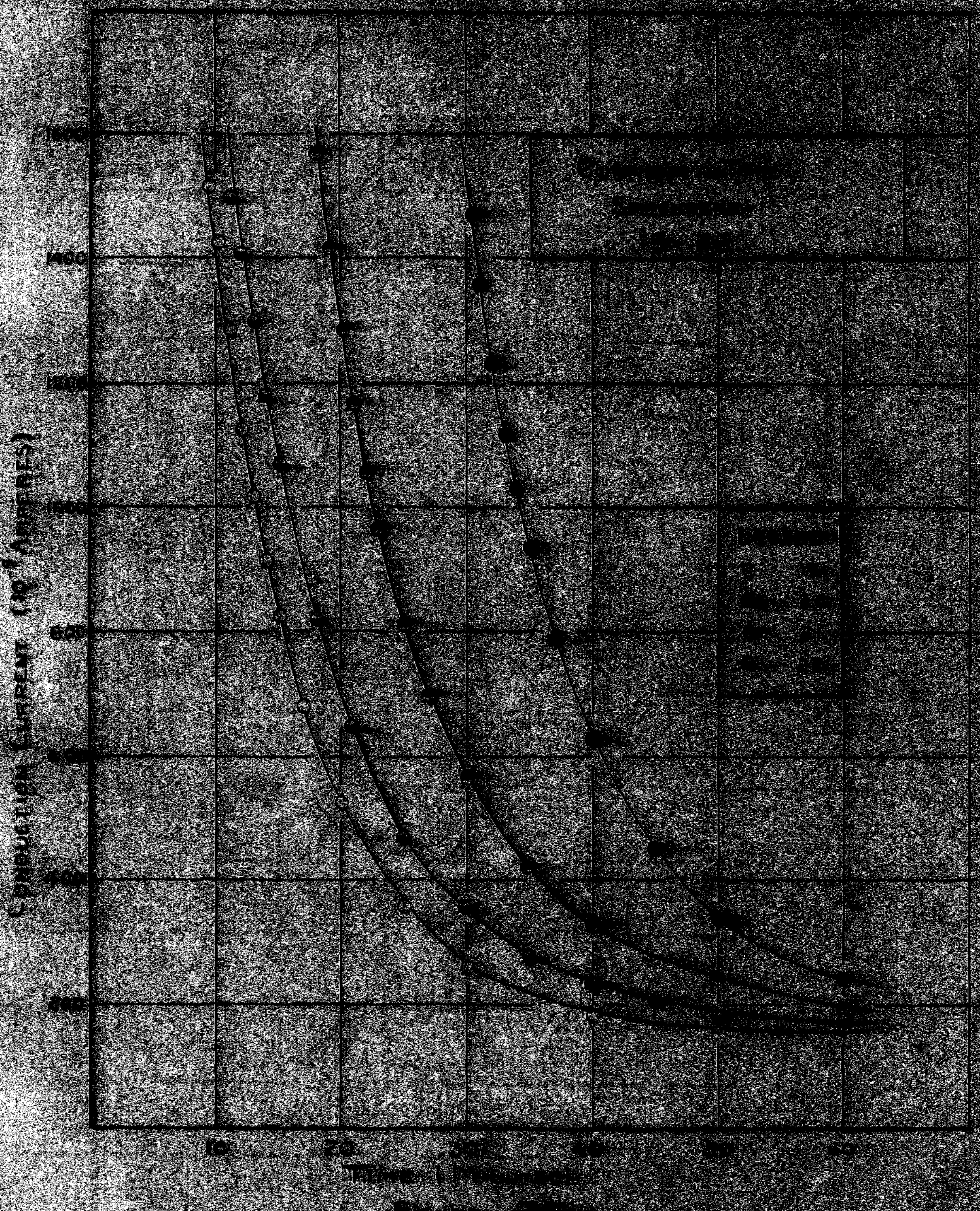
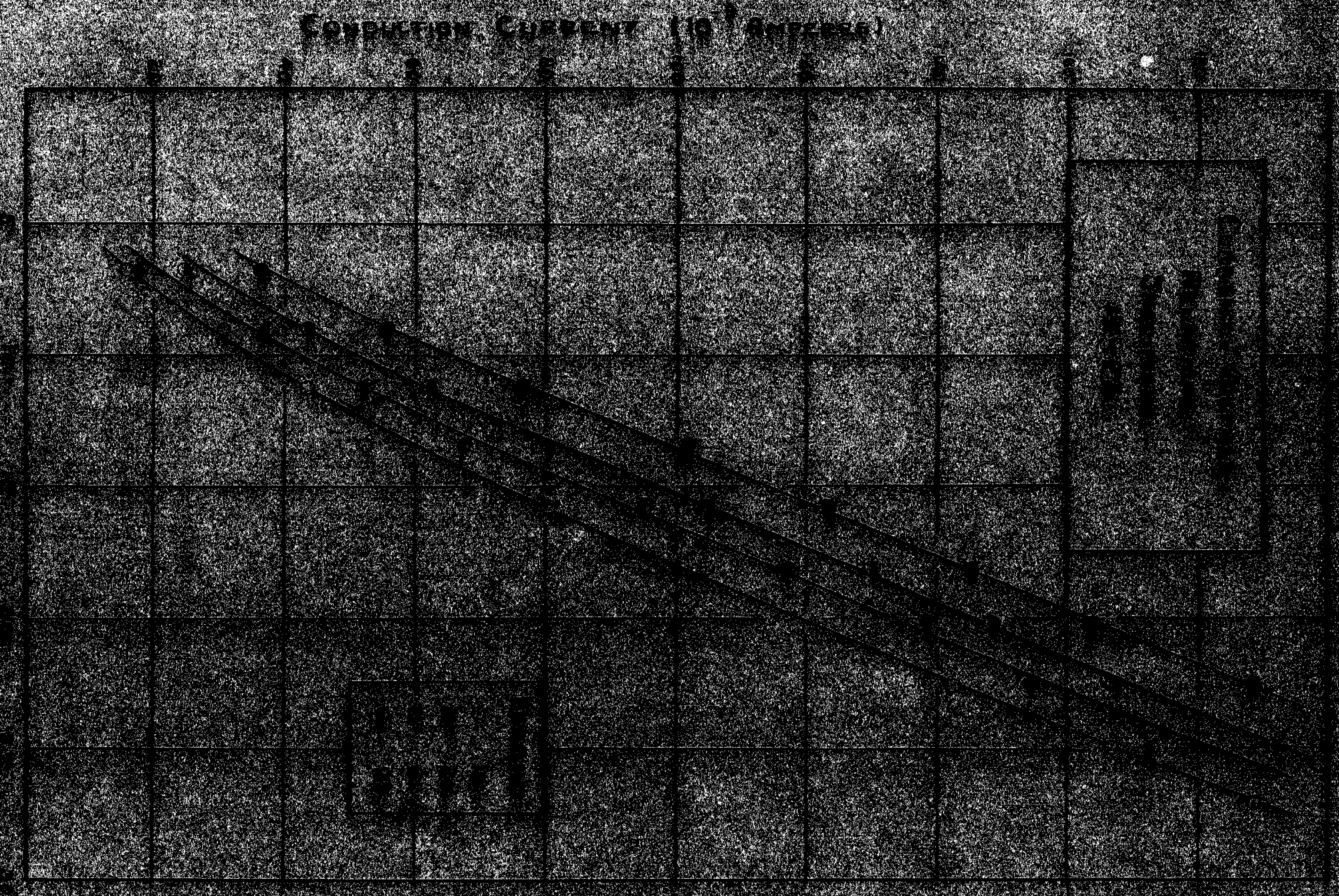

1600
1400
1200
1000
800
600
400
200
CONDUCTION CURRENT (10⁻⁸ AMPERES)
10
20
30
40
50
60
TIME (MINUTES)

FIGURE [illegible]


CONDUCTION CURRENT (10 [illegible] AMPERES)

[illegible]

3. Measurement of thermal conductivity

The data showing the variation of thermal conductivity with porosity for brick specimens numbers 1 to 18 are given in Table X and represented graphically in Fig. 26. This table contains the observed data, the constants used in making the computations, and the calculated values of thermal conductivity.

Similar data for the remaining specimens, numbers 19 to 22, are given in Table XI and illustrated graphically in Fig. 27.

TABLE X

THERMAL CONDUCTIVITY

(Spec. 1 — 18)

Test Specimen Number 1

	Power Input: Center Element	Power Input: Guard Ring
Voltage (V, volts)	8.00	25.0
Current (I', amps.)	0.2155	0.76
Corrected Current (I, amps.)	0.172	
Input (W, watts)	1.375	

Cold Junction

Temp. = 22.0°C.
A = 23.9
B = 0.432

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	14.5	106.0	106.0	106.0	108.5	9.5
Temp. (°C.)	30.2	69.7	69.7	69.7	70.3	28.0
Mean Temp. (°C.)	50.0				49.2	
Temp. Difference (Θ, °C.)	39.5				42.3	
Watts Input (W.)	0.789				0.586	
Thermal Conductivity (K, Watts/cm./°C.)	0.000461				0.001331	

Test Specimen Number 2

	Power Input: Center Element	Power Input: Guard Ring
Voltage (V, volts)	8.01	23.0
Current (I', amps.)	0.215	0.70
Corrected Current (I, amps.)	0.1715	
Input (W, watts)	1.373	

Cold Junction

Temp. = 18.3°C.
A = 20.2
B = 0.434

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	16.0	104.5	104.5	104.5	107.5	12.0
Temp. (°C.)	27.1	65.5	65.5	65.5	66.8	25.4
Mean Temp. (°C.)	46.3				46.1	
Temp. Difference (Θ, °C.)	38.4				41.4	
Watts Input (W.)	0.760				0.613	
Thermal Conductivity (K, Watts/cm./°C.)	0.000457				0.001400	

TABLE X (continued)

Test Specimen Number 3

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	7.94	21.5	Temp. = 21.1°C.
Current (I', amps.)	0.2127	0.66	A = 23.0
Corrected Current (I, amps.)	0.1695		B = 0.433
Input (W, watts)	1.345		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	12.0	86.0	86.0	86.0	86.0	9.5
Temp. (°C.)	28.2	60.2	60.2	60.2	60.2	27.1
Mean Temp. (°C.)	44.2				43.7	
Temp. Difference (Θ, °C.)	32.0				33.1	
Watts Input (W.)	0.630				0.715	
Thermal Conductivity (K, Watts/cm./°C.)	0.000455				0.002076	

Test Specimen Number 4

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.07	22.8	Temp. = 15.6°C
Current (I', amps.)	0.2155	0.70	A = 17.5
Corrected Current (I, amps.)	0.172		B = 0.435
Input (W, watts)	1.389		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	23.5	113.0	113.0	113.0	117.0	19.0
Temp. (°C.)	27.7	66.6	66.6	66.6	68.4	25.8
Mean Temp. (°C.)	47.2				47.1	
Temp. Difference (Θ, °C.)	38.9				42.6	
Watts Input (W.)	0.772				0.617	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001374	

TABLE X (continued)

Test Specimen Number 5

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.02	22.1	Temp.= 16.1°C.
Current (I', amps.)	0.216	0.68	A = 18.0
Corrected Current (I, amps.)	0.1735		B = 0.435
Input (W, watts)	1.391		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	21.5	101.5	101.5	101.5	100.5	18.5
Temp. (°C.)	27.4	62.1	62.1	62.1	61.7	26.0
Mean Temp. (°C.)	44.8				43.9	
Temp. Difference (Θ, °C.)	34.7				35.7	
Watts Input (W.)	0.686				0.703	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001863	

Test Specimen Number 6

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.05	23.0	Temp.= 17.2°C
Current (I', amps.)	0.215	0.706	A = 19.1
Corrected Current (I, amps.)	0.171		B = 0.434
Input (W, watts)	1.376		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	20.0	108.5	108.5	108.5	113.5	15.5
Temp. (°C.)	27.8	66.1	66.1	66.1	68.3	25.8
Mean Temp. (°C.)	47.0				47.1	
Temp. Difference (Θ, °C.)	38.3				42.5	
Watts Input (W.)	0.760				0.616	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001382	

TABLE X (continued)

Test Specimen Number 7

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.02	23.0	Temp.= 16.7°C.
Current (I', amps.)	0.2155	0.709	A = 18.6
Corrected Current (I, amps.)	0.172		B = 0.435
Input (W, watts)	1.379		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	20.0	109.0	109.0	109.0	114.0	15.0
Temp. (°C.)	27.3	66.0	66.0	66.0	68.2	25.1
Mean Temp. (°C.)	46.7				46.7	
Temp. Difference (Θ, °C.)	38.7				43.1	
Watts Input (W.)	0.768				0.611	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001334	

Test Specimen Number 8

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.08	23.0	Temp.= 15.8°C.
Current (I', amps.)	0.217	0.709	A = 17.7
Corrected Current (I, amps.)	0.173		B = 0.435
Input (W, watts)	1.389		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	20.0	111.0	111.0	111.0	115.5	15.0
Temp. (°C.)	26.4	66.0	66.0	66.0	67.9	24.2
Mean Temp. (°C.)	46.2				46.1	
Temp. Difference (Θ, °C.)	39.6				43.7	
Watts Input (W.)	0.784				0.605	
Thermal Conductivity (K, Watts/cm./°C.)	0.000457				0.001310	

TABLE X (continued)

Test Specimen Number 9

	Power Input Center Element	Power Input Guard Ring	Cold Junction
Voltage (V, volts)	8.02	23.0	Temp.= 21.4°C.
Current (I', amps.)	0.2165	0.701	A = 23.3
Corrected Current (I, amps.)	0.173		B = 0.432
Input (W, watts)	1.389		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	10.5	96.5	96.5	96.5	99.5	6.5
Temp. (°C.)	27.8	65.0	65.0	65.0	66.3	26.1
Mean Temp. (°C.)	46.4				46.2	
Temp. Difference (Θ, °C.)	37.2				40.2	
Watts Input (W.)	0.736				0.653	
Thermal Conductivity (K, Watts/cm./°C.)	0.000457				0.001549	

Test Specimen Number 10

	Power Input Center Element	Power Input Guard Ring	Cold Junction
Voltage (V, volts)	8.04	23.0	Temp.= 21.4°C.
Current (I', amps.)	0.2165	0.705	A = 23.3
Corrected Current (I, amps.)	0.173		B = 0.432
Input (W, watts)	1.390		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	15.5	103.5	103.5	103.5	107.5	11.5
Temp. (°C.)	30.0	68.0	68.0	68.0	69.7	28.2
Mean Temp. (°C.)	49.0				49.0	
Temp. Difference (Θ, °C.)	38.0				41.5	
Watts Input (W.)	0.757				0.633	
Thermal Conductivity (K, Watts/cm./°C.)	0.000460				0.001435	

TABLE X (continued)

Test Specimen Number **11**

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.00	22.5	Temp. = 24.2°C.
Current (I', amps.)	0.214	0.690	A = 26.6
Corrected Current (I, amps.)	0.1705		B = 0.431
Input (W, watts)	1.363		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	11.0	96.0	96.0	96.0	101.0	7.5
Temp. (°C.)	31.3	68.0	68.0	68.0	70.1	29.8
Mean Temp. (°C.)	49.7				50.0	
Temp. Difference (Θ, °C.)	36.7				40.3	
Watts Input (W.)	0.733				0.630	
Thermal Conductivity (K, Watts/cm./°C.)	0.000461				0.001501	

Test Specimen Number **12**

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	7.96	22.3	Temp. = 27.2°C.
Current (I', amps.)	0.213	0.682	A = 30.3
Corrected Current (I, amps.)	0.1697		B = 0.429
Input (W, watts)	1.350		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	10.0	88.5	88.5	88.5	89.5	6.5
Temp. (°C.)	34.6	68.3	68.3	68.3	68.7	33.1
Mean Temp. (°C.)	51.5				50.9	
Temp. Difference (Θ, °C.)	33.7				35.6	
Watts Input (W.)	0.676				0.674	
Thermal Conductivity (K, Watts/cm./°C.)	0.000463				0.001820	

TABLE X (continued)

Test Specimen Number 13

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	7.93	22.5	Temp. = 19.2°C.
Current (I', amps.)	0.2125	0.682	A = 21.1
Corrected Current (I, amps.)	0.1694		B = 0.433
Input (W, watts)	1.342		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	14.0	99.0	99.0	99.0	102.5	9.5
Temp. (°C.)	27.2	64.0	64.0	64.0	65.5	25.2
Mean Temp. (°C.)	45.6				45.4	
Temp. Difference (Θ, °C.)	36.8				40.3	
Watts Input (W.)	0.728				0.614	
Thermal Conductivity (K, Watts/cm./°C.)	0.000457				0.001462	

Test Specimen Number 14

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.07	22.5	Temp. = 21.1°C.
Current (I', amps.)	0.2155	0.685	A = 23.0
Corrected Current (I, amps.)	0.1717		B = 0.433
Input (W, watts)	1.383		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	14.0	99.0	99.0	99.0	102.5	9.5
Temp. (°C.)	29.1	65.9	65.9	65.9	67.4	27.1
Mean Temp. (°C.)	47.5				47.3	
Temp. Difference (Θ, °C.)	36.8				40.3	
Watts Input (W.)	0.732				0.651	
Thermal Conductivity (K, Watts/cm./°C.)	0.000459				0.001550	

TABLE X (continued)

Test Specimen Number 15

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.00	22.5	Temp.= 18.3°C.
Current (I', amps.)	0.2135	0.684	A = 20.2
Corrected Current (I, amps.)	0.170		B = 0.434
Input (W, watts)	1.360		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	21.0	106.0	106.0	106.0	110.0	16.5
Temp. (°C.)	29.3	66.2	66.2	66.2	67.9	27.4
Mean Temp. (°C.)	47.8				47.7	
Temp. Difference (Θ, °C.)	36.9				40.5	
Watts Input (W.)	0.734				0.626	
Thermal Conductivity (K, Watts/cm./°C.)	0.000459				0.001473	

Test Specimen Number 16

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.07	22.5	Temp.= 19.4°C.
Current (I', amps.)	0.2155	0.685	A = 21.3
Corrected Current (I, amps.)	0.1717		B = 0.433
Input (W, watts)	1.383		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	13.5	96.0	96.0	96.0	98.5	10.0
Temp. (°C.)	27.1	62.9	62.9	62.9	64.0	25.6
Mean Temp. (°C.)	45.0				44.8	
Temp. Difference (Θ, °C.)	35.8				38.4	
Watts Input (W.)	0.707				0.676	
Thermal Conductivity (K, Watts/cm./°C.)	0.000456				0.001651	

TABLE X (continued)

Test Specimen Number **17**

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.00	21.3	Temp.= 20.3°C.
Current (I', amps.)	0.212	0.670	A = 22.2
Corrected Current (I, amps.)	0.1685		B = 0.433
Input (W, watts)	1.348		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	15.0	97.5	97.5	97.5	101.0	10.5
Temp. (°C.)	28.7	64.4	64.4	64.4	65.9	26.7
Mean Temp. (°C.)	46.6				46.6	
Temp. Difference (Θ, °C.)	35.7				39.2	
Watts Input (W.)	0.708				0.640	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.001554	

Test Specimen Number **18**

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.00	22.5	Temp.= 18.9°C.
Current (I', amps.)	0.2135	0.687	A = 20.8
Corrected Current (I, amps.)	0.170		B = 0.434
Input (W, watts)	1.359		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	18.5	106.0	106.0	106.0	113.5	14.5
Temp. (°C.)	28.8	66.8	66.8	66.8	70.0	27.1
Mean Temp. (°C.)	47.8				48.6	
Temp. Difference (Θ, °C.)	38.0				42.9	
Watts Input (W.)	0.755				0.604	
Thermal Conductivity (K, Watts/cm./°C.)	0.000459				0.001331	

TABLE XI

THERMAL CONDUCTIVITY

(Spec. 19 —22)

Test Specimen Number 19

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	11.9	29.5	Temp. = 28.4°C.
Current (I', amps.)	0.319	0.900	A = 32.0
Corrected Current (I, amps.)	0.254		B = 0.429
Input (W, watts)	3.020		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	13.5	107.0	107.0	107.0	87.0	23.5
Temp. (°C.)	37.8	77.9	77.9	77.9	69.3	42.1
Mean Temp. (°C.)	57.9				55.7	
Temp. Difference (Θ, °C.)	40.1				27.2	
Watts Input (W.)	0.814				2.206	
Thermal Conductivity (K, Watts/cm./°C.)	0.000469				0.00685	

Test Specimen Number 20

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	11.88	26.0	Temp. = 18.3°C.
Current (I', amps.)	0.318	0.795	A = 20.2
Corrected Current (I, amps.)	0.253		B = 0.434
Input (W, watts)	3.010		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	15.0	97.5	97.5	97.5	80.5	22.0
Temp. (°C.)	26.8	62.5	62.5	62.5	55.2	29.7
Mean Temp. (°C.)	44.7				42.5	
Temp. Difference (Θ, °C.)	35.7				25.5	
Watts Input (W.)	0.705				2.305	
Thermal Conductivity (K, Watts/cm./°C.)	0.000456				0.00763	

TABLE XI (continued)

Test Specimen Number 21

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	11.83	28.3	Temp.= 18.9°C.
Current (I', amps.)	0.316	0.860	A = 20.7
Corrected Current (I, amps.)	0.252		B = 0.434
Input (W, watts)	2.980		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	14.0	105.0	105.0	105.0	83.5	25.0
Temp. (°C.)	26.8	66.3	66.3	66.3	56.9	31.5
Mean Temp. (°C.)	46.6				44.2	
Temp. Difference (Θ, °C.)	39.5				25.4	
Watts Input (W.)	0.783				2.197	
Thermal Conductivity (K, Watts/cm./°C.)	0.000458				0.00730	

Test Specimen Number 22

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	11.9	25.9	Temp.= 28.4°C.
Current (I', amps.)	0.319	0.900	A = 32.0
Corrected Current (I, amps.)	0.254		B = 0.429
Input (W, watts)	3.020		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	14.0	106.5	106.5	106.5	86.5	24.0
Temp. (°C.)	38.0	77.7	77.7	77.7	69.1	42.3
Mean Temp. (°C.)	56.9				55.7	
Temp. Difference (Θ, °C.)	39.7				26.8	
Watts Input (W.)	0.805				2.215	
Thermal Conductivity (K, Watts/cm./°C.)	0.000469				0.00698	

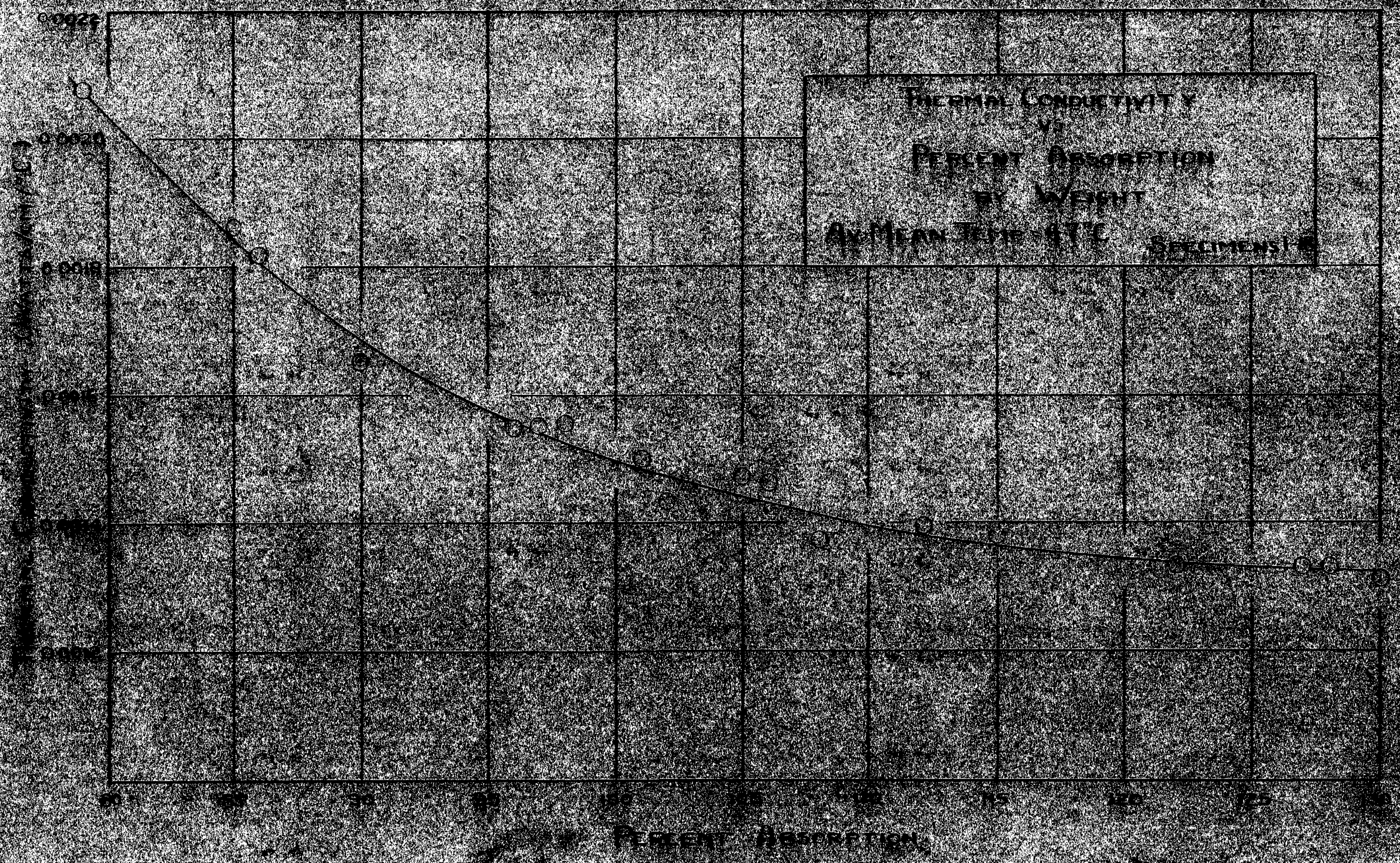
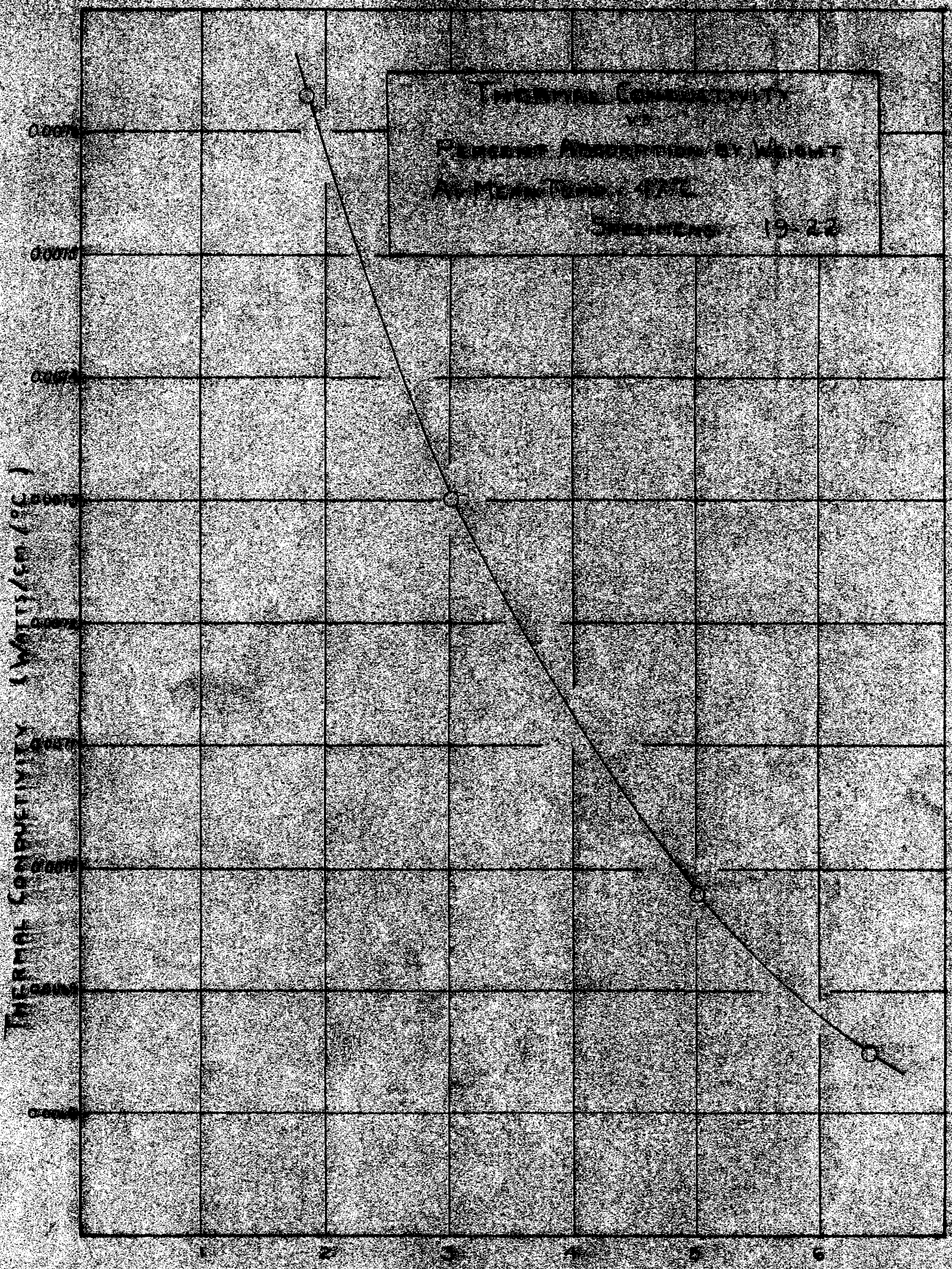

Thermal Conductivity
vs
Percent Absorption
by Weight
Av. Mean Temp. 47°C
Specimens 1-6
0.0022
0.0020
0.0018
0.0016
0.0014
0.0012
80
85
90
95
100
105
110
115
120
125
130
Percent Absorption

Figure 26



PERCENT ABSORPTION

FIGURE 27

4. Measurement of porosity

Table XII contains the data, observed and computed, relating to the porosity of the brick expressed as a percent absorption by weight.

TABLE XII

POROSITY

Test Specimen Number	Dry Weight (grams)	Wet Weight (grams)	Percent Absorption
1	963	2138	122
2	946	2006	112
3	1309	2343	79
4	960	1997	108
5	1242	2300	85
6	943	2027	115
7	950	2165	128
8	940	2162	130
9	924	1811	96
10	906	1829	102
11	978	1965	101
12	1106	2056	86
13	914	1883	106
14	1002	1974	97
15	1005	2061	105
16	945	1795	90
17	980	1940	98
18	970	2202	127
19	2297	2443	6.37
20	2347	2390	1.83
21	2391	2463	3.01
22	2280	2394	5.00

5. Correlation of electrical and thermal conductivity

In Table XIII are shown the data used in calculating the ratio of thermal to electrical conductivity for the first group of specimens. The data presented have been taken directly from Tables III and X. Fig. 28 illustrates the manner in which the ratio varies with porosity.

Table XIV contains data similar to those in Table XIII with the exception that they have been taken directly from the smooth curves in Figs. 19 and 26. The curve in Fig. 28 has been drawn through the points representing the latter data.

Table XV contains like data for the second group of brick samples taken directly from Tables VII and XI. Fig. 29 represents graphically the variation of the ratio of thermal to electrical conductivity as a function of porosity for those brick.

Fig. 30 indicates the variation of the ratio over the entire range of porosities as obtained from the data on all the samples. The points were plotted from data in Tables XIV and XV. The central portion of the curve has been drawn as a dashed line indicating that no data were obtained for the middle range of porosities.

TABLE XIII

RATIO — THERMAL TO ELECTRICAL CONDUCTIVITY

(Spec. 1 — 18)
(Taken from Tables III and X)

Test Specimen Number	Thermal Cond. (watts/cm./°C.)	Electrical Cond. (10^{-14}mhos/cm.^{3})	Ratio
1	0.001331	17.92	74.2 x 10^8
2	0.001400	17.64	79.3
3	0.002076	34.20	60.6
4	0.001374	19.30	71.1
5	0.001863	28.85	64.5
6	0.001382	17.79	77.7
7	0.001334	15.97	83.6
8	0.001310	16.05	81.6
9	0.001549	22.63	68.3
10	0.001435	20.75	69.1
11	0.001501	21.20	70.7
12	0.001820	27.71	65.6
13	0.001462	19.55	74.8
14	0.001550	24.45	63.3
15	0.001473	19.40	76.0
16	0.001651	25.45	64.9
17	0.001554	21.02	73.9
18	0.001331	16.05	83.1

TABLE XIV

RATIO — THERMAL TO ELECTRICAL CONDUCTIVITY

(Spec. 1 — 18)
(Taken from Figs. 19 and 26)

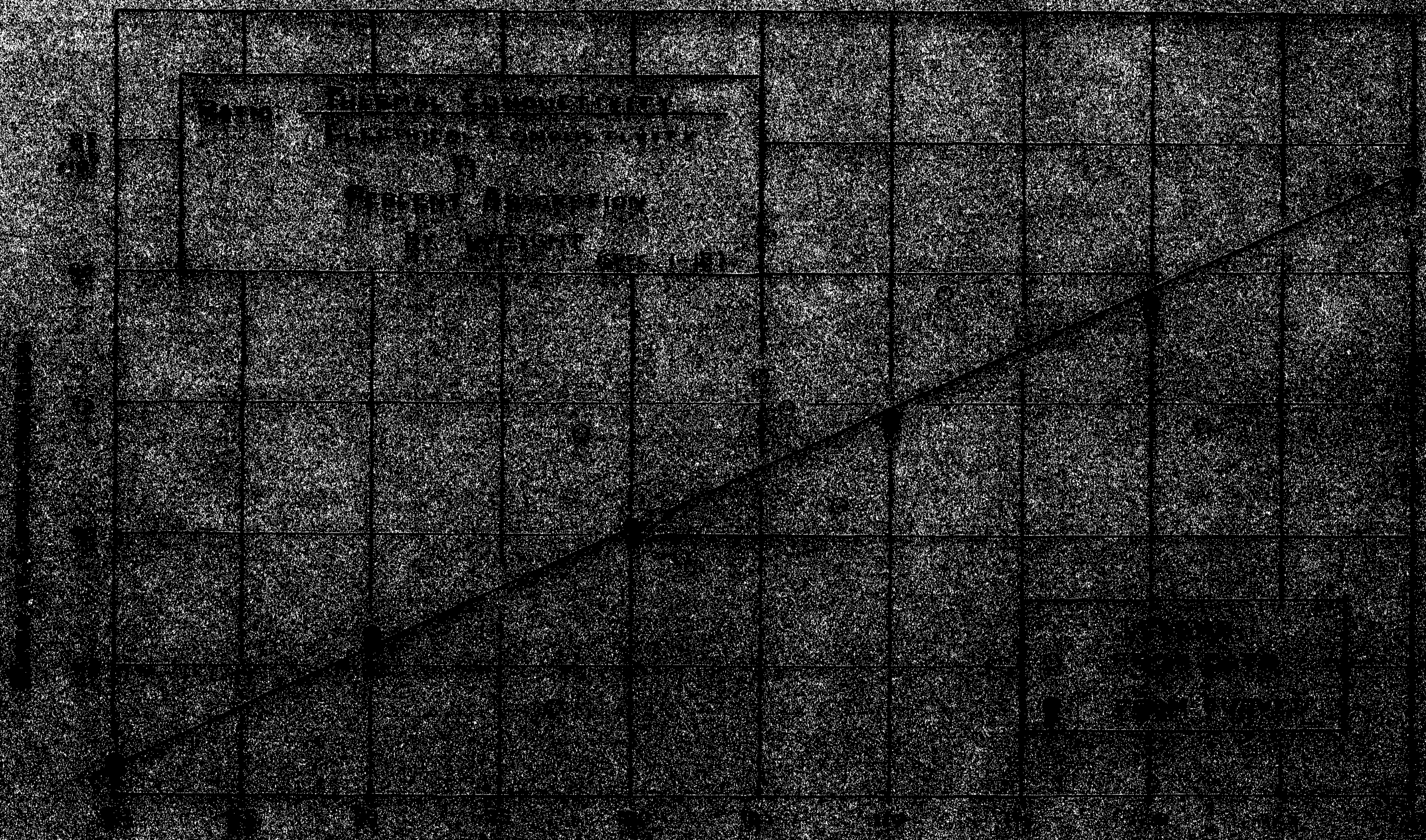
Percent Absorption	Thermal Cond. (watts/cm./°C.)	Electrical Cond. (10^{-14}mhos/cm.^{3})	Ratio
80	0.002035	33.25	61.2 x 10^8
90	0.001695	25.60	66.1
100	0.001500	21.30	70.3
110	0.001395	18.70	74.6
120	0.001340	16.95	78.9
130	0.001325	15.80	83.8

TABLE XV

RATIO — THERMAL TO ELECTRICAL CONDUCTIVITY

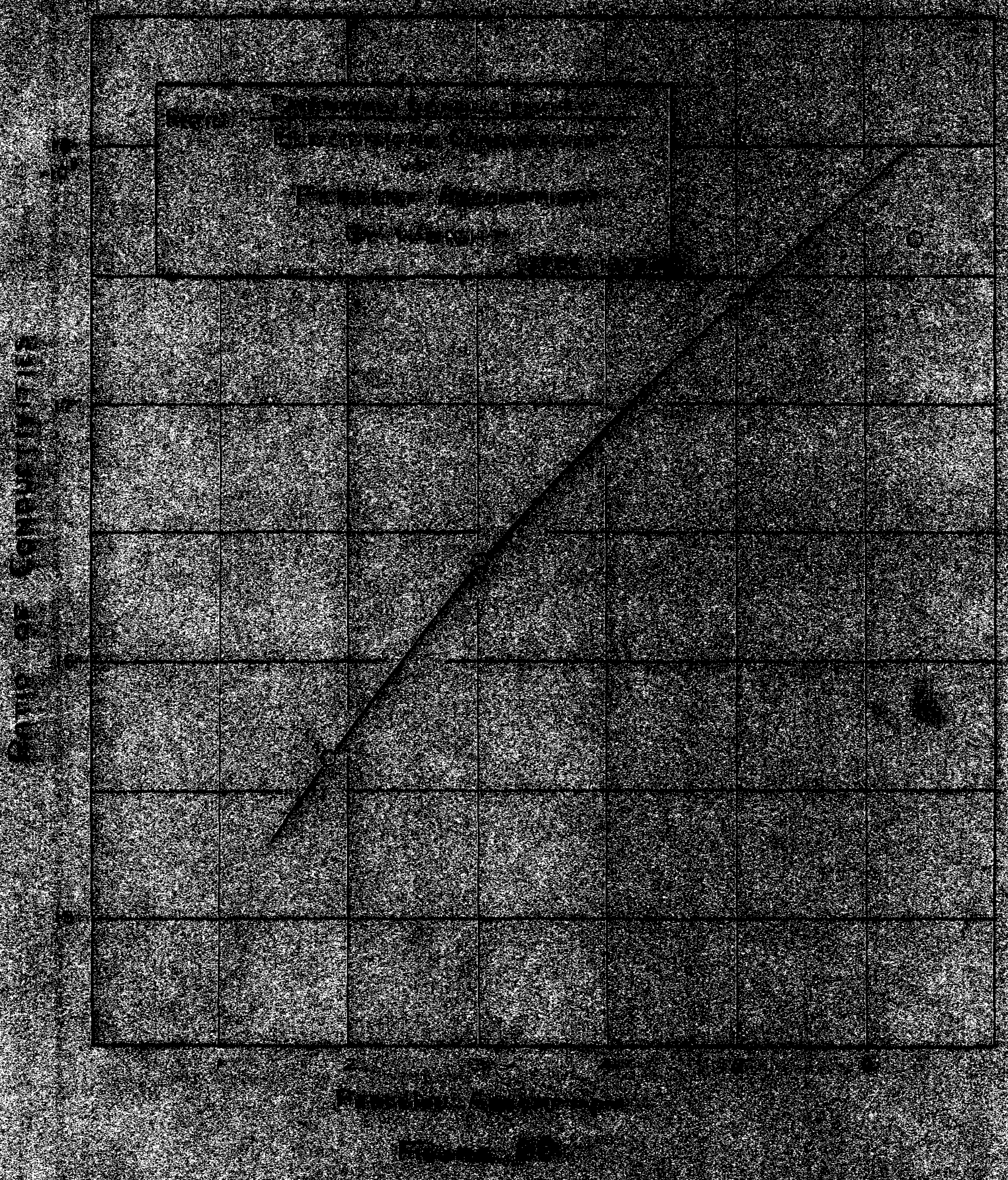
(Spec. 19 — 22)
(Taken from Tables VII and XI)

Test Specimen Number	Thermal Cond. (watts/cm./°C.)	Electrical Cond. (10^{-14} mhos/cm.^{3})	Ratio
19	0.00685	388	17.7 x 10^8
20	0.00763	488	15.7
21	0.00730	446	16.4
22	0.00698	402	17.4



Percent [illegible]

Figure [illegible]



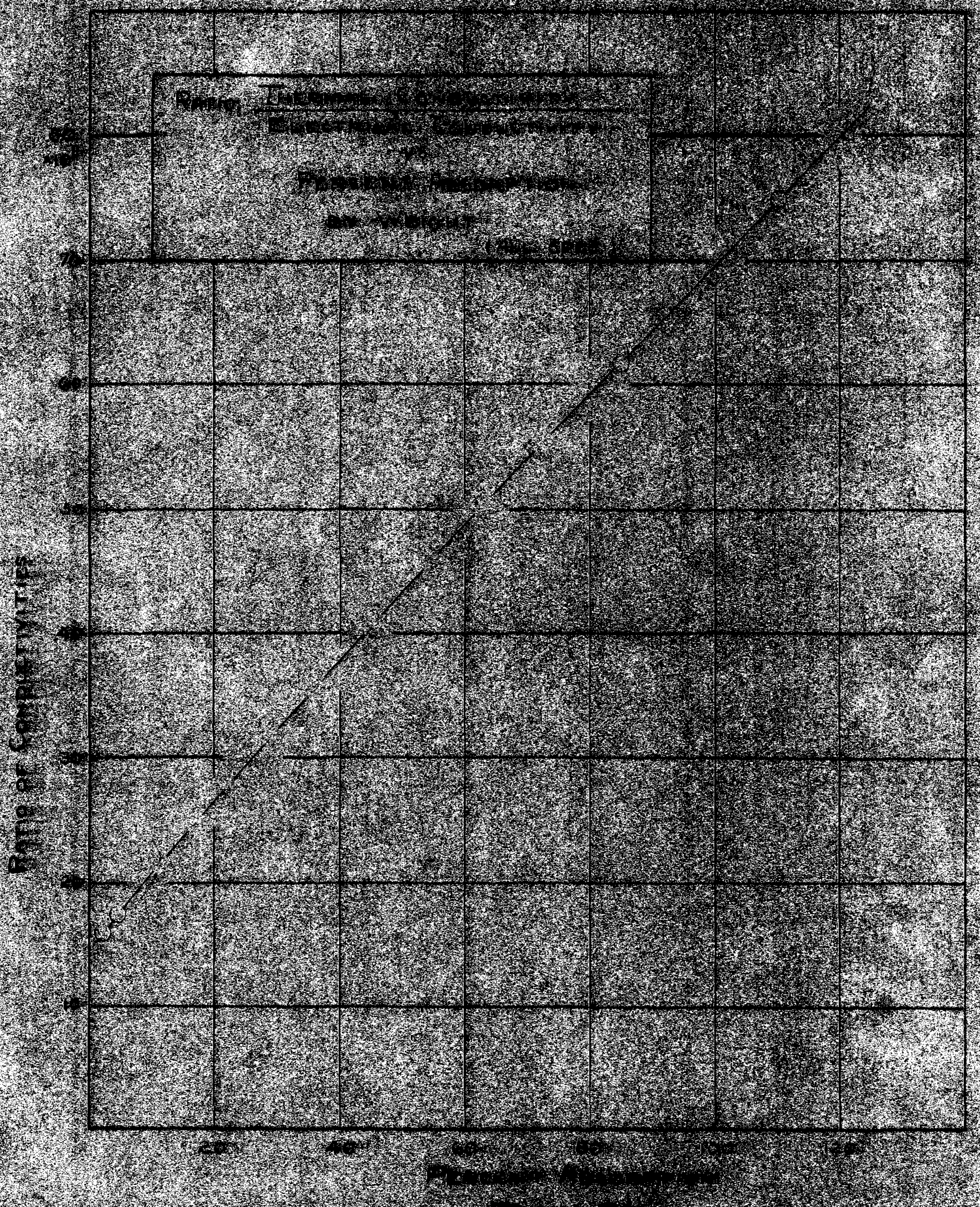

Ratio, Thermal Conductivity
Electrical Conductivity
vs
Percent Absorption
by Weight
(Fig. [illegible])
80
$\times 10^{-8}$
70
60
50
40
30
20
10
Ratio of Conductivities
20
40
60
80
100
120
Percent Absorption

Figure [illegible]

V. DISCUSSION OF RESULTS

A. Preliminary Results

The preliminary investigation involved rather little actual quantitative data.

The contact surface between the electrodes and the test sample was studied to determine the effect which the electrode pressure had upon the electrical conductivity. No measurable difference was noted in the conduction current observed with the electrodes firmly clamped and in that obtained with the electrodes just tight enough to hold the sample in place. The reason for this may be attributed to the fact that any lessening in the pressure merely tended to introduce an air film between certain sections of the solid and the electrode in places where the solid had previously made point contacts with the electrode. Since the air film thus introduced was such a small percentage of the total air thickness in the specimen it did not contribute in any way to the measurable resistance of the brick.

The use of such contact substances as carbon-black paste or metal foil merely eliminated, in general, this extremely small unnoticeable error. Hence the addition of an accurate pressure measuring device to the equipment or the use of contact substances was considered unnecessary.

In order to determine the effect of plate pressure upon the thermal conductivity it was necessary to calculate the actual conductivity of the specimen with varying pressures. The data and calculations for these conductivities of the specimen with tight and loose plates are given in Table I. It will be noted that the variation in the conductivities is less than 0.5 percent of the total conductivity and in the observed data corresponded to a change in the galvanometer deflection for one thermocouple of 0.5 millimeters. Since the image of the galvanometer hair line when reflected onto the calibtated scale at the distance used was nearly of this width, the error might readily have been one of observation.

However, an argument can be offered to show that the apparent thermal conductivity should increase, as indicated by the results, with decreased pressure.

With tight plates the thermocouples measured the temperatures at the edge of both sample and plate, which was, of course, the edge of the series circuit. With loose electrodes, on the other hand, an air film was introduced and the thermocouples no longer measured the temperature at the edge of the circuit or across the entire series circuit between the plates but at points within the circuit. The measured temperature difference was thus less than before. Since the thermal conductivity as calculated depended inversely upon the temperature difference the result was a very slight increase in the apparent conductivity with loose plates compared to that obtained with tight plates.

However, the smallness of this error was so slight that the effect of the air film or plate pressure upon the thermal conductivity was neglected. The only precaution taken in this respect was to obtain pressures sufficiently great to hold the specimen firmly in place.

An additional approximation was made in regard to the variation in mean temperature. Fig. 18 shows the variation of thermal conductivity of the standard cork with mean temperature. From values furnished by the Bureau of Standards a maximum variation of 7.3 degrees Centigrade in the mean temperature resulted in a variation of only 1.6 percent in the thermal conductivity. With the exception of two instances all the thermal measurement were made for mean temperatures which differed by no more than this amount. Hence, although the correction was made for the purpose of determining accurately the power required to produce the observed temperature difference across the cork, the equipment and the time necessary to make these conductivity-mean temperature tests and the smallness of the error introduced justified neglecting the variation of mean temperature.

B. Electrical Conductivity

The curves evident in Figs. 19 and 23 show graphically that the electrical conductivity is an inverse function of the porosity as was predicted in Section III.

The results are comparable on the basis of uniform conditions, temperature and humidity. No measurements were made at temperatures other than 47 degrees Centigrade ($\pm 1^{\circ}$C.) since the high-voltage equipment could not be well enough insulated if elaborate temperature control equipment were used. Inasmuch as a few drops of water on the test specimen varied its conductivity a considerable amount, no attempt was made to make measurements at other than zero humidity.

The effect of temperature variation on the conductivity as might be expected was discussed in Section II.

Certain qualitative tests were made on the more porous brick to determine the effect of moisture upon the conductivity. It was found that as little as one gram of water resulted in conductivities which were from thirty to forty times the conductivity of the dry brick. This merely served to emphasize the importance of perfect dryness in the specimen under test and the futility of attempting any quantitative correlation of conductivity with moisture content.

Fig. 20 shows the manner in which the apparent electrical conductivity of the brick numbers 1 to 18 varied with porosity after a one-minute application of the voltage. The difference between the one-minute values and the final values is pronounced, increasingly so as the porosity is decreased. This appears to be an argument against the practice referred to earlier of considering the electrical conductivity of the material as the value obtained after one minute of voltage application.

No data were obtained for the one-minute values of the electrical conductivity of brick numbers 19 to 22 because the current values at that time were so high that they could not be read with the galvanometer. The amount of time which elapsed before readings could be made, however, was such as to indicate that the differences were still more pronounced on the denser brick.

Figs. 21 and 24 indicate the variation of the current with time for a selected number of the brick. It was deemed unnecessary to illustrate the entire set of data graphically although the data appear in Tables V and VIII.

It will be noted that the values of current for the less porous brick are higher and require a longer time to decay to a constant steady-state condition than do the values for the brick of higher porosity.

The results verify the predictions made in Section III regarding the absorption current in porous materials. There is nothing to indicate whether or not the dielectric absorption currents obtained were the result of the rotation of polar molecules or of the motion of charges during the voltage gradient adjustment. The probability, however, is that the polar molecules were the main cause. Lewis (25, p. 30) found that there was only a very slight variation of current with time in his experiments on paving brick. Since the same type of voltage gradient adjustment was necessary in his specimens, it appears likely that the samples he used were either non-polar in nature and that the entire variation in current with time was due to the charge motion during the gradient adjustment, or that there was a slight assymmetry in the charge centers of the molecules and that the decay he observed was a combination of both polar and gradient effects. In either case, however, the decay resulting from the gradient adjustment must have been slight.

In the specimens used in this study the current-time variations were very pronounced. Certainly the voltage gradient adjustment phenomenon did not contribute much more to the current in one set of results than in the other, whereas the polar molecule absorption current might quite conceivably have been greater by virtue of the different materials involved.

Hence the magnitude of the absorption phenomenon as observed in this study appears to have been mainly influenced by the presence of polar molecules.

The predictions as based on the number of polar molecules present and the manner in which they were accelerated as they turned is substantiated by the higher currents observed for the denser samples and by the exponential shape of the current-time curves.

Figs. 22 and 25 give the graphical representation of the current-voltage relations for a selected few of the brick chosen at random to typify the entire porosity range. The data for these brick are shown in Tables VI and IX. The rapid increase of current with voltage bears out the assumption made that the major portion of the current flow through the dielectric was caused by the motion of ions and the further assumption that these ions were travelling with such a velocity as to produce other ions by collision.

It may be observed that for two brick having different porosities any change in current was approximately proportional to the variation in voltage. Thus the shape of the conductivity-porosity or conductivity-time curves is shown to be practically independent of the impressed voltage providing the voltage is sufficient to cause ionization by collision. The fact that the proportionality between currents for different voltages for two different specimens may still exist below the range for ionization by collision was not brought out in these experiments since the measuring equipment was not sufficiently sensitive to ascertain the low values of current flowing for the lower voltages.

No attempt was made to express mathematically the graphical relations obtained from the data. For the denser brick the points were so few and the porosity range so limited that the accuracy of such empirical expressions would have been questionable. For the higher porosity brick the porosity range was great enough and the points were sufficient in number but the flatness of the curve in that region would have made it possible to fit a number of mathematical curves to the experimental curves. Also the object of this study, both in the case of electrical and thermal conductivity, was not the determination of empirical expressions but the study of the approximate manner in which the variations occurred and to determine, as has been done, the causes of such variations.

C. Thermal Conductivity

As was explained the measurements of thermal conductivity were made for mean temperatures within a limited range and at zero humidity. The results are comparable, therefore, on those bases.

Figs. 26 and 27 show the manner of variation of the thermal conductivity with porosity for the two types of brick. The similarity to the curves for electrical conductivity is evident.

The shape of the curves is as was predicted earlier. Whether or not heat transfer by radiation actually occurred could not be determined from the results of the test. However, the flattening of the curve at the extreme end of the porosity range indicates the possibility that some such phenomenon was taking place to tend to increase the conductivity again.

D. Porosity

A mention was made earlier that the porosity measurement by the absorption method was only approximate. At that time the assumption was made that the percentage of the sealed pores in each brick was the same with respect to the total absolute porosity of that brick with the result that the water absorbed gave a sufficiently accurate relative indication of the porosity to be used in comparing the brick. The uniformity of the graphical results indicates that this assumption was justified.

E. Correlation of Electrical and Thermal Conductivity

Fig. 28 represents graphically the ratio of the thermal to the electrical conductivity for brick numbers 1 to 18 calculated in two different ways. The scattered points, indicated by open circles, were obtained from the actual data. The points indicated by the filled-in circles represent the ratio as obtained from points on the curves of thermal and electrical conductivity plotted against porosity.

Fig. 29 represents the ratio of the two conductivities for the second type of brick, numbers 19 to 22.

The two curves were transferred to the same axes in Fig. 30 which shows the variation of the entire lot of brick tested. The dashed portion of the curve indicates that although no data were taken for specimens in that range of porosities the end portions of the curve suggest strongly that the variation would be a curve slightly concave downward joining the two sets of data.

It is readily evident that the ratio increases with increasing porosity as was predicted in Section III.

If the electrical and thermal conductivities had been purely inverse functions of the first power of the porosity there would have been no variation in the ratio. However, the increase in the ratio with increasing porosity was the result of the steeper electrical conductivity-porosity curve caused by the voltage gradient adjustment or of both it and the flatter thermal conductivity-porosity curve obtained by virtue of the possible heat radiation in the pore spaces. The probability, as has been mentioned, is that the amount of radiation was so small for the temperatures used that its effect on the thermal conductivity may be neglected. Hence it may be assumed with reason that the amount of variation of the electrical conductivity from the hyperbolic relation with respect to the porosity had the greatest influence on the ratio.

The Wiedemann-Franz constant, as obtained by them and approximately verified by other investigators for metals, averages about 6×10^{-6}, measured in the same units as used in the present work. This constant relation for metals differs considerably from the ratio obtained in this study by virtue of the so-called non-metallic types of conduction, both electrical and thermal. These have been shown for porous materials to result in a relation which is not constant but, in the case of the materials used, varies in an approximately uniform manner with the porosity.

However, the great difference between the ratio of thermal to electrical conductivity as obtained in this study on porous ceramic materials and the Wiedemann-Franz constant for metals, evidently can not be entirely explained as above. Some other phenomenon must also contribute to the difference. A possible explanation follows.

It was mentioned that the conduction of heat through metals is due to the flow of electrons. If, on the other hand, the conduction of heat through non-metals be attributed to the vibration of ions and molecules, it is probable that the thermal conductivity is not reduced nearly so much as though the conduction were the result of the actual transfer of such particles. The electrical conductivity, however, is definitely known to be the result of charge transfer, whether in metals or non-metals. It appears reasonable to assume that the resistance of a material to the vibration of particles other than electrons is less than that to the actual transfer of particles. In that case the difference between the electrical conductivity in non-metals and that in metals would be expected to be much greater than the corresponding difference in the thermal conductivities. That some such explanation applies is evident from the relative changes in electrical and thermal conductivity which are observed in passing from metallic to non-metallic materials. On the basis of these assumptions the ratio for non-metals as compared to that for metals should be decidedly greater.

That this change in the type of thermal conduction does not affect the variation of thermal conductivity of porous non-metals with the porosity is evidenced by the relations obtained.

The prediction made in Section III that the ratio increased for materials of lower conductivity is definitely substantiated both by the relations obtained in this dtudy for materials of low conductivity and by a comparison of them with the Wiedemann-Franz constant which is for materials of high conductivity.

VI. CONCLUSIONS

A. Electrical Conductivity

1. The direct-current electrical conductivity of porous materials is an inverse function of some power greater than one of the porosity of the material.

2. That the shape of the curve relating electrical conductivity and porosity is independent of the impressed voltage is evident from the fact that the conductivities of any two different specimens are proportional for any values of voltage.

3. Although two phenomena contribute to the electrical conductivity of porous dielectrics the phenomenon of ionic conduction predominates as indicated by the shape of the current-voltage curves for the materials.

4. Porous non-metallic materials in general exhibit the phenomenon of absorption. For some materials the measured absorption current is entirely the result of the motion of the charges during the voltage gradient adjustment and depends upon the individual dielectric constants and specific conductivities of the component materials in the specimen. For other materials, such as those used in this study, an additional component of absorption current appears by virtue of the presence of polar molecules which move more or less rapidly into alignment with the electric field impressed upon the substance. This component current depends upon the electric moment of the polar molecules, the number of

polar molecules present, and the frictional resistance of the material to the rotation of these molecules.

5. Both the magnitude and time of decay of the absorption current are greater for the more dense materials indicating the presence of more polar molecules and a greater frictional restraint resulting in a longer time necessary for the complete rotation of the molecules.

6. In general the one-minute value of electrical conductivity often used commercially to define the conductivity of the material is not suitable to materials such as were used in the present work.

7. Constant conditions of temperature and humidity are necessary to exact determination of electrical conductivity.

8. Uniformity of electrode pressure is, in general, unimportant in its effect upon the electrical conductivity of porous materials.

B . Thermal Conductivity

1. The thermal conductivity of porous materials varies as an inverse function of the porosity of the material, though, in some cases, to a power less than the first.

2. The mean temperature has little effect upon the thermal conductivity.

3. Only a small amount of heat transfer by radiation occurs in the pore spaces. This radiation is greater with the larger pores which are generally present in more porous materials.

4. The plate pressure has little effect upon the resulting values of the thermal conductivity.

C. Correlation of Electrical and Thermal Conductivity

1. The ratio of thermal to electrical conductivity of porous materials such as the ones used as test specimens in this study increases approximately linearly with the porosity and is apparently almost wholly independent of the material in question.

2. This variation for porous non-metallic materials may be compared in contrast to the approximate constancy of the Wiedemann-Franz constant for metals. The difference occurs as the result of the non-metallic conduction, both electrical and thermal.

3. The non-metallic thermal conductivity for porous materials is defined in this case as the heat radiation in the larger pores which are present with the greater porosities.

4. The non-metallic electrical conductivity may be defined as that conductivity resulting from the ionic motion combined with the effect of the necessary voltage gradient adjustment for a uniform steady-state current. The effect of these upon the apparent electrical conductivity is a more decided decrease in conductivity with increasing porosity than is predicted by the free electron theory of conductivity.

5. The difference between the observed values of the ratio and the Wiedemann-Franz constant may be attributed to the fact that although heat may be actually conducted in metals it may be transferred by the vibration method in non-metals. The result is a probable higher value of thermal conductivity than would be obtained if heat were conducted in non-metals. On the other hand electricity is conducted through both types of material, metal and non-metal. The effect on the ratio is obvious.

VII. SUMMARY

This investigation deals with the determination of certain direct-current electrical properties and thermal properties of porous non-metallic materials and the correlation between the electrical and thermal conductivity of such materials.

Although considerable work has been done in the measurement of electrical and thermal properties of many materials, little has been done in connection with porous ceramic materials.

The correlation of electrical and thermal conductivity on the basis of a constant ratio has been attempted many times and has been found to be generally possible for pure metals and some alloys. However no definite explanation has been given for the lack of proportionality of these properties for non-metals.

It is the purpose of this study to determine and explain the manner of variation of certain of these properties and to determine and explain the relation existing between thermal and electrical conductivity.

A. Electrical Conductivity

The electrical conductivities of porous ceramic materials were measured and compared on the basis of porosity. The graphical representation of the variation resembled approximately an equilateral hyperbola.

The conductivity is made up of two components, electronic and ionic conductivity. The first of these is very small since few free electrons are present in non-metallic materials. The contribution of electronic flow to the total conduction current may be shown to vary as an inverse function of the first power of the porosity. The fact that the voltage gradient necessarily adjusts itself to produce uniform current flow through the material makes no difference in the electronic component of conductivity since such a voltage gradient change does not alter the electronic resistance of either material, the constancy of which is the basis for the derivation of the hyperbolic relationship.

Ionic conduction in this case involves the production of ions by collision. Since the current flow resulting from the motion of these ions is not proportional to the voltage, any change in the voltage gradient produces a corresponding change in the component resistances of the materials in the specimen. That the relation between ionic conductivity and porosity may be represented by a curve steeper than the hyperbolic function may be shown.

As the conductivity, by the theorem of superposition, is the direct sum of the ionic and electronic components of conductivity, the total conductivity may be shown to vary as an inverse function of the porosity raised to some power higher than one.

The shape of the current-voltage curves for the materials indicated that the ionic conductivity was predominate as assumed in the analysis. That the shape of the conductivity-porosity curve was independent of the applied voltage was evident from the fact that the currents for any two materials were approximately proportional at any voltage.

The materials tested exhibited a decided absorption current. It was assumed in the analysis that this was made up of two components, that due to the voltage gradient adjustment and that due to the rotation of the polar molecules. By reference to other tests it appears reasonable to suppose the majority of the dielectric absorption in this case to be the result of the motion of the polar molecules.

The current-time relations indicated that the current in the denser materials required a longer time for decay. The reasons for this were based on the presence of a greater number of polar molecules and the greater frictional resistance to the rotation of the molecules into alignment with the electric field.

By virtue of the absorption phenomenon the apparent conductivities obtained after one minute of voltage application are not, in general, suitable for use as the actual conductivities. However, if the material is to be used in a situation in which the voltage was varied or oscillated, the one-minute values of conductivity might be satisfactory and even advisable depending upon the period of such oscillation.

Throughout the tests it was necessary to maintain the material at a constant temperature and to keep it free of all moisture.

B. Thermal Conductivity

The thermal conductivities of the same materials were measured and compared on the basis of porosity. The curve again resembled an equilateral hyperbola.

The thermal conductivity as measured was made up of two components, the true conductivity and the contribution to the observed value by the radiation within the pores. The first of these is either the result of electron and ion transfer or vibration. In either case true conductivity may be shown to vary as an inverse function of the first power of the porosity.

The radiation phenomenon is more pronounced in specimens of higher porosity in which the pores are larger. The effect upon the measured conductivity is a slight increase over the relation existing between true conductivity and porosity. The graphical representation is thus a curve somewhat flatter than a hyperbola.

During the measurement the mean temperature was kept at approximately the same value. The requirement of constant temperature was not so rigid as in the electrical measurements since the thermal conductivity is essentially independent of mean temperature. The moisture content, however, was kept at a zero value by means of a drying agent.

C. Correlation of Electrical and Thermal Conductivity

Although the electrical and thermal conductivity of pure metals may be related by a constant ratio known as the Wiedemann-Franz constant or the Lorentz constant, such a simple relationship does not hold true for non-metals. The reason for this may be found in the so-called non-metallic conductivities present in non-metals.

The variation of electrical and thermal conductivity of porous materials has just been discussed. If it were not for the presence of radiation in the pores to affect the thermal conductivity and the change in component resistances with the voltage gradient adjustment to alter the electrical conductivity, the ratio as a function of porosity would be a constant for porous non-metals as well as for homogeneous metals. These two non-metallic effects, however, both assist in producing a ratio which increases with porosity. The fact that the relationship is approximately linear in this case can not be relied upon for materials other than those tested. No analytical proof can be given to indicate the reasons for a straight line relation.

Thus, though no constant relation or ratio necessarily exists for non-metals, there is a relationship which indicates that the magnitude of the ratio of the two conductivities of such materials is always the same and which depends upon the porosity of the material. It appears probable that the manner of variation of the ratio with physical properties other than porosity might similarly be predicted.

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XI. APPENDICES

Appendix A — Calibration of Equipment

1. Calibration of D'Arsonval galvanometer

The instrument used for making measurements of current flow through the brick specimen was a Leeds and Northrup wall-type D'Arsonval galvanometer. The sensitivity of the instrument was determined by the deflection method.

The circuit used is evident in Fig. 31. The resistance R represents one, two, or three wire-wound precision resistors of one million ohms each. The voltage was supplied by an ordinary dry-cell battery and controlled by means of the slide-wire potentiometer, Q.

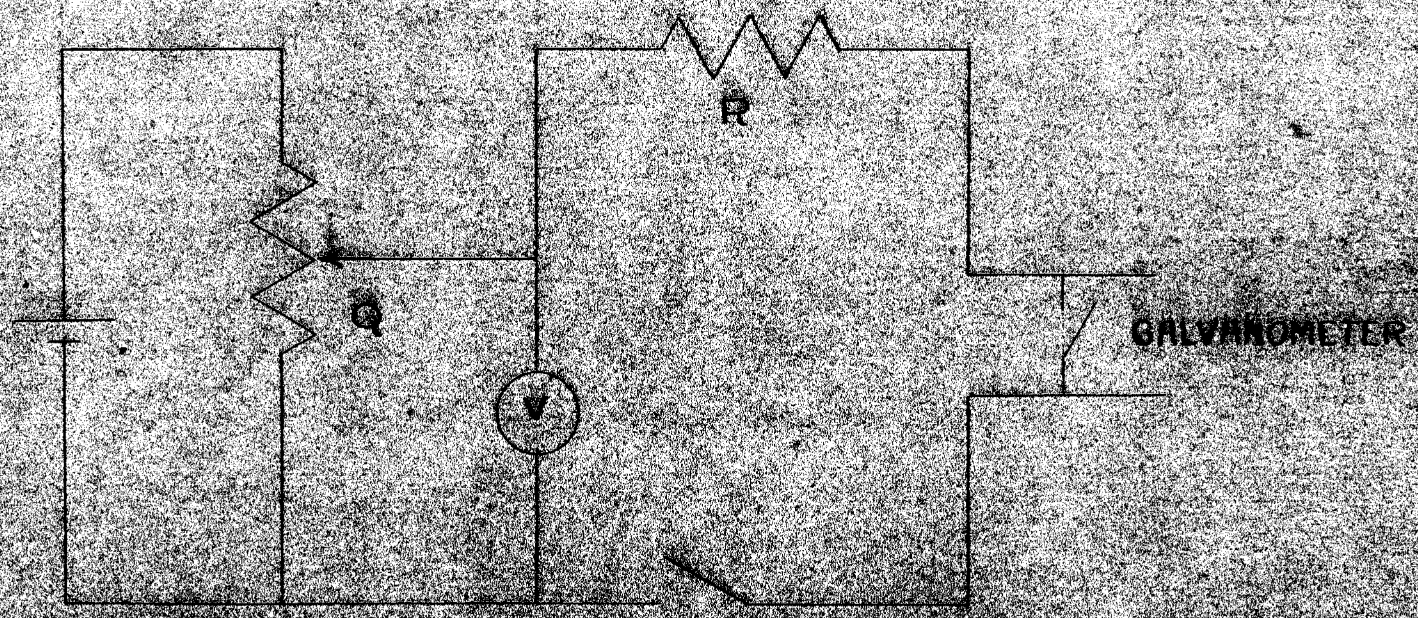
Using one of the precision resistors the relation between galvanometer deflection was observed by taking readings of deflection for different values of impressed voltage.

Further observations were made using two and three precision resistors, respectively.

The sensitivity was determined for each observation as the current per unit deflection. The equation giving this relation is

$$F = \frac{I}{d} \qquad \text{(Eq. 32)}$$

where F is the sensitivity in amperes per millimeter deflection, I is the current in amperes, and d is the deflection in millimeters.



CALIBRATION CIRCUIT FOR GALVANOMETER

FIGURE 31

The current was obtained from the data by using Ohm's Law which may be expressed in this case as

$$I = \frac{V}{R + R_g} = \frac{V}{R} \qquad \text{(Eq. 33)}$$

where I is the current in amperes, V is the voltage across the galvanometer in volts, R is the resistance of the precision resistors, and R_g is the resistance of the galvanometer. The latter was considered negligible as compared to R. Hence the equation used in calculation was reduced to the second part of Eq. 33.

Table XVI contains the observed and computed data.

The final value of sensitivity was determined as the average of the results obtained from the individual measurements.

TABLE XVI

GALVANOMETER CALIBRATION

Voltage	Galvanometer Deflection (mm.)	Sensitivity (10^{-9} amps./mm.)	
0.25	13.6	6.12	R = 3,000,000 ohms
0.50	26.7	6.25	
0.75	40.3	6.20	
1.01	54.0	6.23	
1.26	68.2	6.16	
0.10	8.0	6.25	R = 2,000,000 ohms
0.25	20.7	6.03	
0.40	32.3	6.20	
0.60	48.4	6.20	
0.80	64.6	6.21	
1.00	81.0	6.18	
1.21	97.8	6.19	
1.50	123.2	6.08	
0.05	8.1	6.17	R = 1,000,000 ohms
0.15	24.0	6.24	
0.25	40.6	6.15	
0.35	56.4	6.24	
0.45	72.6	6.20	
0.60	97.2	6.17	
0.75	123.1	6.10	

Average sensitivity = 6.179 x 10^{-9} amps./mm.

2. Calibration of thermocouples

Each of the six thermocouples was calibrated for a series of hot junction temperatures ranging from 15 to 90 degrees Centigrade and over a range of cold junction temperatures of from 10 to 25 degrees Centigrade.

The hot junction of each thermocouple was immersed in a tank of water. The cold junction was held at some constant known value of temperature in the range indicated above. The water in the hot junction tank was heated to about 90 degrees Centigrade and held at that temperature a sufficiently long time to allow the metal couples to come to the same temperature. The source of heat was then reduced and the water and thermocouples allowed to cool slowly. Galvanometer deflections and hot junction temperature readings were made simultaneously for each couple as the temperature was lowered. The hot junction temperatures were measured by means of a Taylor mercury thermometer. The cold junction temperature was checked at several intervals throughout the calibration run in order that any deviation from the desired constant value might be noted and the condition rectified immediately.

The data obtained during the calibration are shown in Table XVII. This table contains galvanometer deflections corresponding to the various hot junction temperatures as observed for each thermocouple. The data given are for three different constant values of cold junction temperature.

A plot of these points, deflection against hot junction temperature, indicated a straight line calibration curve over the entire range of temperatures used. Hence an equation of the form

$$T = A + Bx \qquad \text{(Eq. 34)}$$

was assumed where T is the temperature in degrees Centigrade, x is the galvanometer deflection in millimeters, and A and B are constants whose magnitudes depend upon the cold junction temperature at which the galvanometer readings were taken and the particular thermocouple in use.

The values of the constants for each case were determined by a method of minimum deviations. The galvanometer readings were assumed to be correct and all variations from the straight line were assumed to be the result of inaccurate temperature measurements.

The method consisted in dividing each set of the data into two approximately equal parts and solving for the values of A and B from the simultaneous equations

$$\sum_{n=1}^{n=n} v_n = nA + B \sum_{n=1}^{n=n} x_n - \sum_{n=1}^{n=n} T_n = 0 \qquad \text{(Eq. 35)}$$

$$\sum_{m=1}^{m=m} v_m = mA + B \sum_{m=1}^{m=m} x_m - \sum_{m=1}^{m=m} T_m = 0 \qquad \text{(Eq. 36)}$$

where the first equation represents the summation of the equations resulting when each pair of values of T and x from one portion of the divided data is substituted into the general equation (Eq. 34). The second equation involves a similar summation involving the other portion of the data. The subscripts, m and n, merely indicate the different parts of the data used and the number of pairs of values involved in that portion of the data. The difference between the observed temperature and the temperature as given by the general equation for any value of deflection is indicated by v. It is this variation whose sum for all points on the curve is made equal to zero.

Table XVIII contains the eighteen equations thus obtained for the six thermocouples at the three different cold junction temperatures.

It was found that the constants for the six couples for any given cold junction temperature were well within one percent of the average of these constants. Thus the eighteen equations were reduced to three, one for each cold junction temperature and applying generally to all six thermocouples. These three equations are indicated in Table XIX.

Although calibration curves relating temperature and deflection could be drawn for each of the three cold junction temperatures, this method was not used since it involved interpolation between curves in order to determine the temperatures for other values of cold junction temperature.

Fig. 17, previously referred to, was plotted showing the constants as functions of the cold junction temperature. From this curve the constants of the equation could be determined for any cold junction temperature existing at the time the galvanometer readings were made. The hot junction temperatures or the temperatures measured by the thermocouples were each obtained algebraically by substituting the galvanometer deflection and the constants read from the curve into the fundamental straight-line formula.

TABLE XVII

THERMOCOUPLE CALIBRATION

Cold Junction Temperature = 11.7°C.

Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)
Thermocouple #1		Thermocouple #2		Thermocouple #3	
93.3	182.5	92.5	181.0	91.7	179.5
85.2	165.0	84.7	163.5	84.2	162.0
76.7	144.0	76.4	143.5	75.9	142.0
67.2	123.0	67.0	122.5	66.7	122.0
57.7	101.5	57.7	101.0	57.5	100.5
52.8	88.5	52.5	88.0	52.2	88.0
43.3	67.5	43.3	67.5	43.3	67.5
38.9	58.0	38.9	57.5	38.9	58.0
35.6	50.0	35.6	50.0	35.6	50.0
31.7	41.0	31.7	41.0	31.4	41.0
27.2	31.5	27.2	31.5	27.2	31.5
22.2	20.0	22.2	19.5	22.2	20.0
19.1	12.5	19.1	12.5	19.0	13.0
15.6	5.0	15.6	5.0	15.6	5.0
Thermocouple #4		Thermocouple #5		Thermocouple #6	
90.9	178.0	90.0	175.5	89.1	173.5
83.0	160.0	82.8	158.5	82.2	157.0
75.0	141.0	75.0	140.0	73.3	137.0
66.4	121.0	66.1	120.5	65.5	119.0
57.2	99.5	56.9	99.0	56.7	98.5
52.2	87.5	52.2	87.5	51.9	87.0
43.3	67.0	43.3	67.0	43.0	66.5
38.9	57.5	38.9	57.5	38.6	57.0
35.6	49.5	35.3	49.0	35.3	49.0
31.4	40.5	31.4	40.5	31.4	40.5
27.2	31.5	27.2	31.5	27.2	31.5
22.2	19.5	22.2	19.5	22.2	19.5
19.0	12.5	19.0	12.5	19.0	12.5
15.6	4.5	15.6	4.5	15.6	5.0

TABLE XVII (continued)

Cold Junction Temperature = 19.7°C.

Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)
Thermocouple #1		Thermocouple #2		Thermocouple #3	
94.9	170.5	93.3	166.5	92.8	165.0
86.1	150.0	85.5	147.5	84.6	146.5
77.0	128.5	76.7	127.5	76.1	126.0
67.2	105.0	66.7	103.0	66.4	104.0
58.6	86.0	57.7	83.0	57.8	83.5
52.2	71.0	51.9	70.5	52.0	71.0
45.0	54.5	46.0	54.0	44.7	54.0
41.1	46.0	41.1	45.5	41.1	46.0
36.1	33.0	35.8	33.0	35.6	33.0
31.7	23.5	31.7	23.5	31.7	24.0
27.8	15.0	27.8	15.0	27.8	15.5
22.8	2.5	22.8	2.5	22.8	2.5
Thermocouple #4		Thermocouple #5		Thermocouple #6	
91.7	162.5	91.1	161.0	90.0	158.5
83.9	144.0	83.3	143.0	82.5	141.0
75.0	123.5	74.4	123.0	74.2	122.0
65.9	101.5	65.5	101.5	65.6	101.0
57.2	81.0	57.2	82.0	56.9	81.5
51.7	69.0	51.7	69.5	51.7	69.5
44.5	52.5	44.5	53.5	44.5	53.0
41.1	45.0	41.1	45.5	41.1	45.0
35.6	32.5	35.6	32.5	35.6	32.5
31.7	25.0	31.7	23.5	31.7	23.0
27.8	14.5	27.8	15.0	27.8	14.5
22.8	2.0	22.8	2.5	22.8	2.0

TABLE XVII (continued)

Cold Junction Temperature = 23.4°C.

Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)	Temp. (°C.)	Galv. Defl. (mm.)
Thermocouple #1		Thermocouple #2		Thermocouple #3	
91.7	154.0	91.1	157.0	92.0	155.0
83.9	135.5	83.3	133.5	82.6	133.0
77.8	120.5	77.2	119.0	76.8	118.0
71.1	106.0	71.1	105.5	71.2	105.0
65.5	93.0	65.5	91.5	65.0	92.0
56.1	71.0	55.8	70.0	55.6	70.0
51.9	60.0	51.7	59.5	51.7	59.5
46.6	47.5	46.6	47.0	46.5	47.5
42.8	39.5	42.2	39.0	42.3	39.0
38.6	31.0	38.3	30.5	38.4	30.5
35.3	23.5	35.3	23.0	35.3	23.0
32.5	17.0	32.5	17.0	32.6	17.0
29.4	9.0	29.4	9.0	29.5	9.0
26.7	2.0	26.7	1.5	26.7	2.0
Thermocouple #4		Thermocouple #5		Thermocouple #6	
92.2	160.0	92.8	157.0	93.0	158.0
82.3	131.0	81.7	130.0	81.1	128.0
76.1	116.5	75.5	116.5	75.0	114.5
70.6	103.0	70.0	103.0	69.7	102.5
64.7	90.5	64.4	89.5	63.9	88.5
55.6	68.0	55.6	68.5	55.0	68.0
51.4	57.0	51.1	57.0	51.1	57.0
46.1	45.5	46.1	46.5	45.5	46.0
42.0	38.0	42.0	38.0	42.0	38.0
38.4	29.5	38.4	30.0	38.4	30.0
35.3	22.0	35.3	22.5	35.6	22.5
32.6	16.5	32.6	16.5	32.6	16.5
29.2	8.5	29.2	8.5	29.2	8.5
26.7	1.0	26.7	1.5	26.7	1.5

TABLE XVIII

THERMOCOUPLE EQUATIONS WITH CONSTANTS

Thermocouple Number	Equation	
1	$T = 13.53 + 0.4375x$	
2	$T = 13.59 + 0.4370x$	
3	$T = 13.51 + 0.4375x$	Cold Junction Temp. = 11.7°C.
4	$T = 13.71 + 0.4360x$	
5	$T = 13.71 + 0.4370x$	
6	$T = 13.64 + 0.4370x$	
1	$T = 21.50 + 0.4320x$	
2	$T = 21.42 + 0.4340x$	
3	$T = 21.38 + 0.4330x$	Cold Junction Temp. = 19.7°C.
4	$T = 21.55 + 0.4345x$	
5	$T = 21.50 + 0.4330x$	
6	$T = 21.58 + 0.4325x$	
1	$T = 25.50 + 0.4315x$	
2	$T = 25.60 + 0.4300x$	
3	$T = 25.50 + 0.4320x$	Cold Junction Temp. = 23.4°C.
4	$T = 25.80 + 0.4300x$	
5	$T = 25.70 + 0.4320x$	
6	$T = 25.65 + 0.4320x$	

TABLE XIX

THERMOCOUPLE EQUATIONS WITH CONSTANTS AVERAGED

Cold Junction Temperature = 11.7°C.

$$T = 13.62 + 0.4370x$$

Cold Junction Temperature = 19.7°C.

$$T = 21.49 + 0.4332x$$

Cold Junction Temperature = 23.4°C.

$$T = 25.63 + 0.4313x$$

3. Calibration of thermal conductivity testing cabinet

Before conducting any test on the thermal conductivity of the test specimens, the equipment was adjusted as has been mentioned in the section on methods of procedure.

Two specimens of dried standard cork board were placed in the apparatus and the thermal conductivity of one calculated as though it were unknown. A calculated value which was incorrect indicated that the guard ring temperature was not adjusted correctly and a lateral flow of heat was resulting. Since the thermocouples were the only means of determining the values of input for which the temperatures of the center element and guard ring were equal the fault evidently lay in the placing of the guard ring thermocouples. By making several trials in the adjustment of the couples a position was found which, when the guard ring and center element heaters were adjusted to equal temperatures, gave a calculated value of the thermal conductivity differing by less than one percent from the known value. Table XX contains the observed and calculated data for two positions of the guard ring thermocouples, the first in which the couples were well out of adjustment and the second in which the adjustment was accurate to within one percent.

One percent was chosen as the limitation on adjustment of the equipment on the basis of the accuracy of the galvanometer readings. The readings were estimated to one-half millimeter. An error of this magnitude in one couple was found to produce an error in the calculated conductivity of about four-tenths percent. The error in the reading, however, will not exceed one-fourth of a millimeter due to the fact that the mid-point between the divisions could be determined quite easily. Hence, six couples, each in error by two-tenths percent would not produce a total error much greater than one percent, even if the individual errors in no case compensated.

TABLE XX

CALIBRATION OF THERMAL CONDUCTIVITY TESTING CABINET

Test Specimen Number (Standard)

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.25	25.5	Temp.= 15.6°C.
Current (I', amps.)	0.220	0.783	A = 17.5
Corrected Current (I, amps.)	0.175		B = 0.435
Input (W, watts)	1.444		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	21.0	128.5	128.5	128.5	128.0	19.5
Temp. (°C.)	26.6	73.4	73.4	73.4	73.1	26.0
Mean Temp. (°C.)	50.0				49.6	
Temp. Difference (Θ, °C.)	46.8				47.1	
Watts Input (W.)	0.936				0.508	
Thermal Conductivity (K, Watts/cm./°C.)	0.000461				0.000249	

Test Specimen Number (Standard)

	Power Input		Cold Junction
	Center Element	Guard Ring	
Voltage (V, volts)	8.27	21.7	Temp.= 15.6°C.
Current (I', amps.)	0.218	0.66	A = 17.5
Corrected Current (I, amps.)	0.173		B = 0.435
Input (W, watts)	1.430		

	Standard		Guard Ring		Test Spec.	
Thermocouple Number	1	2	3	4	5	6
Galv. Defl. (mm.)	22.5	105.0	105.0	105.0	106.0	21.5
Temp. (°C.)	27.3	63.2	63.2	63.2	63.6	26.8
Mean Temp. (°C.)	45.2				45.2	
Temp. Difference (Θ, °C.)	35.9				36.8	
Watts Input (W.)	0.709				0.721	
Thermal Conductivity (K, Watts/cm./°C.)	0.000456				0.000453	

Appendix B — Sample Calculations

This section contains a representative set of the calculations made in arriving at the results presented in this paper. Inasmuch as some of the calculations, particularly those of thermal conductivity, were somewhat involved, the presentation of a complete set of typical calculations was deemed advisable.

1. Preliminary calculations

a. Calculation of the galvanometer sensitivity. The galvanometer was calibrated as explained in Appendix A and the sensitivity or galvanometer constant obtained from Eq. 32 and Eq. 33. The calculations given below are for a value of R equal to one million ohms and a voltage of six-tenths of a volt.

$$F = \frac{V}{Rd} = \frac{0.60}{10^6 \times 97.2} = 6.17 \times 10^{-9} \text{ amperes /mm.} \qquad \text{(Eq. 37)}$$

The constant used in this study was taken as the average of twenty observations and found to be 6.179×10^{-9} amperes per millimeter deflection.

b. Calculation of thermocouple constants. Since the thermocouple readings were substituted into a linear algebraic equation and the temperature thus determined, it was necessary to find the constants for these equations. The calculations given below are those which were followed in obtaining the constants for the general equation (Eq. 34) for thermocouple number 1 and for a cold junction temperature of 11.7°C.

The data are shown in Table XVII. The data were divided into two equal parts and each pair of values substituted into the thermocouple equation. By adding the equations obtained from the first half of the data an equation involving the constants as unknowns was obtained. A similar equation was obtained from the sum of the equations for the last half of the data. The summation equations have been given symbolically in Eq. 35 and Eq. 36. The numerical substitutions result in the following two equations:

$$7A + 872.0B - 476.2 = 0 \qquad \text{(Eq. 38)}$$

$$7A + 218.0B - 190.3 = 0 \qquad \text{(Eq. 39)}$$

The values of A and B obtained from the solution of this pair of simultaneous equations are

$$A = 13.53 \quad \text{and} \quad B = 0.4375$$

The thermocouple equation for this particular couple and for the cold junction temperature used may be written

$$T = 13.53 + 0.4375x \qquad \text{(Eq. 40)}$$

Similar equations were obtained for the other five thermocouples and for the other cold junction temperatures used in calibration. The algebraic equation used for all the couples for a given cold junction temperature was obtained by averaging the constants of the six equations for that cold junction temperature.

c. Calculations for the calibration of the thermal conductivity testing cabinet. The calculations for this case were essentially the same as those used in the actual calculation of thermal conductivity. Hence no sample calculations are included at this point.

d. Calculation of porosity. The porosity of each specimen was calculated as the percent absorption by weight. The data for the following calculations of the porosity of brick number 1 were obtained from Table XII. The dry weight of the brick was 963 grams. The wet weight was 2138 grams. The weight of water absorbed was obtained by direct subtraction of these two values and found to be 1175 grams. The percent porosity was then obtained from the equation

$$P = \frac{\text{weight of water absorbed}}{\text{Dry weight}} 100 \qquad \text{(Eq. 41)}$$

or

$$P = \frac{1175}{963} 100 = 122\%$$

2. Calculation of electrical conductivity

The electrical conductivity was calculated by the use of Eq. 23 and Eq. 24. The calculations given here are for the final conductivity of specimen number 1 at 25,000 volts. The data are given in Table III.

$$I = Fd$$

$$= 6.179 \times 10^{-9} \times 1.1 = 6.79 \times 10^{-9} \text{ amperes} \qquad \text{(Eq. 42)}$$

$$C = \frac{LI}{AV} = \frac{6.35 \times 6.79 \times 10^{-9}}{9.62 \times 25{,}000}$$

$$= 17.92 \times 10^{-14} \text{mhos/cm.}^{3} \qquad \text{(Eq. 43)}$$

3. Calculation of thermal conductivity

The calculations given here are for the same specimen as the one used above. The data are presented in Table X. The measured values of current and voltage for the center heating element of the hot plate were 0.2155 amperes and 8.0 volts, respectively. The correction for the current flowing through the voltmeter was made as follows:

The current through the voltmeter was equal to the measured voltage divided by the voltmeter resistance. The resistance for the meter used was 184 ohms. This gave a voltmeter current of 0.0435 amperes.

The current flowing through heating coil was calculated as the difference between the measured current and the voltmeter current.

$$I = I' - I_v = 0.1720 \text{ amperes} \qquad \text{(Eq. 44)}$$

The power input to the coil was then calculated as the product of this last current and the measured voltage.

$$W = IV = 0.1720 \times 8.0 = 1.375 \text{watts} \qquad \text{(Eq. 45)}$$

The temperature of the cold junction was read as 22°C. From Fig. 17 the constants A and B were found to be $A = 23.9$ and $B = 0.432$. The temperature was calculated from the equation

$$T = 23.9 + 0.432x \qquad \text{(Eq. 46)}$$

For the first couple the deflection was 14.5 millimeters from which the temperature was found to be $T = 30.2^\circ C$. The temperatures measured by the other thermocouples were similarly computed using the same values of A and B.

The temperature differences between the hot and cold plates for the standard and the test brick were obtained merely as the algebraic differences of the two temperatures on the two faces of the cork board and the brick, respectively. The calculations need not be illustrated.

The mean temperatures were obtained as the arithmetic average of the hot and cold plate temperatures referred to in the above paragraph. Since the thermal conductivity of the standard cork was known to vary in a definite manner with the mean temperature, that value of conductivity corresponding to the observed mean temperature was used. It was found, by referring to Fig. 18, to be 0.000461 watts per centimeter per degree Centigrade.

The equation for thermal conductivity was rewritten to read

$$W_c = K_c \theta_c \frac{A_c}{d_c} \qquad \text{(Eq. 47)}$$

from which the power used in maintaining the observed temperature gradient across the standard was calculated.

$$W_c = 0.000461 \times 39.5 \frac{66.1}{1.525}$$

$$= 0.789 \text{ watts}$$

The remaining power input was that power required to raise the temperature of the hot face of the test specimen to the observed value. It was obtained by subtracting the value of W_c just found from the total power input, $W = 1.375$ watts, which gave a value of W_b equal to 0.586 watts.

The thermal conductivity of the brick was then found by making use of Eq. 29.

$$K_b = \frac{W_b d_b}{\theta_b A_b}$$

$$= \frac{0.586 \times 6.35}{42.3 \times 66.1}$$

$$= 0.001331 \text{ watts/cm./}^{\circ}\text{C.}$$

All other values of thermal conductivity, including those associated with the calibration of the testing cabinet, were calculated in a similar manner.

4. Calculation of the ratio of thermal to electrical conductivity

The ratio of the thermal conductivity to the electrical conductivity was calculated in two ways, from the data as observed and from points taken off the respective conductivity curves. Mathematically, of course, the calculations were the same. For the same specimen used in the two preceding sub-sections to illustrate the manner of conductivity calculation, the ratio from the data gave the value of 74.2×10^8. Since the numerical value was all that was desired, no units were attached to the ratio.