DESIGN, CONSTRUCTION AND USE OF A GUARDED HOT PLATE FOR THE MEASUREMENT OF THE THERMAL CONDUCTIVITY OF INSULATING MATERIALS

by

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ABSTRACT

In the work that follows factors affecting the thermal conductivity in solids, in particular insulating materials, are described. The theory of the square guarded hot plate is presented, and a particular design of a square guarded hot plate and its construction are explained in detail.

The designed apparatus was used to test the thermal conductivity of a kind of glass wool (Izocam), styrofoam, and corkboard.

The tests conducted indicate that the thermal conductivity of Izocam increases quite significantly with temperature and the value of the manufacturer is not correct for all of the given application range. Normal amount of moisture has negligible effect on the thermal conductivity value of Izocam, but the effect of density is significant and the thermal conductivity reduces sharply with density in the range of the tests conducted.

The results of tests on styrofoam and corkboard show that at low mean temperatures (around 60 °F) styrofoam is a better insulator.

TABLE OF CONTENTS

I. INTRODUCTION

Heat is conducted through a material according to Fourier's equation, which is

$$q_x = -k \frac{\partial T}{\partial x}$$

where q_x is heat conducted per unit area per unit time in the x direction, k is the thermal conductivity and $\frac{\partial T}{\partial x}$ is the temperature gradient in the x direction.

In nature there exist materials for which the value of thermal conductivity, k, ranges from about 2700 Btu-in/hr-ft^2-°F for a material such as copper, to as low as .18 Btu-in/hr-ft^2-°F for carbon black. Also different materials show different variations in the value of k under various conditions. For example at temperatures above 200 °R, k value for aluminum is almost constant whereas for common insulators k value generally increases rather sharply with temperature. The reasons for these differences can be understood by a study of micro and macro structure of the materials. The understanding of the underlying reasons provides valuable insight for evaluating the k value of any material.

In the remaining part of this section various factors influencing k are briefly summarized. Discussion is then extended to cover the k values of insulating materials, the understanding of which are essential for this thesis. Finally, the theory of the guarded hot plate is given, which provides the theoretical background for the apparatus used.

A. The Mechanism of Heat Conduction and Thermal Conductivity in Solids

Conduction in solids occur in two basic modes, electron conduction, in which heat is carried by free electrons, and lattice conduction, in which heat is carried by the transmission of vibrations of the particles of the material. Electron conduction is much more effective than lattice conduction, therefore most metals in which free electrons are abundant are generally more conductive than non metals in which conduction is mainly by lattice vibrations. However, this is too broad a generalization and factors such as the interaction of lattice and electron conduction, purity, homogeneity and the nature of the crystal structure must be evaluated to obtain a better idea about the value of the k Generally speaking the more uniform, the purer and the more homogeneous a substance, the higher its thermal conductivity. Also, the less complex the molecular and the crystal structure the higher will be the lattice conduction, which corresponds to high k value in non metals.

The nature of bonding of a substance is a very good indication to its k value. In metals atoms are a mass of specks in an electron cloud. Free electrons are good carriers of energy and they are also very efficient carriers of heat. Not all the metals are good conductors, however. The degree of the mobility of the electrons are responsible for this fact. If there are plenty of energy levels available for the valence electrons, according to the free electron theory of metals, they can absorb great amounts of heat easily by changing their energy levels. If however their motions are restricted because there are scanty energy levels attainable their effectiveness is reduced. For example for copper there are twice as many energy levels as there are free electrons, and

$k = 2700$ Btu-in/hr-ft^2-°F. For aluminum, with 3n valence electrons, 4n energy levels, $k = 1440$ Btu-in/hr-ft^2-°F. But for iron, with 2n free electrons and 2n energy levels, $k = 648$ Btu-in/hr-ft^2-°F. In these metals lattice conduction may become an important part.

All other bonding types are less effective because there is an absence of free electrons and bonding contributes to lattice conduction only. With ionic bonding the positive ions surround themselves with negative ions and vice versa. This distributes the attractive forces in all directions which makes bonding very weak. This weak bond is very inefficient in transmitting vibrations. For example, NaCl has $k = 48$ Btu-in/hr-ft^2-°F. In ceramic materials, which are composed of metallic and non-metallic compounds with mostly ionic bonding we have likewise very low k , which makes ceramics suitable for insulation. With covalent bonding, which is very strong, we still get a low value for k, because bonding exists only in the molecules themselves and molecules are very weakly attracted to each other (by v. d. Waals forces). Since vibration transmitters are molecules, not the atoms in this case, we have a very low k value. This is why organic compounds are good insulators.(Silk has $k = .24$ Btu-in/hr-ft^2-°F, cotton $k = .48$ Btu-in/hr-ft^2-°F.)

In lattice conduction the arrangement of atoms also have an important effect on the value of k . If the crystal structure is simple, vibration transmission is easier. If the material has an amorphous structure instead of regular patterns of crystals, vibrations are more inhibited. For example glasses which have a continuous network of bonds have lower k values than crystals of the same composition.At 32°F quartz glass has $k = 13.2$ Btu-in/hr-ft^2-°F, quartz crystal has $k = 72$ and 132

Btu-in/hr-ft^2-°F. When we have a molecular composition rather than a monatomic solid, k value reduces sharply. The reason is that some of the heat conducted is spent in internal vibrations of molecules, which do not contribute to k . Whereas in a monatomic (non-metal) solid all the heat being transmitted is used for the atomic vibration and takes part in conduction.

Impurities and irregularities in a material produce additional resistance to heat flow. In metals the effect of impurities is very large. For example, only 2.5 % Zn in Cu causes the k value to drop by about 10 %. Alloys usually have their k values lower than both parent metals. With lattice conduction irregularities are the more important. Dislocations, vacancies, and interstitialties disrupt the normal transmission of vibrations. For this reason heat treated steel has a much higher k value than cold worked steel. Heat treatment also enlarges the grains of a metal, the boundaries of which are resistive to heat flow. We can cite an Al-Cu alloy as an example: 7% Cu, 93 % Al alloy has when cast, non-treated, k = 1002 Btu-in/hr-ft^2-°F, when annealed at 450 °C k = 1164 Btu-in/hr-ft^2-°F.

The atomic picture explaining the variation of k with temperature is rather complicated and beyond the scope of this introduction.* Only the basic trends of k for various materials as a function of temperature will be given here.

Metals and non-metals have a very high peak at low temperatures and for normal and high temperatures they are practically constant,

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* For an extensive treatment see Ref. 1.

increasing or decreasing linearly at a small rate (Fig. 1).

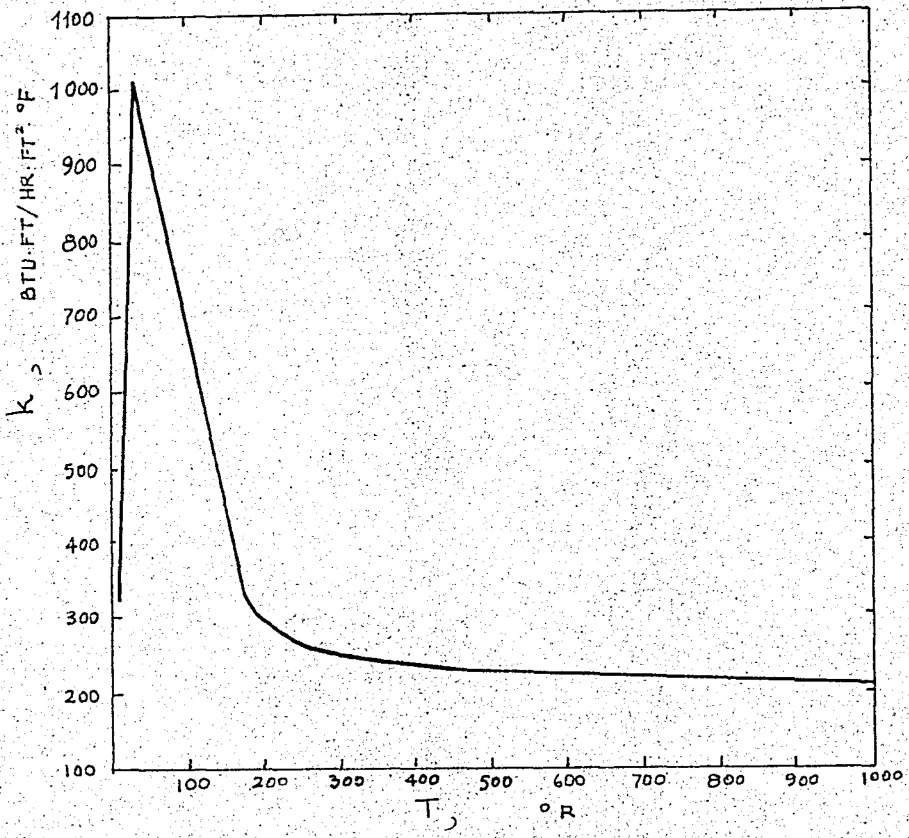

Fig. 1. Thermal conductivity vs. temperature for copper.$^{(2)*}$

Impurities present pull this curve down, the shape being essentially the same.

Crystalline materials start high and they have decreasing k with temperature (Fig. 2).

Glassy substances, however, have the opposite trend (Fig. 3).

If a material contains its components in both crystalline and amorphous phases k vs. temperature curve may undergo a maximum (e.g. SiC brick). This is due to the fact that at low temperatures the thermal

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* Parenthetical references superior to the line refer to bibliography.

resistivity of glass is important, whereas, at high temperatures resistivity of crystal becomes dominant. The place of the maximum is determined by the percentage of each phase.

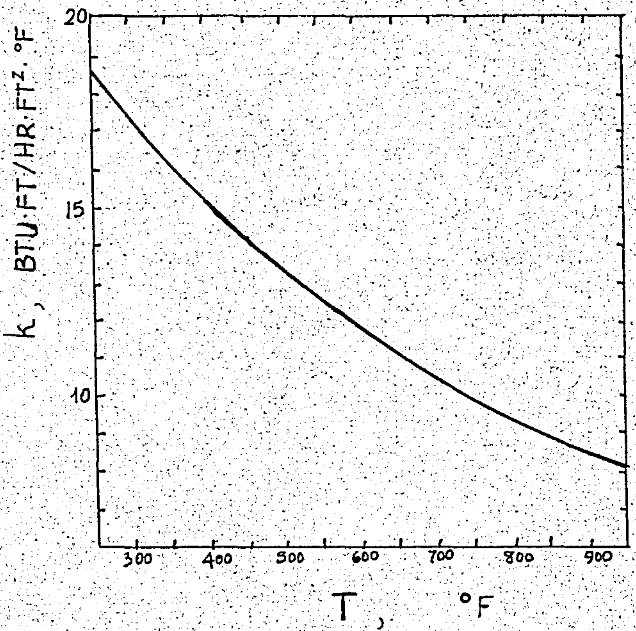

Fig.2. Thermal conductivity vs. temperature for polycrystalline, maximum density MgO.(3)

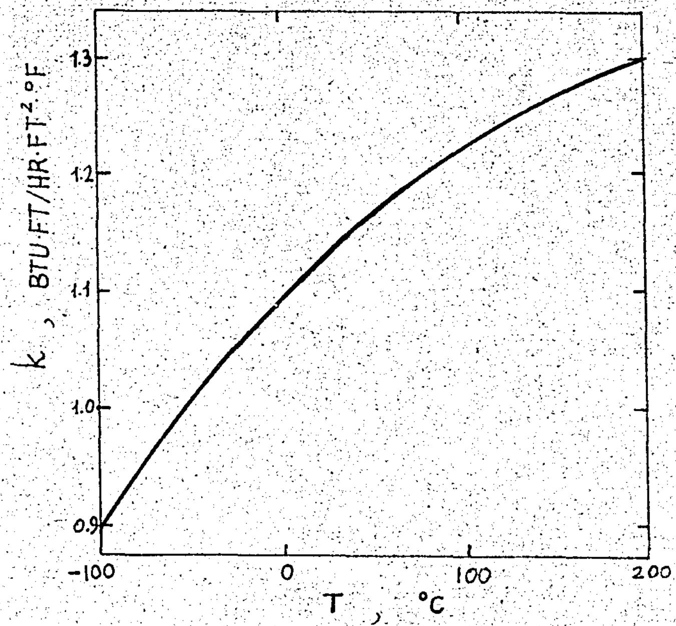

Fig.3. Thermal conductivity vs. temperature of quartz glass(4).

B. Thermal Conductivity of Insulating Materials

Today there are so many insulating materials in use that it would be impossible to study all of them in this work. Below a classification is attempted only according to their macroscopic structure which is in turn coupled to the mechanism of heat transmission. Also, since we are dealing with conduction in this work reflective insulation has been omitted.

From the preceding section, it can be seen that the more complicated the inner structure the lower is the k. This provides a first rule for insulators. With few exceptions they all have impurities, breaches in crystal structure, several different textures such as fibers, grains, etc. A second rule for insulators is the frequent inclusion of air in the texture of the material. At 32°F air has $k = .17$ Btu-in/hr-ft^2-°F; thus if properly used air can be very effective. Third general fact about insulators is that any complicated texture material can be an insulator, examples being ceramics, glasses, organic materials and rocks.

Now we will look at the basic types.

1. Porous Insulators and Fine Powders

These are materials that have air filled pores in their structure. Examples are woods, cork, porous bricks, and powdered charcoal.

Two definitions are useful in talking about these insulators. These are apparent density, ρ_a, which is equal to weight of the body divided by the volume of the body; and porosity, p, which is

$$p = 1 - \frac{\rho_a}{\rho_s}$$

where ρ_s is the density of the contingent material.

The existence of air in pores in the texture changes the picture of heat transmission somewhat. Around the pores in the contingent material heat transmission is by conduction only. But across the pores they are by conduction, convection (if the pores are big enough) and radiation. These facts plus the existence of air filled pores make k dependent on many more factors than simply temperature and density.

It is clear that the value of k depends on porosity (Fig.4).

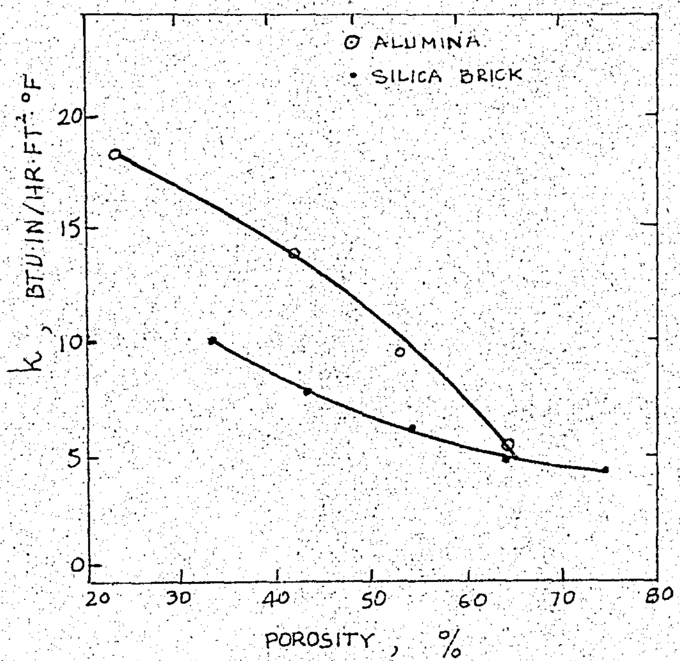

Fig. 4. Thermal conductivity vs. porosity for alumina at 1600°F and Silica Brick at 1400°F, two examples of refractories(5).

If the pores are big and connected, convection currents may arise in the insulator.

Nearly all porous insulators can absorb great amounts of moisture, and thus seriously increase the value of k (Fig. 5).

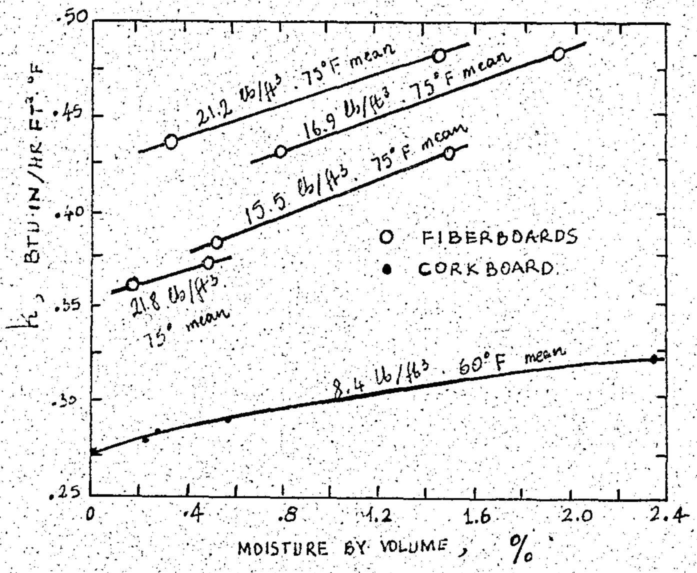

Fig. 5. Thermal conductivity vs. percentage of moisture by volume. Fiberboards.(5)

We have mentioned that across the pores some heat is transmitted by radiation. Then k also depends on the emissivity of the pore surface. This effect of radiation increases as the temperature is increased. It has been observed that kapoc and asbestos dusted with aluminum powder gave 15.5 and 18.0 per cent reduction in k value, respectively.(5)

Some insulators on the other hand are almost completely transparent to radiation, e.g. silica aerogel. Therefore in measuring k, high emissivity plates must be used. Since air in the pores are conductive, we should expect air pressure to alter the value of k and therefore k of the insulator to change. However, conduction in gases occurs by the transmission of the collisions of the particles of the gas and when pressure is increased the mean free path of the gas becomes smaller but since atoms also increase in number by the same factor k does not change. There is one exception to this rule, and that is that if the dimensions of the pores become less than the mean free path of the gas

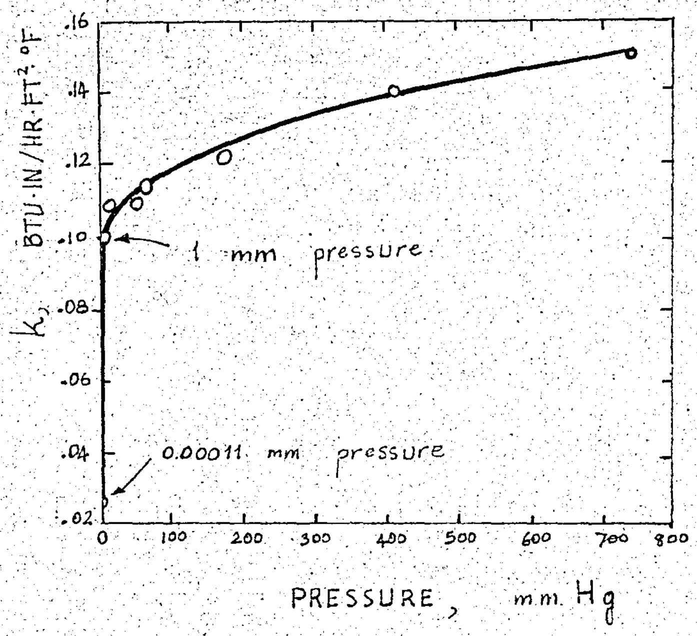

Fig. 6. Thermal conductivity vs. pressure. Silica aerogel.

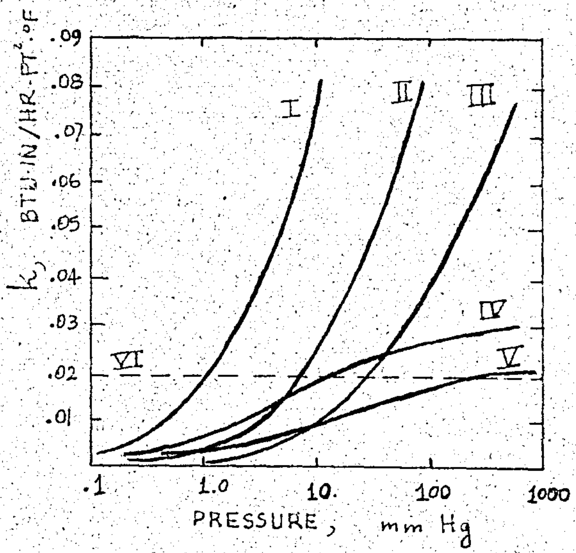

Fig. 7 Apparent thermal conductivity of powders.(4)

I.	Quartz sand, grains .26 mm	granular powders
II.	Zinc dust, grains .028 mm	
III.	Zinc dust, grains .0062 mm	
IV.	Diatomaceous earth	spongy powders
V.	Lamp soot	
VI.	Air	

molecules at that pressure and temperature, then k of air is directly proportional to pressure and becomes zero at zero pressure. In a material which has fine pores such as silica aerogel the pores can be made smaller than the mean free path of air at ordinary temperature and pressure. Thus porous insulators with k values less than that of air has been possible to obtain. Fine powders are another example of this type (Fig. 7).

With porous insulators pore size affects the k vs. temperature curve. Since there is more radiation across the pores if the pores are big the k vs. temperature curve will be more steep.

2. Loose Fill Insulators

These are materials made by filling some space loosely by some low k substance. The main function of this substance is not the retardation of the heat flow as such, but rather to hold air in between and prevent convection currents. Examples of these type of materials are mineral wools, glass wool, cotton and the like and granular insulators.

With these materials also, heat transfer is by conduction through the air and the filling, by radiation through the air, and by convection if conditions are favorable.

Since the air in these materials has easy passage in and out as well as through the texture itself, convection currents may easily set up and increase the value of k. The degree of convection depends on the thickness and the height of the specimen and the temperature difference across it. In Fig. 8 the results of tests made by changing the material thickness keeping mean temperature and density constant are shown. The experimenters have attributed the variations partly to contact resistance between the plates of the apparatus and partly to convection currents.

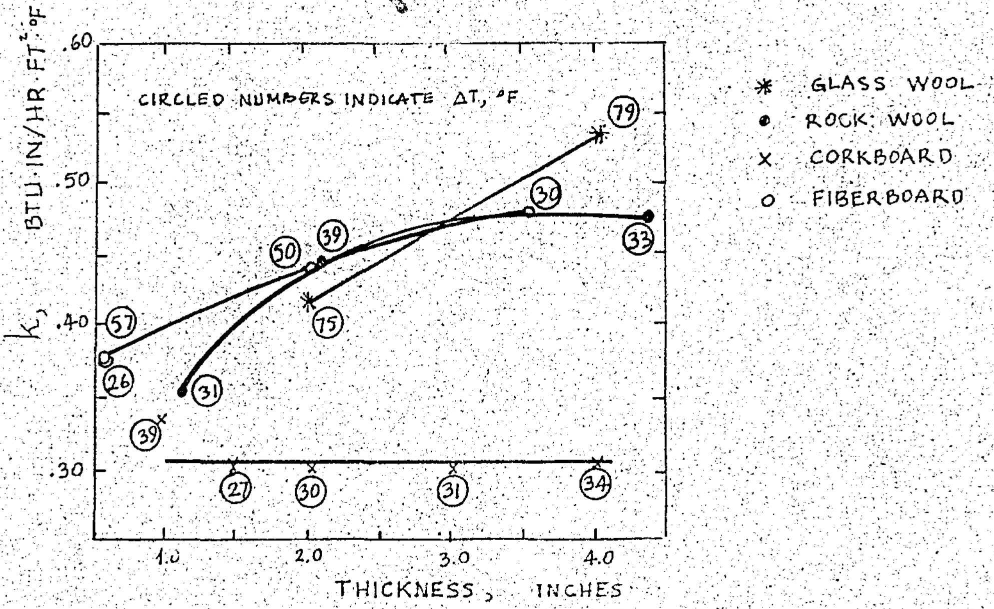

Fig. 8. Thermal conductivity vs. thickness. Position of the insulator during test is vertical.(5)

Some loose fill insulators such as glass wool are semitransparent to radiation. It has been found that by preventing radiation through glass wool, k value can be reduced by as much as 20 per cent for one pound per cubic foot density. For 3 lb/ft^3 this was 9 per cent, and for 6 lb/ft^3 it was 7 per cent.(5)

Many fibrous loose fill insulators have a minimum when their density is increased (Fig. 9).

Density has an adverse effect on convection. If a loose fibrous insulator is very dense convection will stop at a certain temperature difference between the two sides of the insulator and at a certain insulation height.

According to Wilkes,(5) some insulators like rock wool and glass wool are not appreciably affected by the relative humidity of the air if the temperature throughout the insulation is above the dew point of the surrounding air.

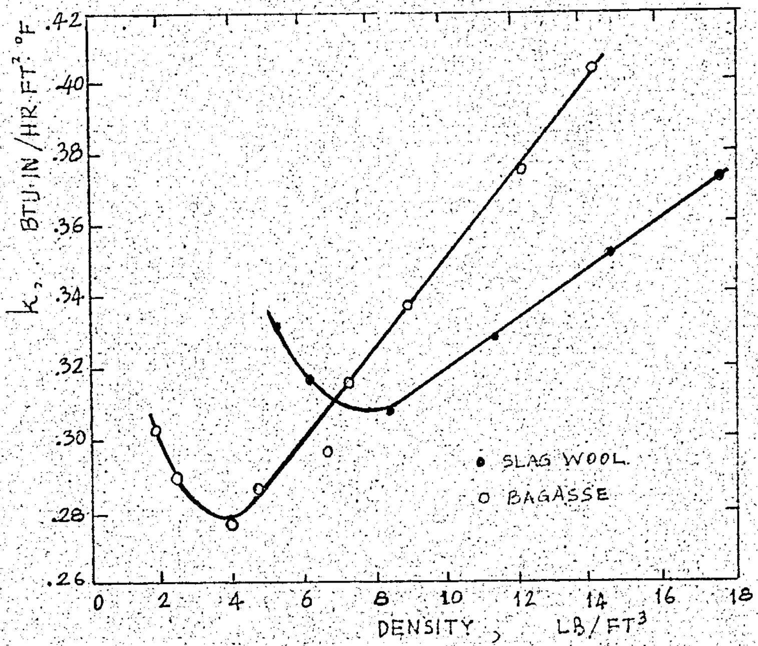

Fig. 9. Thermal conductivity vs. density of loose fibrous insulators.(5)

C. The Guarded Hot Plate

1. The Main Features

The guarded hot plate is the standard apparatus for measuring the thermal conductivity of insulating materials in the form of flat slabs.* There are two types of the guarded hot plate, metal surfaced, in which heater plates are metal, and refractory surfaced, in which heater plates are of refractory material. The metal surfaced guarded hot plate is used for low temperature applications (hot plate up to 500°F) whereas the refractory surfaced guarded hot plate is used for high temperature ranges

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* See for example ASTM Standards, C177-63; Türk Standardları, TS 388, 1966.

hot plate between 200° and 1300°F. Guarded hot plates can be square or round, depending on the choice of the designer.

For practical purposes, the operating range of the guarded hot plate has been limited for the determination of thermal conductances not in excess of 10 Btu/hr-ft^2-°F by the American Society for Testing and Materials. (Conductance is k divided by insulator thickness.)

The guarded hot plate basically consists of an electrical heating element in the middle, on the two sides of which are two pieces of the specimen to be tested, and two cooling plates which sandwich the assembly.

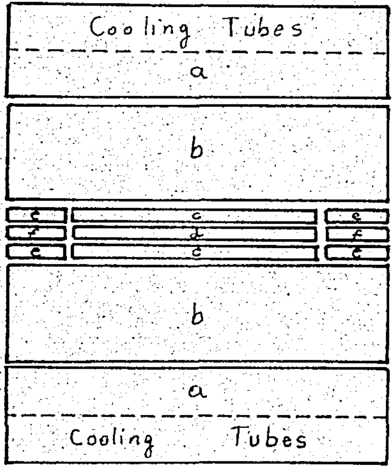

Fig. 10. Cross Section of a Typical Guarded Hot Plate. Not to scale. The symbols of the figure denote, a- Cooling plates, b- Sample, c- Main heater plates, d- Main heater, e- Guard heater plates, f- Guard heater.

Power is applied to the heater and a temperature difference is maintained across the sample under steady state conditions. Using the Fourier heat conduction equation for one dimensional heat flow

$$q = kA\,\Delta T/\Delta X$$

and using the measured values of the power input, q, the combined thicknesses of the two samples, ΔX, the combined temperature difference across the two samples, ΔT, and the heated area of the specimen, A, the value of k can be calculated.

In order to justify this procedure there must be one-dimensional heat flow through the samples. To realize this, the electrical heater consists of two sections, the main heater and the guard heater which surrounds the main heater (see Fig. 10). The guard heater is heated separately to maintain negligible temperature difference between the facing edges of the heater plates. This secures unidirectional flow at the hot side of the samples. The function of heater plates is to distribute heat generated in the heaters equally over the surface. The whole apparatus is surrounded by good insulation (not shown in Fig. 10) to prevent significant heat losses in or out of the specimen.

2. Components of the Guarded Hot Plate and Requirements for Good Performance*

a. Main and Guard Heaters. The function of the main heater is to supply heat to the test area, and of the guard heater is to control the temperature unbalance in the plane of the heater. ASTM standards require that the distance between heater windings be at most 3/4 in. It has been found that for windings 3/16 in. apart, 1/16 in. thick copper hot plates reduce variations in temperature on the sample side of the copper plates to less than .1 per cent, while 1/8 in. thick copper plates reduce these variations to less than .01 per cent.(7) As will be shown in the theory of guarded hot plate, thin copper plates reduce errors; therefore the

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* See ASTM Standards, C 177-63.

winding spacing should be small so that thinner plates may be used.

b. The Gap. Using two heaters, one for power input, the other for control would necessitate a gap between them. A gap is usually also used in the copper plates, and some low conducting substance is placed in between in order to minimize any lateral heat flow.

ASTM standards for the guarded hot plate recommend that the gap not be greater than 1/8" for all sizes of guarded plates. However a detailed theoretical analysis has revealed that for each size there is an optimum gap distance for minimizing errors.(7)

c. Metal Hot Plates. On each side of the main and guard heaters highly conductive metal plates are placed in order to equilize the heat flow over their surfaces. Copper or aluminum may be chosen for this purpose, however it has been shown that aluminum plates always increase errors.(7)

ASTM standards require that maximum departure from planeness on the surface of the metal plates should not exceed .003 in. per ft. Although this requirement is justified for rigid insulators in order to prevent air pockets, for other type of insulators it might not be necessary.

d. Specimens. It is necessary that surfaces of rigid specimens should be as plane as possible to prevent air pockets. Also, accurate determination of the test thickness is necessary. Since the thickness is usually small, errors in measurement may give large percentage errors.

In order to provide good contact and thus reduce contact resistance the standards stipulate that unless easily compressible specimens are used a reproducible constant pressure of about 50 psf be used over the specimens.

The American standards recommend that tests are run on a bone-dry sample. Furnace drying or, if not suitable, dessicator drying is advised. The specimen should be weighed before and after each test to determine any moisture absorbtion during the test. The necessity of air insulation also leads to confining the whole apparatus in a moisture proof compartment.

e. Cold Plates. The requirements for cooling plates are that the same planeness as in the case of the hot plates should be obtained, and that uniform distribution of temperature be realized over the surface.

f. Surrounding Insulation. The standards require that the minimum thermal resistance of the insulation be

$$R = (5x/Sk)\left[(4x+2y)\left(\frac{Tm-Ta}{\Delta T}\right) + y\right]$$

where x = thickness of each specimen in inches,

y = thickness of the heating unit in inches,

S = lenght of the side (or diameter) of the guard section in inches,

k = thermal conductivity of the specimen in Btu/hr-ft^2-$^\circ$F,

Tm= mean temperature of the specimen in deg. F,

Ta= temperature of the air surrounding the apparatus in deg. F, and

ΔT= temperature difference across the specimens in deg. F.

However, it has been found that the optimum thickness of the insulation is equal to the thickness of one sample, and that for accuracy considerations k of the insulation should be equal to the k of the specimen. The surrounding air temperature should be around the mean temperature of the sample in order to keep the errors due to the leakage through the insulation low.

g. Measuring. For temperature measurements within the apparatus thermocouples are most convenient. Large thermocouples are slow in coming to equilibrium, and they may lead to heat losses resulting from fin effect. The standards require No. 25 and 29 B & S gage thermocouples to be used.

The sensitivity requirement on the potentiometer output is 1 μV or better.

h. Temperature Control. In order to have no side loss from the main hot plates, a temperature balance between the main plate and guard plate is necessary. Any temperature difference existing between main and guard plates are detected by suitably placed thermocouples which preferably automatically control a desired temperature difference by feedback control. It has been found that this temperature control must be in strict limits in order to have satisfactory performance. This will be further treated in the next section.

3. Theory of Heat Conduction in the Square Guarded Hot Plate

Various people have tried to assess the deviations from unidimensionality in the guarded hot plate.* However, in all of these studies assumptions are made which are hard to evaluate accurately. Moreover, each investigator deals with a single source of error at a time, thus the relevancy of other parameters and their overall effects are not clear. The most complete mathematical analysis, taking all the

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* See the references of Ref. 8.

parameters of the apparatus into account has been made by Donaldson.(8) What follows is a summary of his work.

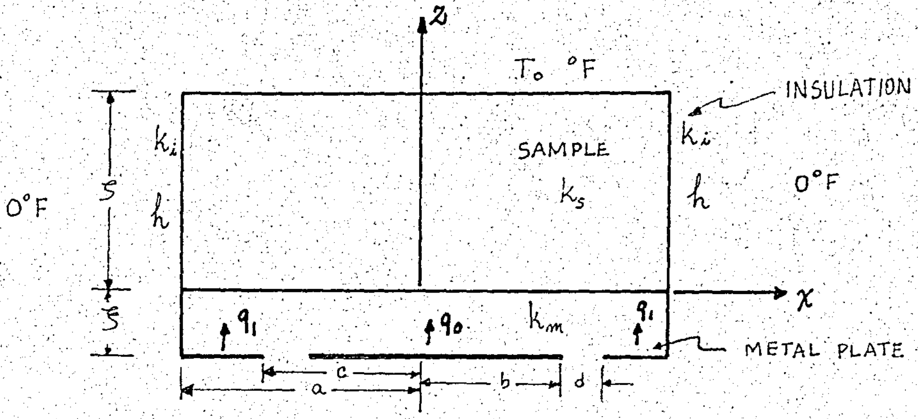

Fig. 11. The mathematical model used in Donaldson's work.

Donaldson used a unified heater plate in his analysis and justified this by assuming that there is no unbalance between the actual hot plates.

He also assumed a uniform convection coefficient in place of the surrounding insulation. Then he solved the Laplace equation for the two layers in Fig. 11 with the heat input per unit area as shown. The ambient temperature was taken as reference, and a uniform constant temperature, T_o was assumed over the cold surface of the specimen.

The solution of the Laplace equation is correct only if we have complete balance in which case, as far as the unbalance errors are concerned, it does not matter if we have a gap or not. Therefore the effects of the side insulation, and hence the resulting error, can be found from this solution. Similarly, the effects of the variations in air temperature can be estimated by varying T_o. In the theory ambient temperature is at zero deg. F, but varying T_o and keeping ΔT constant is effectively the same as varying the surrounding temperature.

In order to find the effect of insulation we have to estimate the convection coefficient, h. One thing to be noted is that the heat conduction in the surrounding insulation is two dimensional and now the Laplace equation must be solved for the insulation. Donaldson found that provided insulation thickness p is greater than the thickness of one sample, further increase in insulation thickness does not alter h.

Donaldson's results also enable us to estimate the error due to the existence of the gap. This error arises because heat is not supplied in the gap area, whereas the heat input is actually spread over the gap area through the specimen. Thus there is uncertainly as to what area to use in the calculations. Normally an "effective" test area is used, which is taken as the area of the square with central gap lines as sides. It is possible, by varying the distance c in the theory, and by rising the effective test area, to estimate this error.

We have dealt so far with every source of error in the apparatus except the temperature unbalance between the center plate and the guard plate. For some of the errors caused by this unbalance the above theory still can be used, but for other errors it is more convenient to use another equation. To understand this we must consider the causes of error arising from the unbalance.

When there is a temperature difference across the central plate and guard plate there is heat flow from plate to plate across the gap, and there is also heat flow from plate to plate through the specimen. To estimate the error of across-the-gap flow we assume a hypothetical unbalance without a gap such that it produces the same heat flow from the heater area to the guard area (or vice versa) as in the actual case when there is a gap. From this we develop a temperature difference which can be used with the theory of Donaldson.

For the error that is brought about by lateral heat flow through the sample itself Donaldson's result is impractical for calculations. However, Woodside(9) has developed an equation the results of which agree well with Donaldson's results (within 10% for a plate 8 in x 8 in. test area, a = 6 in.).

4. Theoretical Errors in the Square Guarded Hot Plate:

It is interesting to note that with the preceeding theory not only errors of a particular design can be found but actually all design parameters may be varied to choose the optimum dimensions and operating conditions for a perfect square guarded hot plate. This has been done,(7) and it was found that the optimum plate material is copper, and the optimum size of the perfect square guarded hot plate is

$$a = 6 \text{ in},$$

$$d = \tfrac{1}{4} \text{ in}.$$

Effective test area = 10x10 sq. in.

With sample thickness chosen as one inch, the surrounding temperature kept at the mean temperature of the specimen, and using $k_i = k_s$ with insulation thickness equal to the thickness of one sample, the total theoretical error resulting from this plate is less than .2 per cent.(7) The actual error would be the theoretical error plus the operating errors.

Donaldson(10) has made calculations for the optimum square plate for various operation conditions. His calculations are not extensive but provide the background for a learned guess for the errors of a designed hot plate. His results for an optimum copper square hot plate are given below.*

a. <u>Errors due to the existence of gap.</u> For one inch thick specimen and $\frac{1}{4}$ inch gap, -1.07 per cent for copper plates. This error does not vary with the other design parameters and is fixed for the designed apparatus.

b. <u>Additional errors due to edge heat losses.</u> These errors are approximately proportional to k_i/k_s and vary practically linearly with sample thickness (Fig. 12), and they are not affected by other parameters of design.

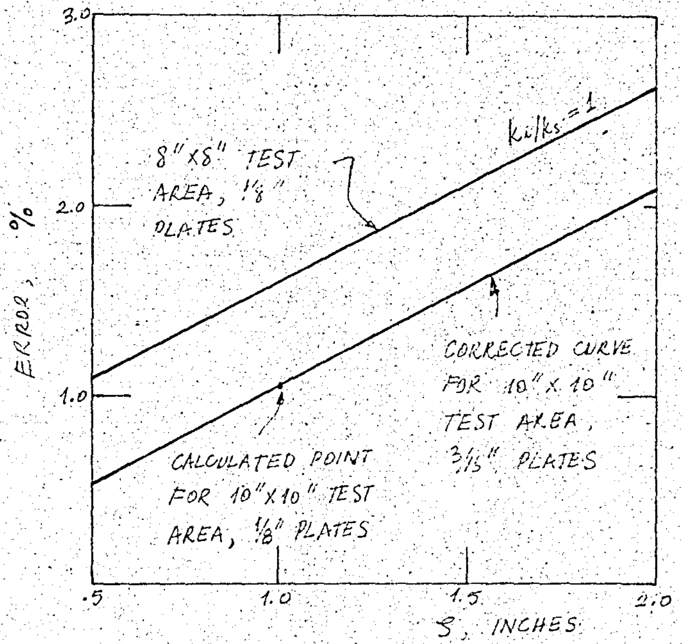

Fig. 12. Errors of imperfect side insulation. Air temperature at the mean temperature of the specimen.(10)

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* These results apply also to the plate designed for this thesis with slight modifications.

In the designed hot plate the copper plates are 3/16 in. thick as opposed to 1/8 in. thickness above. However, calculations(10) have revealed that the change in error would be less than 3.5 per cent and therefore negligible. A correction is needed for the difference in test area, however. The result is shown in Fig. 12.

When air temperature is different from the mean temperature of the specimens additional errors may rise (Fig. 13).

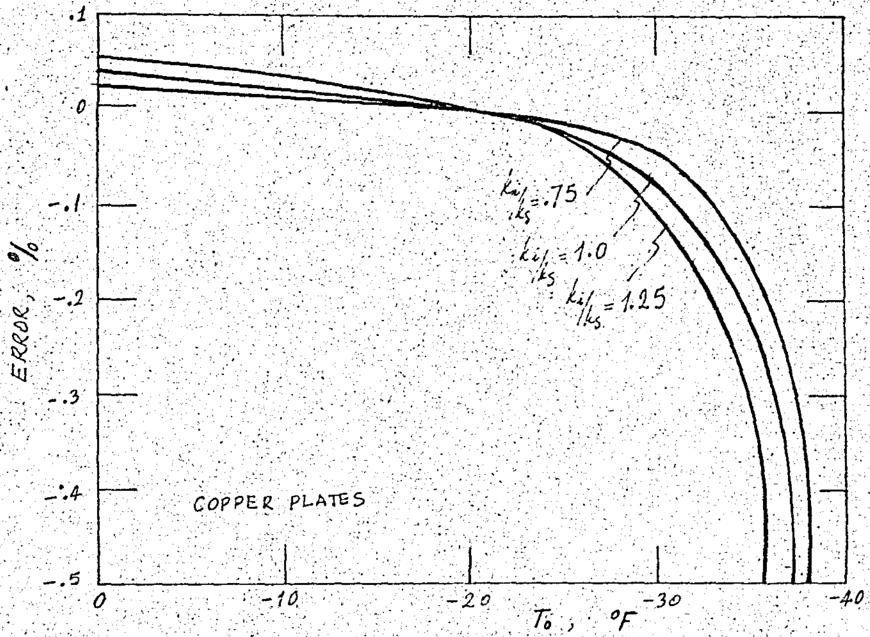

Fig. 13. The additional error rising when air temperature differs from the average temperature of the sample. Here effective test area is 8"x8", sample is 1" thick, k_s=.24 Btu-in./hr-ft²-°F, metal plates are 1/8" thick, ΔT=40°F.(10)

Extrapolation for the designed plate is not necessary since errors are minimal. For $\Delta T \neq 40°$ simple proportional calculations should give very close results.

c. Unbalance Errors Due to Heat Flow in the Sample. For a one inch thick specimen, the error is .47 per cent for one degree temperature difference across the gap. This figure is a little smaller than the actual amount because Woodside's equation was used, which ignores h. But the difference is less than 10 per cent. The conductivity value of the specimen has no effect on this unbalance error.

Variation of this error with sample thickness is not negligible (Fig. 14).

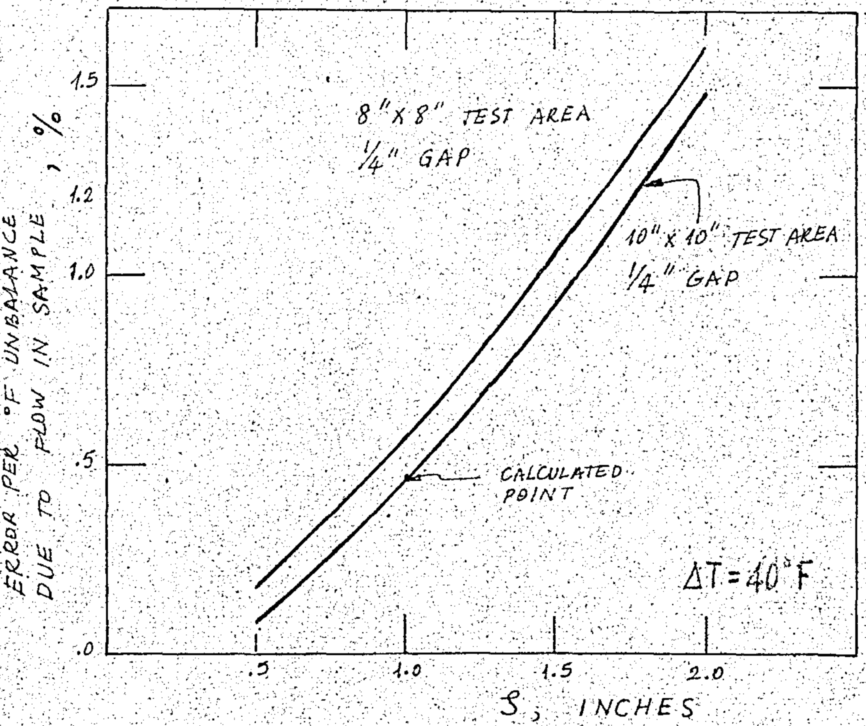

Fig. 14. Unbalance errors vs. sample thickness for a 8"x8" test area, d=¼" plate for one deg. F unbalance and estimated value for a 10"x10" plate with ¼" gap. (Plotted with values of Donaldson'.)

d. Unbalance Errors Due to the Heat Flow Across the Gap. These errors are directly propotional to δ, ξ, the thermal conductivity of the gap and the unbalance. They are inversely propotional to the thermal conductivity of the sample and to the gap width, and are independent of k_i.

For a 10 in. x 10 in. test area plate, 1/8 in. thick metal plates, one inch sample, .26 Btu-in./hr-ft^2-°F of effective gap conductivity, $\frac{1}{4}$ in. gap the error is .52 per cent per deg. F. unbalance. These values are slightly different for the designed apparatus therefore corrected values are given below.

Variation with plate thickness is as seen in Fig. 15.

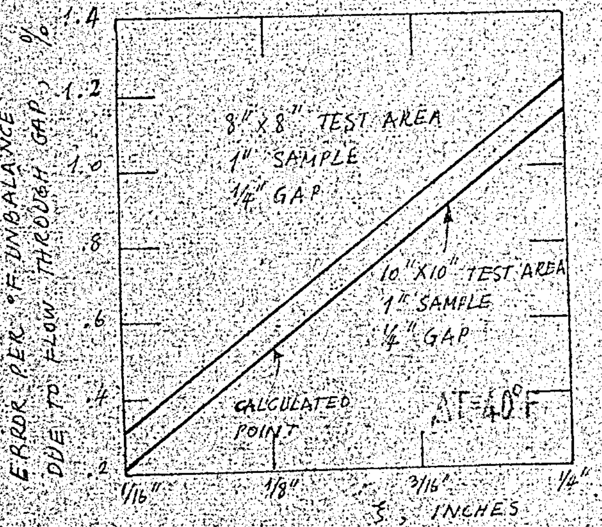

Fig. 15. Percentage error vs. plate thickness.
k_{gap}=.26 Btu-in./hr-ft^2-°F, k_s=.24 Btu-in./hr-ft^2-°F.
The curve for the 8"x8" plate is plotted from calculated values of Donaldson and values are extrapolated for a 10"x10" plate based on one calculated point.

Since in the design of the thesis plate thickness is 3/16 in. for a sample thickness of one inch, from Fig. 15 we read an error of 0.83 per cent.

Variation of errors with sample thickness is again linear (Fig. 16).

In the designed apparatus the gap is filled with air and the conductivity of air depends on the temperature of the hot plates. However, to take the conductivity of the air as the effective conductivity of the gap would be wrong since radiative effects should also be considered making the value higher. The conductivity of the air being around .2 Btu-in/hr-ft^2-$^\circ$F at 212°F, it would not be too erroneous to take k_{gap} to be .26 Btu-in/hr-ft^2-$^\circ$F. For extreme operation conditions this value would be subject to change.

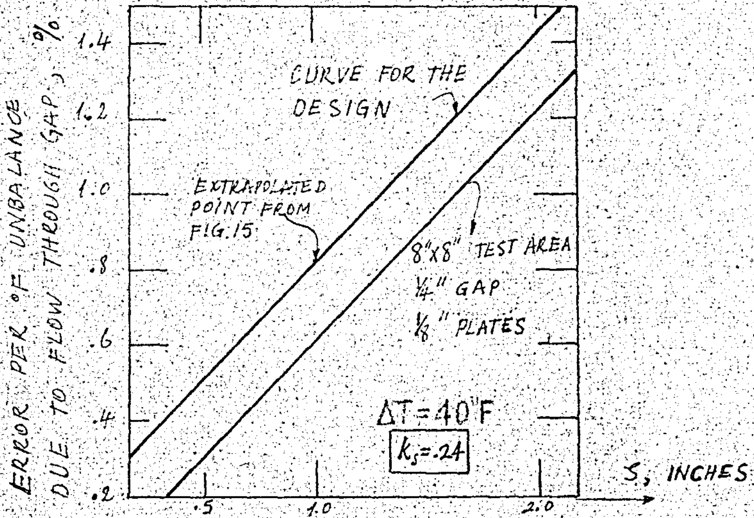

Fig. 16. Percentage error vs. specimen thickness for a 8"x8" plate, plotted from calculated values of Donaldson and extrapolated values for the design of the thesis based on the extrapolated value found in Fig. 15. Here too k_s=.24 and k_{gap}=.26 Btu-in/hr-ft^2-$^\circ$F.

Donaldson$^{(7)}$ gives the following total unbalance errors for a guarded hot plate with 10 in. x 10 in. test area, ¼ in. gap, 1/8 in. copper plates, one inch sample, .26 Btu-in/hr-ft^2-$^\circ$F gap conductivity and .1°F unbalance.

k_s	% error
.24	.10
.48	.08
.72	.07
.96	.06

Since the unbalance errors due to the through-sample heat flow were independent of k_s for the same operating conditions, the above values can be corrected to give

k_s	% error
.24	.52
.48	.33
.72	.23
.96	.13

per degree F. When we plot these we get Fig. 17.

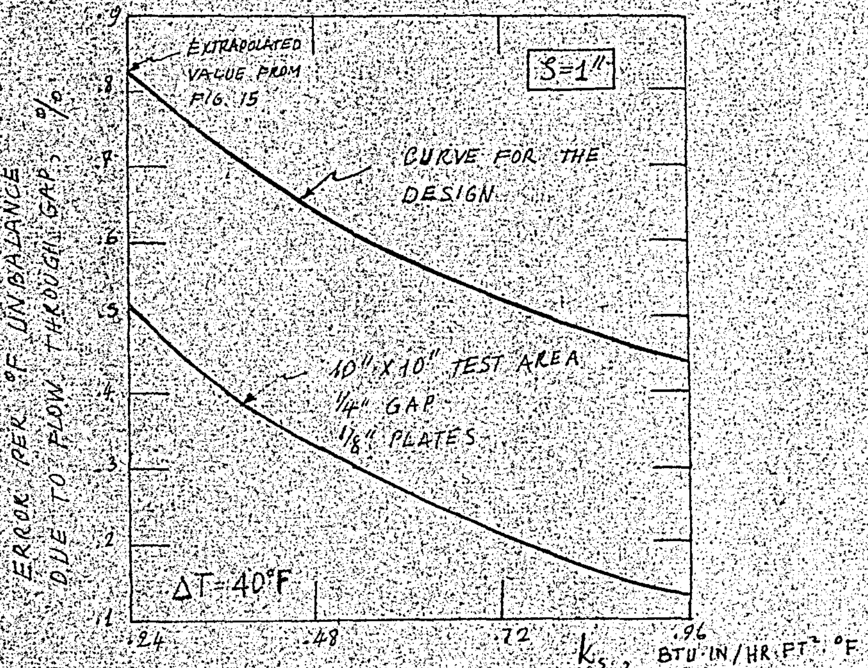

Fig. 17. Percentage error vs. k_s for a 10"x10" plate with $\frac{1}{4}$" gap, 1/8" copper plates, 1" sample, k_{gap}=.26 Btu-in/hr-ft^2-°F and the extrapolated curve for the designed apparatus.

Now it is possible to evaluate any conditions of testing by using the preceding information.

II. THE APPARATUS

A. General Description

The guarded hot plate equipment consists of four main parts: the guarded hot plate itself, the cooling system, the control system, and the electrical circuit.

As shown in Fig. 18, the apparatus itself is composed of a main heater and a guard heater, central hot plates and guard hot plates, asbestos sheets holding the differential thermocouples, the samples, and the cooling plates.

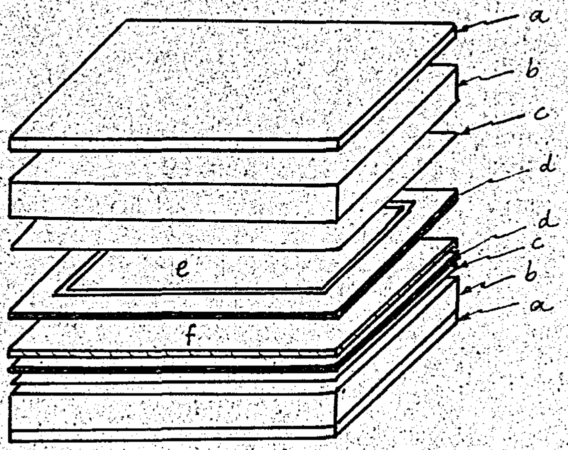

Fig. 18. The apparatus. The symbols denote, a- Cooling plates, b- Specimens, c- Asbestos sheets, d- Guard hot plates, e- Central hot plate, f- Main and guard heaters.

The cooling plates have connections for water circulation, as shown in Fig. 19. Also see the photograph on page 36 and Figure 19 on page 29. The electrical connections to the heater, and the thermocouple wiring are not shown in these figures. They are explained in a later section.

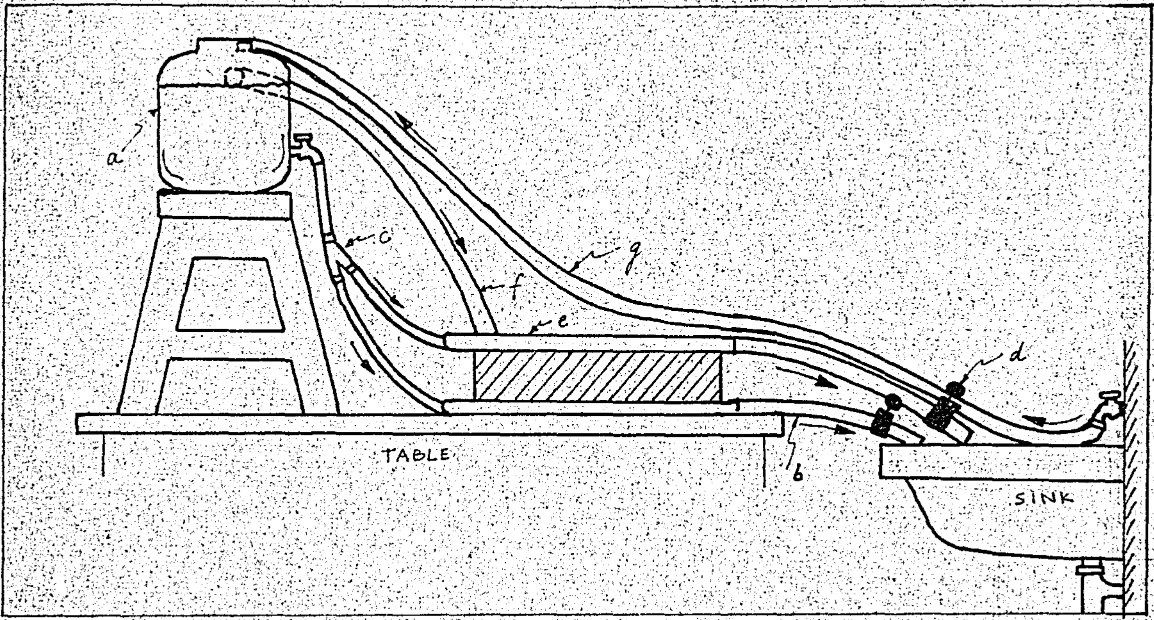

Fig. 19. Cooling system. The symbols denote, a- Water tank, b- Drain pipes, c- Flow divider, d- Flow adjuster, e- Cooling tubes, f- Excess water flow pipe, g- Main inlet pipe.

The guard heater control system is composed of a light source, a mirrored galvanometer, a photocell unit, an amplifier-relay set, and a d.c. power source. Schematically it is presented in Fig. 20. See also Fig. 30 on page 47.

Electrical circuits for the main heater and for the guard heater are shown in Fig. 21 below.

B. Design Criteria and Details of Design

The results of Donaldson(7, 8) have been very useful in establishing the design criteria. Although ASTM standards (C 117-63) were frequently consulted, it was felt that strict adherence to them is not justified.

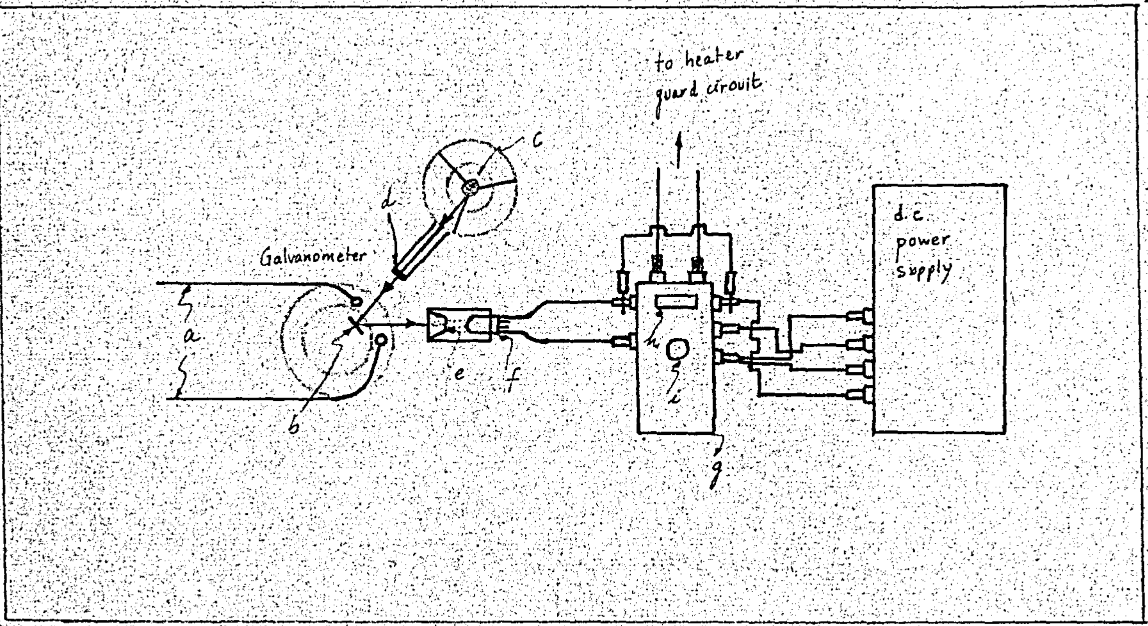

Fig. 20. Control system. The symbols denote, a- Differential thermocouple leads, b- Galvanometer mirror, c- Light bulb, d- Collector lens, e- Photocell lens, f- Photocell, g- Amplifier-relay set, h- Relay, i- Vacuum tube.

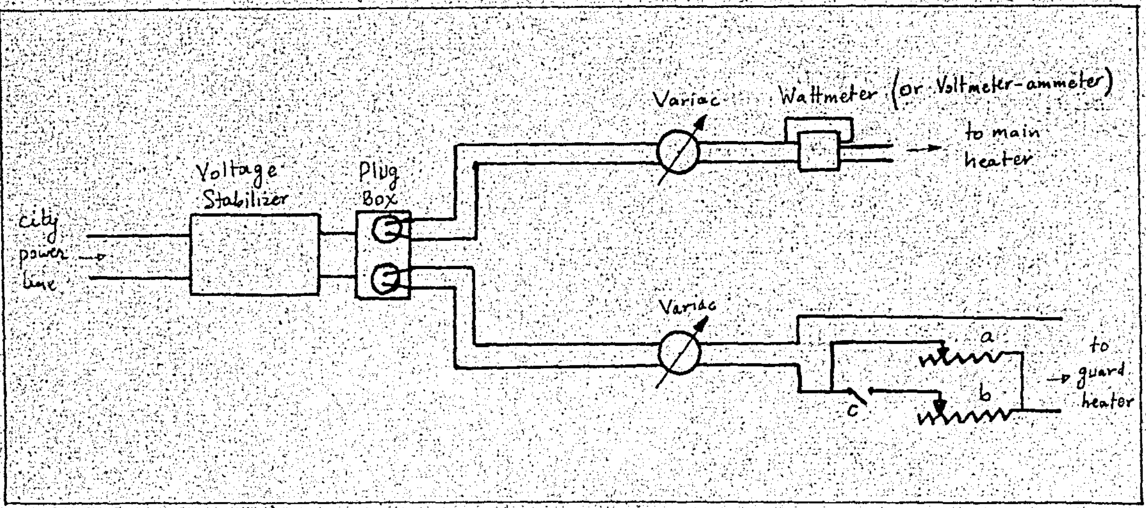

Fig. 21. The electrical circuit. The symbols denote, a- Fixed rheostat, b- Relay rheostat, c- Relay contacts.

1. The Geometric Shape and Type

The shape of the plate was chosen to be square, since a full theoretical analysis was obtainable only for this shape of plate. A second reason was that, as indicated in the ASTM standards, the metal surfaced guarded hot plates are usually square and only occasionally circular. It was thought that unforseen practical reasons may have been influencing this selection.

Horizontally operating apparatus was chosen since it is simpler than the vertical one. The vertical guarded hot plate requires a stand whereas the horizontal one does not. The vertical one needs systems of levers or springs to compress the specimens whereas with the horizontal one we only need to put a weight on the apparatus. Besides, the horizontal plate is symmetrical with respect to the convection heat losses through its insulation whereas with vertical plates special provisions must be made to obtain uniform heat losses.

2. Dimensions

The dimensions were chosen to be 12in.x12in. because of ease in handling. Guard plate and main plate dimensions were taken from the previous analysis (see page 21) so that b= 9.75in. and c= 10.25in. This means 10in.x10in. effective test area and ¼in. gap width. Heaters had the same dimensions as well.

All the plates were chosen to be copper in order to minimize errors.(7)

3. Hot Plates

Hot plate thicknesses were deigned to be 1/8in. thick, again taking Donaldson as reference. However, the excess thickness allowed at initial rolling of copper was too difficult to machine off. Therefore, errors being still low, the plates were left to be 3/16in. thick.

4. Cold Plates and the Cooling System

Cold plates were made so as to cover the hot plates. Their thickness had to be so chosen that it would give the same maximum variation of temperature over its surface as the hot plates. It was found(7) that when the heater windings are 3/16in. apart, 1/8in thick copper hot plates would reduce the temperature variation on their surfaces to less than 0.01 per cent, and that 1/16in thick plates would reduce the variations to 0.1 per cent. It was assumed that in constructing the heater, the winding would be 3/8in. apart. Then temperature variation over the hot plate surface would be about 0.1 per cent. ASTM standards recommend that the temperature difference between the hot and cold plates for good insulators be a minimum of 40°F per inch. Assuming we have 40°F temperature difference, 80 °F hot plate temperature, error due to the variation of surface temperature of the hot plate would be 0.20%. This is already significant if we want an overall accuracy of 1% from the measurements. Therefore, surface temperature variation over the cold plates should not exceed this amount. From the given figures above we can roughly say that for a plate thickness to winding spacing ratio of 2/3, we have 0.1 per cent temperature variation. On the cold plate it was assumed that after construction the width of cooling channels would be about one inch and their separation would be about half an inch. In that case the cold plate would be almost equivalent to a heater with windings ½in. apart. Then for the same temperature variation we need 1/3in. thick cold plates. After the construction, the excess thickness allowed for safety purposes did not have to be removed, and the final plate had a thickness of 0.43in. The material was copper.

In the design of cooling system, the primary objective was to choose the simplest and the least expensive design. The coolant was choosen to be water since it is easy to get and is cheap. Coolant circulation was not considered since a motor-pump system alone would cost 1000.-TL., about 1/3 of the total costs. The tap flow in the ME lab was tested for sufficiency. Flow of the tap was around 18 lt/min at all times of the day. One tap rather than two was chosen since using two taps increases the flow rate by only about 2 lt/min. Direct water transmission from tap to plates was clumsy since the drain would have to be right below the tap. Also the flow should be guarded against any fluctuations. These facts necessitated a tank with provisions for head control. A head loss estimation was necessary to see if we could have sufficient height. Before doing this the cooling tubes had to be designed.

There exist designs for the cooling channels which provide excellent uniformity of temperature on the cold plate.(11) These were disregarded, and a simple system (Fig. 22) which is composed of copper tubes soldered on the cold plate was considered.

To provide ease in working, nine tubes of one inch in diameter were used, with spacing as shown in Fig. 22.

ASTM Standards indicate that for practical purposes the range of guarded hot plate is limited to measuring a maximum of 10 Btu/hr-ft^2-^{o}F conductances. Taking this as the upper limit for measurements, the maximum heat input at the hot plates would be approximately

$$q = kA\,\Delta T/\Delta x$$

$$q = (k/\Delta x)A\,\Delta T$$

$$q = 10 \cdot 1 \cdot 40$$

$q = 400$ Btu/hr for one side, and

$q = 800$ Btu/hr for two sides.

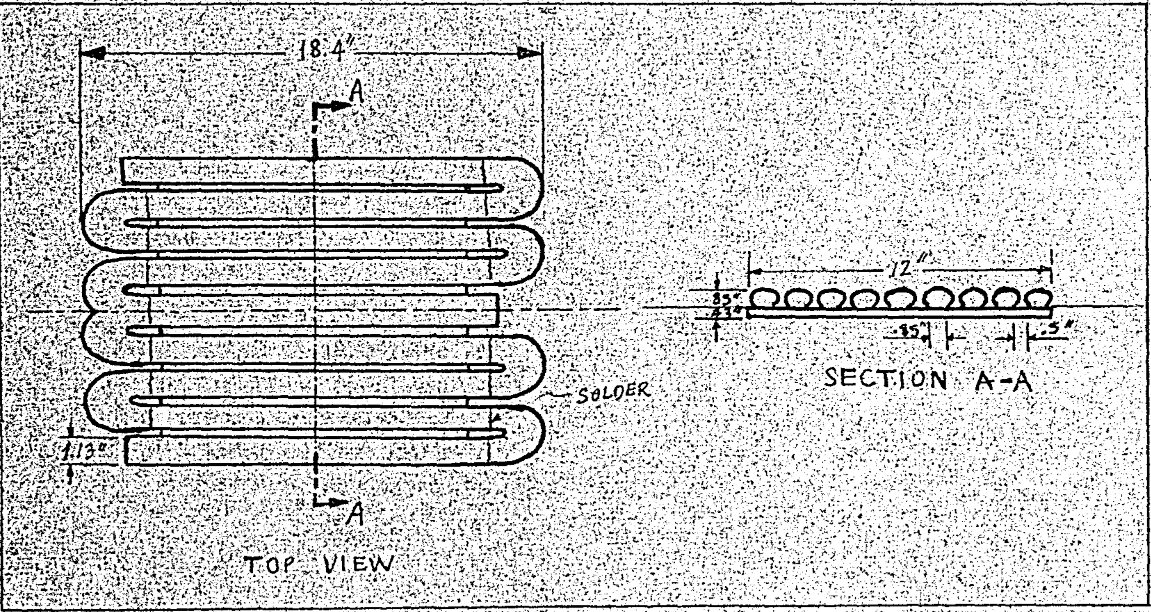

Fig. 22. Top view and cross section of a cold plate.

Since this heat should be removed at the cold plates, we can approximate the temperature rise in the water and thus the temperature variation on the cold plate which is nearly the same as the rising temperature of the water. We can use the formula

$$q = wc\,\Delta T_w$$

where w is the mass flow rate, c, the specific heat of the water and ΔT_w is the temperature rise of the water.

w for one cooling plate is 9 kg/min = 19.8 x 60 lb/hr = 1190 lb/hr

Thus $\Delta T_W = 400/1190 = .34\ ^{o}F$.

This figure is high, but here we consider that we are estimating for the maximum case. When we measure a low conductivity specimen, for instance a k of .24 Btu-in/hr-ft^2-^{o}F with Δx = 1 inch, q would be

$$q = .24\ .\ 1\ .\ 40$$

$$q = 9.6 \text{ Btu/hr} \qquad \text{for one specimen}$$

Then $\Delta T_w = 9.6/1190 = .00806\ ^oF$. This is about .02 per cent of the assumed temperature difference of the cold and hot plates (40 ^{o}F). Therefore, any errors due to this would be negligible.

The head loss estimation was made as follows: Neglecting the size contraction due to flattening of copper tubes, Area of copper tubes, $A = \pi/4 \text{ in.}^2 = .785 = .785/144 = .0056 \text{ ft}^2$. Radius, R = .5in = .042ft.

Velocity of water, $V = \frac{19.8/2}{62.4}\ .\ \frac{ft^3}{min}\ .\ \frac{1}{.005 ft^2}$ = 31.fp m, ignoring the middle pipe .

Assuming water at 50^{o}F, $\nu = 1.41 . 10^{-5}\ ft^2/sec$.

Reynolds number, $Re = VD/\nu = (31.5/1.41 . 10^{-5})\ (1/12)\ (1/60)$

$$= \frac{31.5}{72 . 1.41} \cdot 10^4 = .31\ 10^4$$

From Moody's diagram friction factor f, for smooth pipes is f = .042 .

Head loss $h_L = f\ \frac{L}{4R}\ \ \frac{V^2}{2g}$,

where L is the lenght of the pipe and

$g = 32.2\ ft/sec^2$.

Therefore $h_L = .042\ \frac{9}{4\ .5/12}\ \frac{ft}{ft}\ (\frac{31.5}{60})^2\ \frac{ft^2}{sec^2}\ \frac{1 sec^2}{64.4\ ft} = (.042)\ \frac{54}{64.4}\ (\frac{31.5}{60})^2$

$= .00969$ ft = .01 ft

For the bend losses we have

$$h_L = c_L V^2/2g$$

where c_L = 2.2 form Ref. 12.

For eight 180° bends we have

$$h_L = 8 \cdot \frac{2.2}{64.4} \quad \left(\frac{32.5}{60}\right)^2 \text{ ft}$$

$$= .75 \text{ ft}$$

Thus we have .76 ft heat loss for one plate.

From the above calculations we see that the design is satisfactory and can be operated with a water tank.

A plastic water tank was chosen with a capacity of about 25 lts.

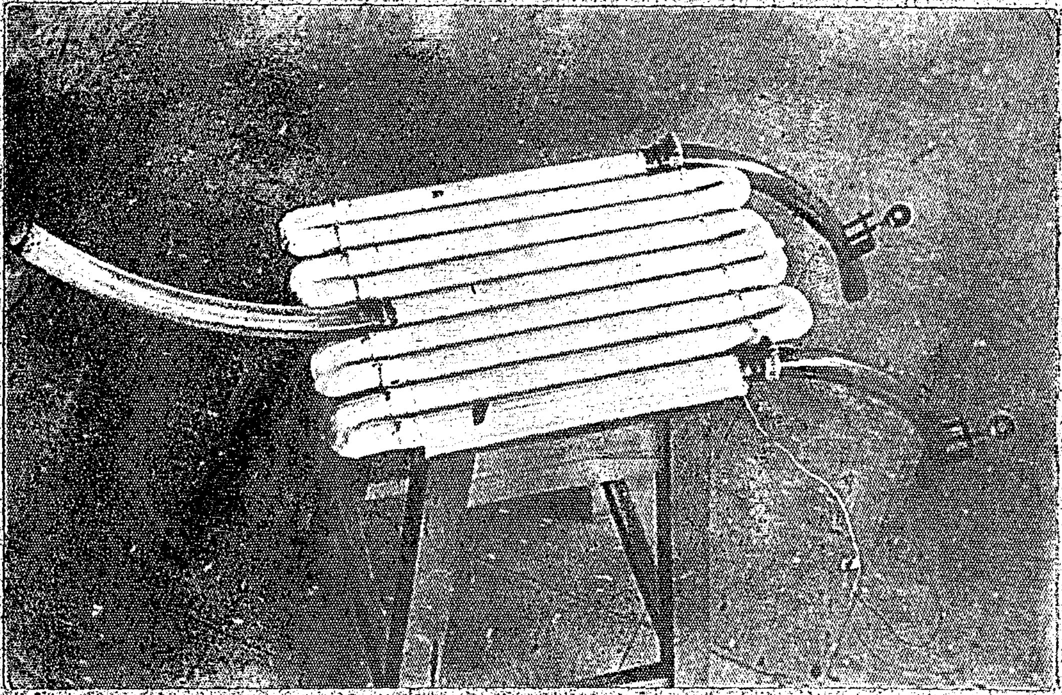

Fig. 23. Top cold plate as seen from top.

The water tank had an overflow opening to maintain a constant head. Flow from the tank was separated for the top cold plate and the bottom cold plate, with adjusting valves at the end of drain pipes (Fig. 23) to equalize the flow.

5. Gap Filling

No gap filling was used since air has very low conductivity. Convection effects were thought to be negligible, since gap space is restricted, and since the temperature difference across the gap is very small, if any.

6. Surface Emissivity of the Plates

According to the ASTM standards the surfaces of all plates should have an emissity of .80 or higher since loose fill insulators are semi-transparent to radiation and some of the heat transfered across them is by radiation. In the design, there exists an asbestos sheet next to the hot plates. The emissivity of asbestos is about .93 for the ranges of temperatures used. Neverthless the hot plates were painted with flat black stove-paint to have a high emissivity. High emissivity surfaces act to reduce the effects of air pockets, if any. The emissivity of the plates, hot and cold were not measured. However, for both plates the emissivity value should be satisfactory.

7. Differential Measuring of Temperature

In order to obtain zero unbalance on the surface of the hot plates we must be able to measure the temperature unbalance on the plates and using this measurement to correct any existing unbalance. For this purpose, the most suitable instrument is the differntial thermocouple.

The questions arising with differential thermocouples are how many and what kind of thermocouples to be used and how to place them in the apparatus.

Two kinds of thermocouple wires were at hand. No. 24 copper-constantan and No. 24 iron-constantan. Of the two, iron-constantan was more suitable for differential readings across the gap because heat flow across the gap through the copper wire could affect the readings. The thermoelectric output of the two thermocouple wires being almost the same, the above point was the determining factor.

Across the gap we want to be able to correct temperature unbalances as low as .1°F. To have an idea about the number of the thermocouples, a mirrored galvanometer was tested for deflection. With an iron-constantan thermocouple with about 2Ω in resistance the galvanometer deflected full scale for 6°F. The total resistance of the differential thermocouples being about 2 ohms a 4° F total differential reading was chosen. This necessitated 40 differential thermocouples, 20 on each side of the apparatus and five on each side of the hot plates.

Placing the differential thermocouples right next to the hot plates presented some problems. First was the danger of contact and the second was the exact placing with maximum ease. Sticking them directly on the plates would have been the simplest procedure for the top hot plates, but when the bottom plates were being placed this practice would have been impossible. Finally they were stuck with cellophane paper on a .5 mm thick asbestos paper, exactly at the places corresponding to the opposite places across the gap. This was realized by cutting the asbestos exactly the same size as the guard plate and by marking the position of gap on it Fig. 24.

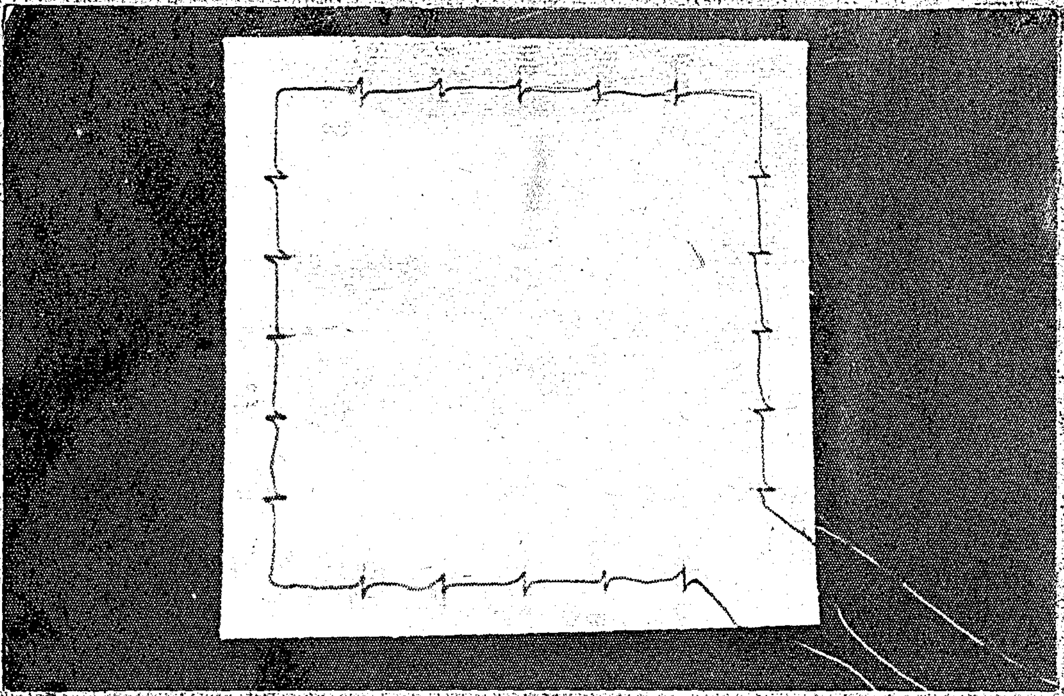

Fig. 24. Differential thermocouples placed on an asbestos sheet.

8. Direct Measuring of Temperature

The temperature must be measured at the two surfaces of the specimen. This is best done with thermocouples. Here a choice was to be made between iron-constantan and copper-constantan thermocouples. The thickness of the wires at hand were a little bigger than allowed in the ASTM standards but those were the only ones available. Both kinds of thermocouples are for low temperature applications, iron-constantan from -423° to 600°F and copper-constantan from -423° to 700°F. They can both be used at oxidizing or reducing atmospheres, iron-constantan preferably reducing, with the absence of protection.(13)

With properties this close to each other the only design factor influencing the decision was the thermoelectric power. Iron-constantan has almost 30 μV per degree F whereas copper-constantan has 23.8 μV per degree F in the range, 32° to 212°F. Therefore, so far as accuracy of the readings was concerned, iron-constantan was considered preferable.

The junction of the thermocouple should be as small as possible. Therefore beaded junctions were used.

The construction, calibration, and mounting of thermocouples will be explained in a later section.

Only central reading of temperatures was considered as sufficient.

9. Electrical Circuit for Thermocouples

There was one potentiometer for measuring the emf of the measuring thermocouples and several thermocouples to be connected to it. This necessitated a selection switch box. The circuit design is shown in Fig. 25 below.

This switch box provides for individual readings of hot and cold side temperatures, and it also permits the differential readings of top and bottom sides.

The two rotating knobs in the figure are commutator switches. Another design using only one commutator switch with six terminals would have been simpler but the commutator was not available .

10. Automatic Balance Control

The necessity of close temperature control requires that automatic control be used. Several types of control systems were considered. The simplest was found to be an on-and-off system using a mirrored galvanometer, a light source, a photocell, an amplifier and a relay. The signal of unbalance results in deflection of the galvanometer mirror, which then reflects a light beam on to a photocell (Fig. 20). The photocell becomes conducting with light, and transmits the signal to the amplifier where it is amplified and thus the relay is energized. The relay opens or closes part of the electrical circuit of the guard heater (Fig. 21). This system should work provided the response of the system is fast, and provided it does not have much overshoot. Below the elements of the control circuit are given and the criteria for their selection are summarized.

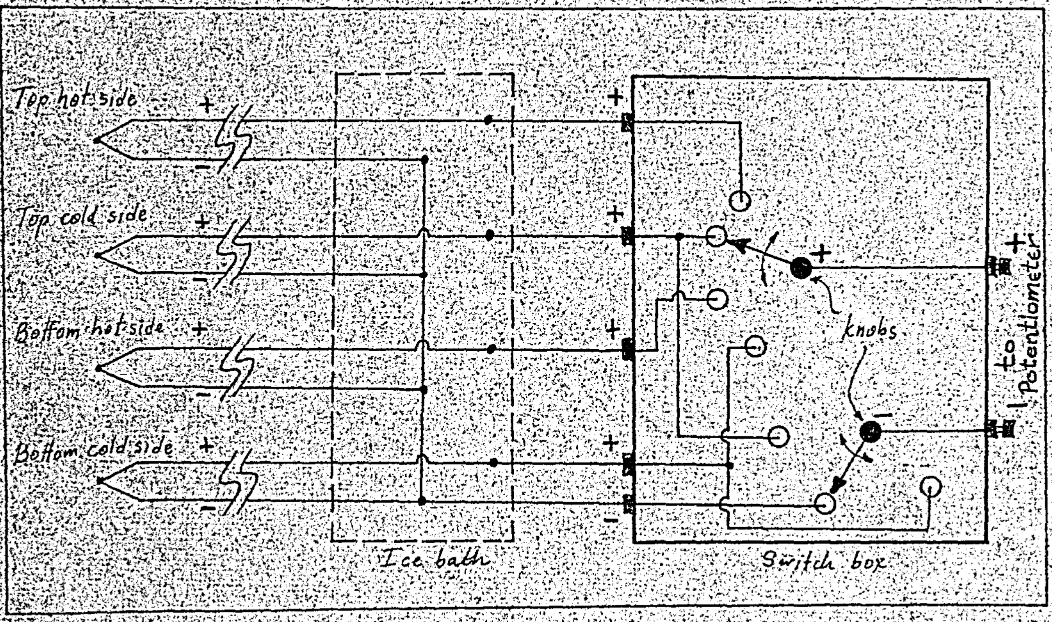

Fig. 25. Electrical circuit for thermocouples.

a. Mirrored Galvanometer.* This unit was the only one available from the measurements laboratory.

b. The Photocell. After considerable market search, a photocell was found, but no volt-ampere characteristics were supplied. Its characteristics were established in a laboratory test. The resulting curve is given in Fig. 26.

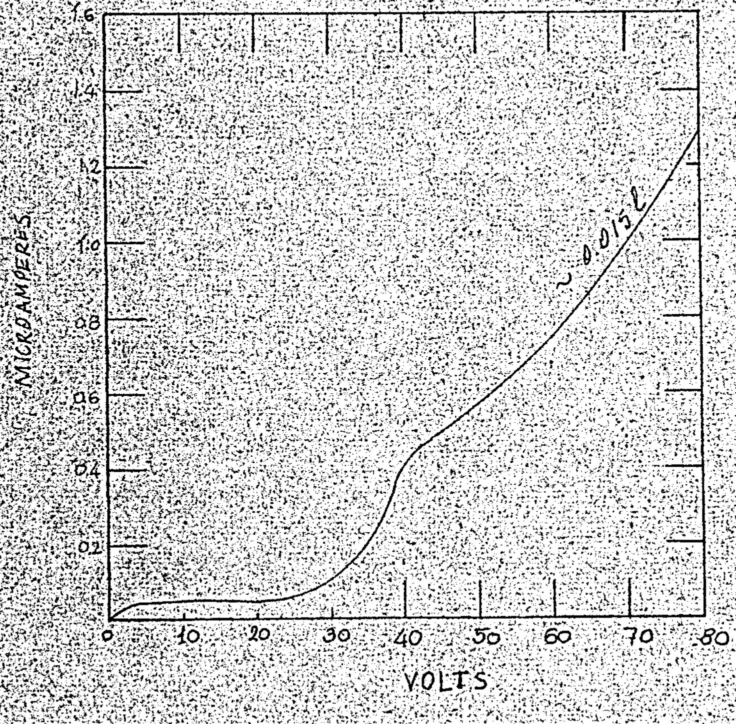

Fig. 26. Ampere vs. voltage for photocell.

The shape of the curve indicates that this is a gas filled phototube.

It was found from Ref. 14 that the maximum operating voltage for

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* For a complete list of instruments used with specifications see Appendix A.

gas filled photocells is around 90 volts, maximum operating current being about 1.5 μA for a projected sensitive area of 1.1 cm^2. The purchased tube had about 3 cm^2 area; therefore the current could probably be increased up to 3 μA, and the voltage up to 100 volts.

c. <u>The Light Source and Lens System</u>. The deflection of the galvanometer mirror should reflect the light onto the photocell. The problems here were sending a small concentrated beam to the mirror, collecting the light after reflection from the mirror and directing it to the cell, and not exceeding the photocell current carrying capacity. Use of lenses solved the first part of the problems. In finding the appropriate size of the lenses, and in choosing the wattage of the electric lamp, a trial method was used. The result indicated that a 30 watt light bulb would give a sufficient amount of light for the cell if the light contained in a cone of angle 7.6° was collected. An electric bulb of 40 watts was chosen. A small lens, 2 cm in diameter, with a focal distance of about 3 cm, was purchased. Accordingly, a lamp and collector lens holder was designed (Fig. 27).

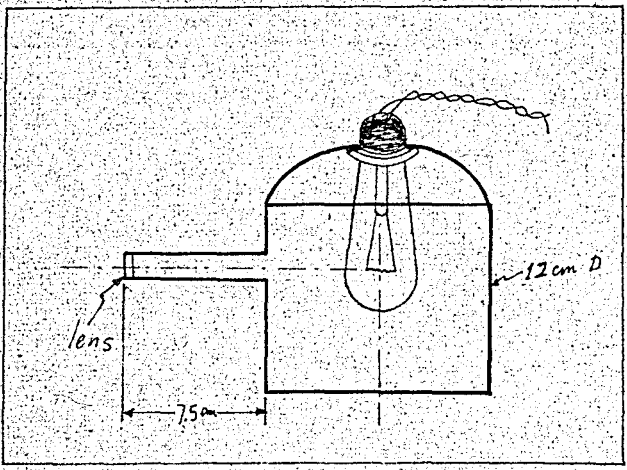

Fig. 27. Cross section of lamp holder and collector lens.

The cone angle for the incident light on the lens was 9.3°. The lamp being nearly at infinite distance from the lens, the image could be made as small as one centimeter in diameter, which is the size of the galvanometer mirror. However, it was noticed that focusing the image exactly on the mirror tended to diverge the light beam after reflection. If the image was formed just behind the mirror, the light reflected from the mirror converged and formed the real image a few centimeters in front of the mirror after reflecting. When this was done, only about half of the collected light fell on the mirror.

In order to distribute the light falling on the photocell over the surface of the photocell, another lens of the same size as the previous one was used. For this purpose, and also to prevent stray light falling on the cell, a cylindrical case was made for the photocell (Fig. 28).

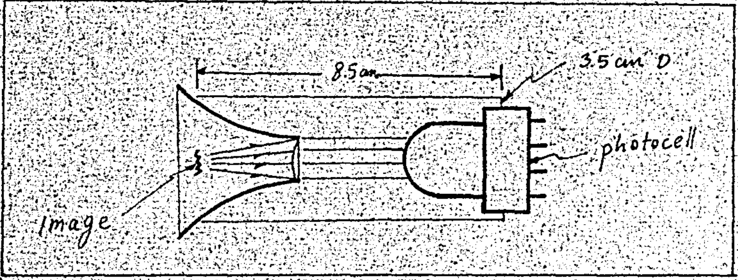

Fig. 28. Cross section of photocell holder.

d. The Relay. The more sensitive the relay, the less would be the required amplification, so that a simple one stage amplification could be possible. A good relay was found in the market with two coils, which could close or open five different circuits, and was said to operate at 14 and 28 milliamperes.

The range of this relay was tested in the electronics lab. It was found that it closed the circuit at 17.5 ma and released at 15 ma. Its internal resistance was 4 kΩ. These values were used in the amplifier design.

e. The Control Circuit and the Amplifier. In principle, as the light beam falls on the photocell it becomes conducting and causes a voltage drop across a series resistance. This voltage drop is amplified by an electron tube, and a current passes throught the anode of the tube. This anode current closes the relay, which in turn closes a circuit supplying part of the electrical power to the guard heater, and the guard power input is increased. Fig. 29 shows this circuit.

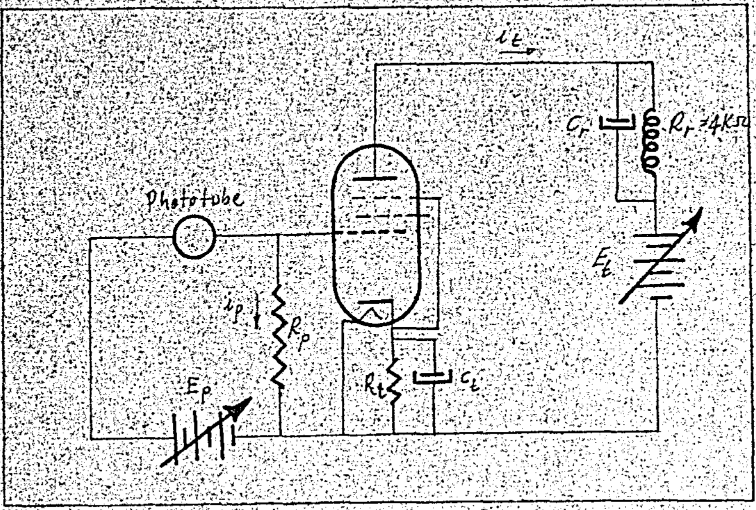

Fig. 29. The control circuit.

The photocell current was chosen to be 1 a. The current needed at the relay, i_t, was 20 ma maximum.

For the electron tube, a triode or a pentode would work. A pentode was selected since it was possible to modify the circuit if it did not work satisfactorily. From the Philips Electron Tube Catalog the pentode EL 86 was found to be sufficient with E_t = 100 V. or less.

Suppose that when the photocell is operating i_t = 20 ma. For maximum amplification the grid voltage of the electron tube should be as close to positive as possible but nevertheless not positive.

This required that the voltage increase due to photocell current in R_p should be very close to but nevertheless less than the bias voltage generated in R_t. Many combinations are possible that are about equally good. It was decided that the optimum would be found by trial and error. This gave $R_t = 500\Omega$, R_p = 7 MΩ, E_t = 92 V, E_p = 92 V. The voltages were purposely selected to be the same for convenience. The capacitances C_t and C_r were added to short circuit any a.c. components of input, and to short the inductive kick, respectively.

Although designed with these values, the design has versatility in that a regulated d.c. power supply was used for the d.c. voltage, which could be varied in operation to time the operation of the relay.

The filament voltage was taken from the d.c. power supply.

The power supply, light system and the amplifier-relay set are seen in Fig. 30.

In summary, temperature control was achieved as follows. When the guard heater is colder than the main heater, the unbalance is detected by differential thermocouples, the output of which moves the galvanometer mirror. The light falling on the mirror is then reflected to the photocell. A current passes through the cell causing a voltage drop in a resistance. This voltage drop is amplified by means of a pentode. The resulting current energizes the relay and the relay closes. This causes additional power input to the guard heater.

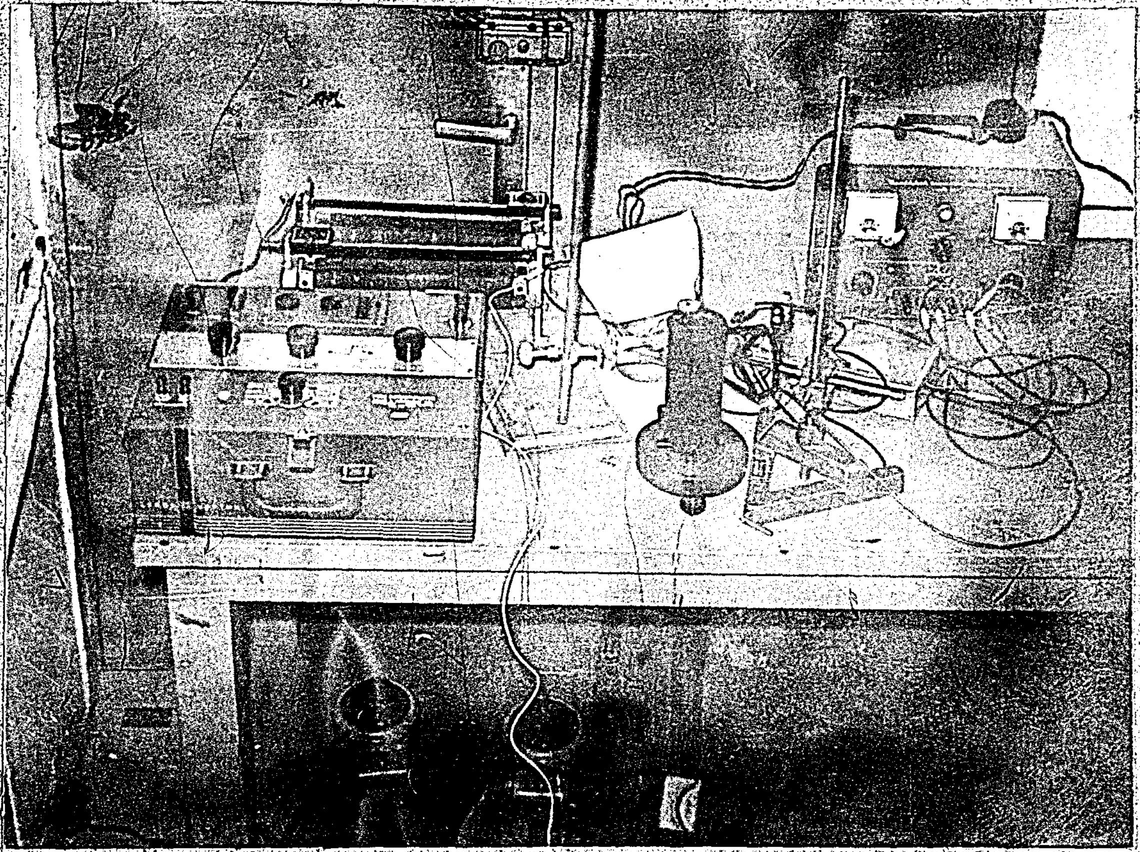

Fig. 30. Light system, power supply and amplifier in operation.

11. Electric Circuits

City power supply was used because of convenience. The inputs to the main and guard heaters therefore were both alternating current.

In order to control the input voltage easily, variacs were added to the circuits. Finer adjustments, which were necessary only with the guard heater, were made by rheostats connected as in Fig. 21.

In Istanbul, city power supply undergoes large fluctuations, therefore a voltage regulator was used.

For a complete circuit diagram see Fig. 21. The fixed and the relay rheostats were chosen as 40Ω, 1.1 amp, and 340Ω, 0.57 amp, respectively, after some trial calculations. However, during the test it was found that it is possible to have good control of balance with the relay rheostat shorted.

12. Main Heater

The capacity of the main heater was chosen such that the apparatus would measure the highest conductance specified in the ASTM standards. We have found previously that the power to one side for this purpose would be 400 Btu/hr (p. 34). By simple ratio, the amount that the main heater requires is

$$\begin{aligned} q_m &= 800\ (100/144) \\ &= 556 \text{ Btu/hr} \\ &= (556/3600)\ 1054.9 \\ &= 162.8 \text{ watts} . \end{aligned}$$

This determines the upper limit. At the upper limit we can take the voltage to be 110 volts. Then the resistance of the electrical windings must be able to give this power. That is

$$\begin{aligned} R &= \frac{E^2}{W} \\ &= \frac{12100}{163} \\ R &= 74.2\ \Omega . \end{aligned}$$

In the market, chrome-nickel strip resistance wire was found with 2.5 mm width and 0.1 mm thickness. Its resistance was 3.69Ω/m. This wire was wound around a 0.3 mm thick mica sheet with a wire spacing of 3.5 mm. This spacing is less than 3/16", and hence the copper plates are of sufficient thickness (see p. 32).

After making the heater, its resistance was measured and was found to be 73.2 , which was satisfactory.

The inductance of the heater was measured to be 0.58 mh, and the capacitance 0.45 μf. Both were negligible for all practical purposes.

13. Guard Heater

The amount of power required for the guard heater would be larger than 800 - 556 = 244 Btu/hr, because of heat losses to the environment. A 20 per cent heat loss was estimated, giving

$$q_G = \frac{(244)\ (1.2)}{3.415} = 85.6 \text{ watts}$$

Again considering the extreme case

$$R = \frac{12100}{86.5} = 140\ \Omega$$

With the kind of electrical wire used, the resistance of the guard heater turned out to be 128.9Ω.

This wire was 0.3 mm in diameter, and had a resistance of 10.1Ω/m.

14. Moisture Isolation

Moisture is a real problem in insulators, and must be guarded against. A moisture proof box design would have been very expensive, as it would require additional equipment. Instead, the apparatus was simply wrapped in cellophane paper. Dehumidification was still possible by using dessicants in the system, with or without previous oven drying of the specimen.

C. Construction

1. Copper Plates

These were manufactured by rolling into sheets, and then pressed under a hydraulic press. Since flatness of the surfaces of the cold plates was very poor, they were machined flat. Filing only was sufficient for the hot plates.

Both plates were heat treated before surface flattening so as to improve their thermal conductivities.

The manufacturer of the copper plates claimed that the copper was 99.9 per cent pure. However, a change of color was easily visible in the copper after machining. The effect of any impurities on the accuracy of measurements is not possible to evaluate.

The hot plates were painted on both sides with black stove paint to increase their emissivity. The cold plates also were treated with a thin layer of the same paint.

2. Main Heater

The resistance wire was wound on a 9.75" x 9.75" mica sheet of 0.3 mm thickness. Prior to winding, the mica surfaces were treated with a thermosetting resin (trade name "404"). When dried the resin secured flatness, and prevented any danger of contact.

The windings were parallel to one side. It was thought that diagonal winding was harder and not necessary.

Enamel coated thin wire, which was tested and found reliable, was used as lead wire. The heater wire was connected to the lead wire at the gap separating the main heater from the guard heater.

3. Guard Heater

The same thickness mica (0.3 mm) was used as in the case of the main heater. The mica was cut to the size of the sandwiching metal plates, and the surfaces were treated with the same resin. The heater wire was wound diagonally over the surface. The windings are schematically shown in Fig. 31.

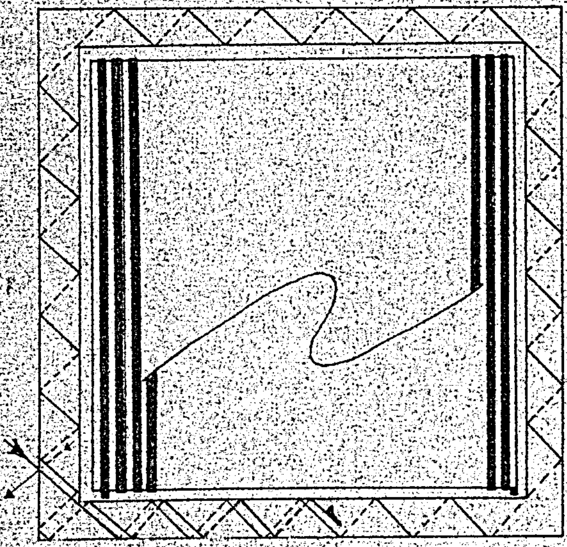

Fig. 31. The windings of the heaters.

After the heaters were completed, they were packed between two 12" x 12" 0.3 mm thick mica sheets, using the same resin as before, making a complete unit. The mica sheets both held and electrically insulated the heaters.

4. Thermocouples

In making the beaded junctions a 20 V d.c. battery system was found to be sufficient. The enamel coating at the tips of the thermocouple wires was scraped off just enough to hold with a pair of pliers. Then using a graphite rod as negative and the other two wires as positive, an arc was formed between the graphite and the tips of the wires. In this way, very small beads were obtained.

In order to make sure the thermocouples measured correctly, a calibration test was made. Having no reproducible temperature sources in the ME lab the thermocouples were tested against two reliable thermometers. The thermocouple junctions were placed in good thermal contact with the bulb of the thermometer, and the assembly immersed in warm water in an insulated container. Simultaneous readings were taken at two different water temperatures. The results are tabulated below. The capital letters THP, TCP, BHP, and BCP correspond to the thermocouples of the top hot plate, top cold plate, bottom hot plate, and bottom cold plate, respectively. Under each heading the first column gives the thermometer readings in deg. F, and the next two columns give the μV readings and the corresponding temperature.

THP			TCP			BHP			BCP		
^{o}F	mv	^{o}F	^{o}F	mv	^{o}F	^{o}F	mv	^{o}F	^{o}F	mv	^{o}F
154.5	3.550	154.7	154.0	3.540	154.3	153.6	3.525	153.8	153.3	3.516	153.5
115.5	2.405	115.8	115.4	2.405	115.8	115.2	2.339	115.7	115.1	2.395	115.5

It is seen that the error in the readings is less than one per cent in all cases and in all cases it is of the same order of magnitude. Since in measurements differential values are used the errors would tend to cancel. Considering also that the potentiometer sensitivity is 0.1°F the inaccuracy is negligible for the calculations of thermal conductivity. For the calculation of the mean temperature, the error introduced is negligible.

Therefore, standard tables were used, without correction, for converting emf output of the thermocouples to degrees Fahrenheit.

5. Ice Bath

A thermos bottle was used for this purpose with a cork cover and glass tubes of about ¼" in diameter. The glass tubes were filled with light machine oil which was assumed to be free of acids and the cold junctions were placed in the tubes with the accompanying copper leads.

6. Water Tank

The water tank was plastic. Top connections at the top provided for water inlet, and for discharge of excess water. One connection was made at the bottom for the water to the cold plates. (See Fig. 19 on p. 29).

7. The Amplifier-Relay Box

This item was made at the electronics laboratory of R.C. The final design is shown in Fig. 32.

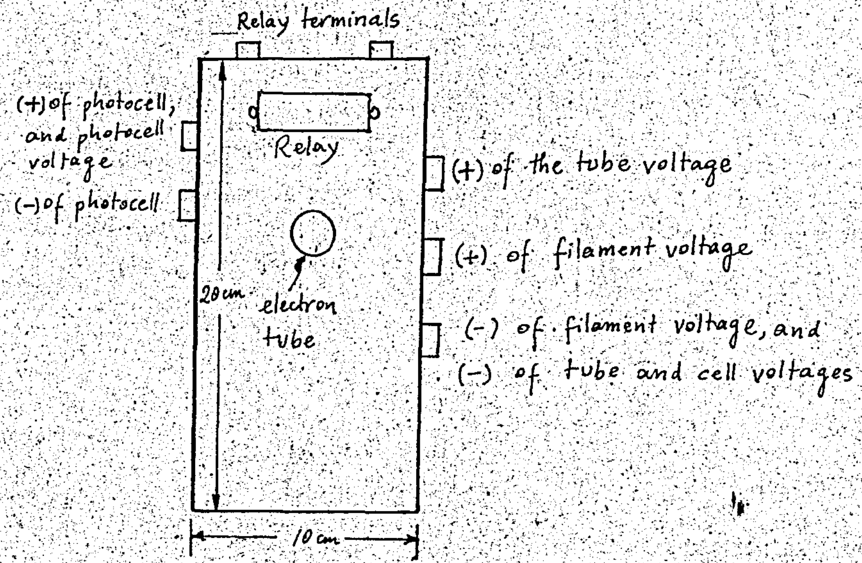

Fig. 32. Top view of amplifier and relay box.

The box was made of aluminum, which caused leakage problems. To eliminate this, the box, together with the photocell stand, has to be connected to the negative of the supply power.

D. The Range and Limitations of the Apparatus

The range of the operation was chosen to include conductances up to 10 Btu/hr-ft^2-^{o}F. This means a k of 10 Btu-in/hr-ft^2-^{o}F if the specimen is one inch thick. This is a very high value for insulating materials. However, this is by no means a deficiency of the apparatus, which can measure any k below this value by simply reducing the voltage.

The maximum operating temperature of the apparatus is probably very high, the upper limit being when the plates start to distort at high temperatures. This depends on the material of the plates, and remains to be tested.

The simplified cooling system has certain disadvantages. One of them is that steady state conditions may be upset by fluctuation in the water temperature. A test duration can be considerably shortened if water temperature is controlled. Tap water flow rate was constant for all practical purposes.

A second disadvantage of the simple cooling system is that at low mean temperatures a small temperature difference is maintained across the specimens, and therefore slight unbalances have a significant effect on the accuracy of the results. The water temperature can be made lower by using ice, but this presents practical difficulties.

Not controlling the air temperature also has disadvantages. It was seen in the error analysis for the square guarded hot plate, that when the air temperature approaches that of the hot plate large errors may result. This fact rules out the possibility of obtaining reliable results at normal room temperatures (around 65°F) when low mean temperature tests are conducted.

With this design the room temperature should not fluctuate significantly during a test. The guard heater input depends to a large extent on the surrounding temperature (see p. 23). Therefore any significant change in air temperature would upset the galvanometer balance.

In view of the above limitations, the tests conducted on the specimens were made during the evening when radiators are shut off and room temperature is almost constant, and when water flow rate is nearly constant.

III. TESTING

A. Preparation for Test

The first step in preparation would be to prepare the specimens.* The specimens should be cut into 12" x12" squares and should be checked for uniformity of density and thickness. Good contact between the plates and the specimen, and elimination of air pockets are important.

Stops may be necessary to fix the test thickness. If the specimens are not easily compressible, such as brick etc., it is sufficient that the specimens be put directly in the apparatus without any stops. If the specimens are easily compressible, such as glass wool etc., eight stops should be made, four for each side, such that during the test the specimens are not compressed more than the stops allow. Stops could be made of hard wood or similar material, but the thermal conductivity of the stops should be of the same order as the specimens themselves. The stops should be cut to exact size on a lathe or by some other means, and surface polish by fine sandpaper must be used to ensure uniform thickness. Wide stops may cause significant errors. Therefore, they should be made such that they barely cover the corners of the gap only. If the tested specimens are not highly compressible, a force-deflection curve of the specimens may be necessary. The ASTM standards recommend that the pressure on the specimens during the test be about 50 lb/ft^2. This is to minimize the effects of surface resistance. It is estimated that the top cold plate has a weight of about 30 lbs during operation.

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* Preparation of the specimens depends on their kind, and for detailed information Ref. 6 should be consulted.

The weight of the four hot plates and the heating unit is estimated to be around 15 lbs.

Thermocouple making was described above. The placing of the measuring thermocouples depends on the kind of specimen. If there is good contact and the specimens are compressible the thermocouples can be attached to the asbestos sheets and to the cold plates by scotch tape. In this case, since the thermocouples will sink into the specimen by a slight amount, the junction would read the correct temperature. If the specimens are rigid the thermocouples may be put in grooves of the cold plate, or, better, they can be placed on the specimen. However, the junction in this case should be as small as possible, since otherwise the junction would greatly alter the heat flow lines.

In order to make sure that the thermocouples are measuring correctly, they should be calibrated and checked for any inhomogeneities. There was no reproducible temperature source in the laboratory but some reliable thermometers were used for this purpose, as described above.

Moisture insulation and drying requires some preparation. If the test is to be a dry test the specimens should be dried in a ventilated oven between 215° - 250°F. If the specimens are not heat resistive they should be dried in a dessicator between 130° - 140°F.(6). It was found from the experiments that setting up the apparatus takes 30 to 50 minutes. Some insulators such as glass wool absorb moisture at a very fast rate so that oven drying or dessicator drying lose their meaning since during the setting up of the apparatus the specimens are exposed to humid air. Therefore it is suggested that the apparatus be set up with a good dessicant, with or without drying beforehand, the dessicant and the apparatus being kept together in a cellophane paper envelope. After sufficient time the test can start.

Before testing, and preferably after testing also, the density of the specimen, or a part of the specimen should be measured. The moisture in the specimen should also be determined by weighing after the drying.

B. Setting Up the Apparatus

First a cellophane bag is slit open at one side, and four holes are made at the bottom for the drain pipes. The bag is placed on the table on a sheet of soft cardboard or paper. Then the bottom cold plate is placed on the cellophane sheet passing the drain pipes through two of the holes. Then the specimen, the asbestos sheet, the plates, the heater, the top plates, the asbestos sheet, the specimen and the top cold plate are put in place and the two drain pipes are passed through the cellophane sheet. At each step the elements should be aligned. The differential thermocouples on the asbestos sheets should face the hot plates adjacent to them. Also the asbestos sheets and the measuring thermocouples should be so placed that the thermocouple leads come out of the apparatus at one corner only.

Then the bottom cold plate cooling water pipe is connected to the faucet and fastened with a piece of iron wire and the top cold plate pipe is fitted to the bare end of the flow divider.

After that, the guard heater terminals are connected to the power supply, and the apparatus is covered with the cellophane sheet. If a dry test is being made the dessicant is also placed in the sheet. The sheet is sealed with scotch tape so that there are no openings for air.

The plastic pipe connections at the faucet and the flow divider must be covered with wax so that there are no leakages. Then a weight is placed on the cold plate if necessary.

Now the electrical circuit, the control circuit, and the thermocouple circuits are connected as described on pp. 30 - 41.

The apparatus is now ready to start testing.

C. Test Procedure

Trial experiments indicated that in order to obtain steady state conditions in a short time certain procedures are better than others. Below the optimum procedure is described.

If the water is continuously flowing, the water temperature drops at night at the rate of about one degree per hour for a few hours, after which it is essentially constant. Therefore letting the water run for a few hours before a test should improve steady state conditions.

The first step is to read the temperature of the water. At a steady state the temperature of the water will probably be a few degrees Fahrenheit below this value. The cold plates being essentially at the same temperature as the water, add the intended temperature difference between hot and cold side temperatures, obtaining the hot side temperature at steady state.

Estimate the heat input to the main heater for the specified temperature difference. Operate the voltage stabilizer, and supply the main heater with about 20 times the estimated power by using the variac. Supply the guard heater with about 1½ times this power, and continually measure the hot side temperature. When the thermoelectric output comes near to that corresponding to the desired hot side temperature, reduce the main heater power to its right amount and reduce the guard heater power to 1½ times this power. Start the cooling water flow. Adjust the water flow rate using the flow adjusters, making sure that the flow paths are completely filled with water. After about 10 minutes check the hot side temperature to see if it is rising or falling. If it is rising, reduce the power a little; if it is falling, increase the power. Then connect the galvanometer leads, and turn on the control circuit. The galvanometer should be previously calibrated as to deflection vs. temperature, and as to the meaning of deflecting to the right or to the left in terms of the direction of unbalance between the guard and the main hot plate temperatures. The galvanometer should be level so that the mirror hangs with no friction.

Note from the deflection whether the guard is too cold or too hot, increasing or decreasing the guard power accordingly. After some practice the speed of rotation of the mirror should give a good indication of the degree of unbalance.

When the mirror deflection becomes very slow and there is good balance, reduce the guard power a little and place the photocell in front of the reflected light a small distance away from the point of exact balance. Try a 35Ω fixed resistance and short the relay resistance. If it does not reverse, adjust the power unit to the guard heater. When it reverses, make the oscillation equal on both sides by moving the photocell, varying the control circuit d.c. voltage and varying the relay resistance. The tests indicated that when the relay resistance was shorted the galvanometer oscillation period was about ten minutes.

Check the hot side and cold side temperatures. If there has been a significant change, find the rate of temperature change, and estimate the test mean temperature that will be reached. Acordingly make an adjustment of power.

If the two cold sides give different readings, vary the water flow by adjusting the flow adjusters.

When the temperatures change very slowly start taking readings of the power, the hot and cold side temperatures, the water temperature, and the room temperature at half hour intervals. Stop taking readings when the readings do not show any rising or falling trend, and when the variation in the readings during two hours is less than one per cent.(6)

D. Tests Made and Results

Altogether 14 tests were made. Twelve of these were made on glass wool containing bakelite (trade name IZOCAM-ITK) to determine the variation of the k of this material with moisture, density and mean temperature. Two other tests were made on styrofoam and corkboard to compare the thermal conductivity of these materials and of the glass wool, which are the principle insulating materials in the market at present.

1. IZOCAM : k vs. Mean Temperature

A total of six tests were made to determine the effect of mean temperature on the thermal conductivity of IZOCAM. Three of these tests were made consecutively without unpacking the apparatus. The specimens were not dried, and at packing, room temperature was 58.4 °F and dew point temperature 43°F, with 56 per cent relative humidity. These values were found by means of a sling psychrometer *. Density at packing was 1.06 lb/ft^3, with two per cent humidity by weight. The test procedures were essentially the same as explained previously. Fiberboard pieces were used as stops (Fig. 33). The stop thicknesses were 1.003" for the top side and 1.005" for the bottom side. The other dimensions of the stops were 1 1/2" x 3/4". For fiberboard the value of k is about 0.23 $Btu\text{-}in/hr\text{-}ft^2\text{-}{}^\circ F$ at 50° F.(5) This is close to the value of k for the tested material, and should not introduce any significant error. In all three tests the unbalance was negligible because the galvanometer deflected to both sides equally, the maximum amplitude for the unbalance being

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* See Appendix A.

approximately 0.15° F. In the guard power circuit the fixed resistance was 31.3 Ω in all three tests, and the relay resistance was shorted. In these tests as well as others the relay operated satisfactorily at 92 V photocell and tube voltages, although with slight modification of voltage. The main power readings were taken on a wattmeter, the readings of which were later corrected based on the results of a calibration of the wattmeter. Such a calibration was found necessary, as the readings on the wattmeter were suspected of inaccuracy. The thermocouple readings were taken on a potentiometer with a sensitivity of 3 μV.

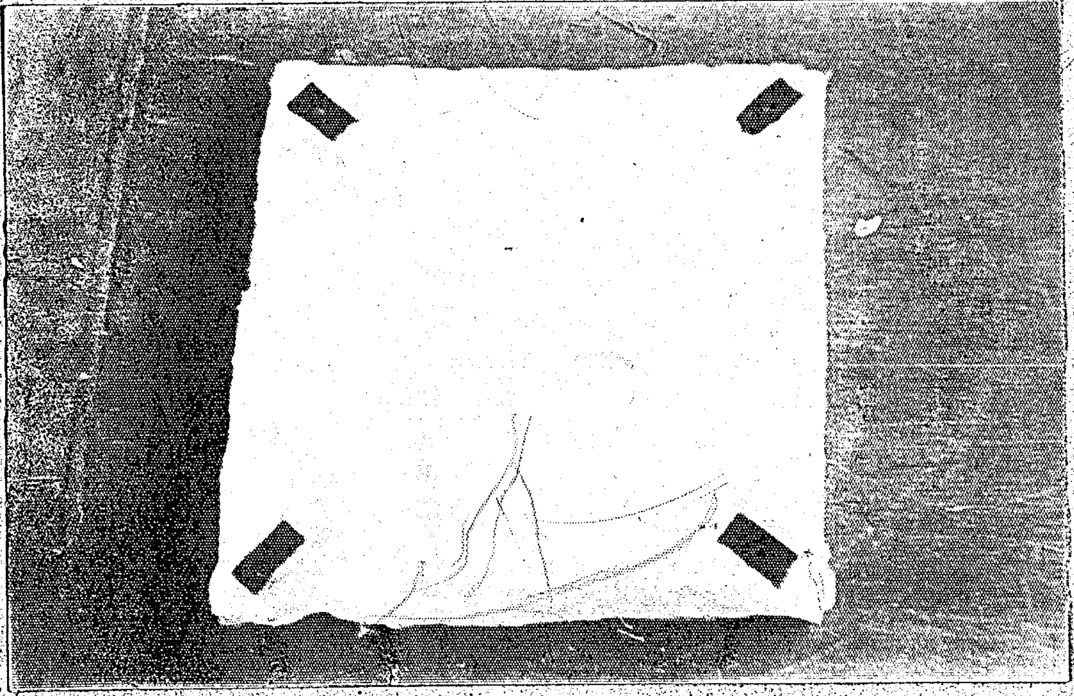


Fig. 33. The IZOCAM specimen with stops inserted.

The data for these and for all the subsequent tests are given in Appendix B. A sample calculation is given in Appendix C.

A second group of consecutive tests, consisting of two runs, were made under the following conditions.

The humidity values of the air were : Room temperature 56.5° F, dew point 47.5° F, humidity = 72 per cent. Drying was not used. The sizes and material of the stops were the same as before except that for the top and bottom sides they were 1.000" thick. The balance was good, the maximum amplitude of the oscillations being about 0.1° F. The resistances of the guard power circuit were the same. The power readings were taken on a voltmeter-ameter set and wattmeter corrections were not necessary.

Finally, another test was made at a higher mean temperature than the others (100° F) to obtain a better idea about the variation of k versus mean temperature. In this test, the moisture values at the time of packing were, dry bulb 69.5° F, dew point 52° F and 53 per cent relative humidity. No drying was used. The stop sizes were the same as in the previous test. The balance had a maximum of about 0.2° F with equal oscillations. The resistances of the electric circuit were the same as before. The power readings were taken by using a voltmeter and an ammeter.

The results of all of these tests are plotted in Fig. 34.

2. IZOCAM : k vs. Moisture Content

Two tests were made to determine any change in k when the specimens were dry. One of these was at low mean temperature and the other at high mean temperature. These temperatures corresponded to two temperatures of the previous tests so that a comparison would be possible.

The specimens were not dried in an oven prior to test. Instead, they were packed in the apparatus with about one kg. of $CaCl_2$, a common dessicant. Oven drying was not done because moisture absorbtion rate of Izocam from the air was found to be too fast for the packing time. It took about 10 minutes for a piece of Izocam to be saturated with the moisture of air, whereas the normal packing time was 30 to 50 minutes.

At the time the first readings were taken the specimens had been exposed to $CaCl_2$ drying for 12 hours.

After the first test the apparatus was not unpacked and the next test was run. At the time of the second set of readings which were at the higher mean temperature the specimens had been exposed to $CaCl_2$ drying for 26.5 hours.

The effect of $CaCl_2$ drying was also tested. A piece of specimen was packed with the apparatus and it was taken out after $5^1/2$ hours to determine the reduction in weight. It was found that while the initial weight of the piece was 11.420 gms., it was 11.4160 gms after exposure to $CaCl_2$. The same piece was oven and dessicator dried and then the weight was 11.416 gms. These values showed that $CaCl_2$ drying had been effective. The dimensions of the piece used were 20 cm x 26.8 cm x $\sim$ 3 cm. The top and the bottom areas of the specimen piece were not exposed to $CaCl_2$ drying when packed with the apparatus. Therefore by simple proportion we can estimate the time it would take for the specimens to reach the same dryness. The dimensions of the specimen and the surrounding insulation which was of the same material was 35 cm. Therefore $1.7 \times 5.5 = 9.5$ hours were enough to dry up the specimens. The fiberboard stop thicknesses were the same as in the first series of tests, with $\Delta x_{top} = 1.003''$, and $\Delta x_{bottom} = 1.005''$. Dry density was found to be 1.04 lb/ft^3. The unbalance was estimated to be about 0.15° F amplitude and symmetrical oscillation was maintained. The rheostats had the same resistances as before. The power readings were taken on the calibrated wattmeter.

There was no noticeable effect of drying on the value of k. The results are given in Fig. 34.

3. IZOCAM : k vs. Density

Four tests were made to determine the effect of density on the value of k at low temperatures. The mean temperature was chosen to be around 58° F, since in actual use the mean temperature is around this value.

During these tests the thickness of the fiberboard stops were varied on the same piece of specimens from 20.4 mm to 13.9 mm, thereby varying the density from about 1 lb/ft^3 to 2 lb/ft^3 (See Fig. 35). The other stop dimensions were as before, $1^1/2$ " x 3/4 ".

Two values from the previous tests were taken as additional points. The apparatus was unpacked after each test and different stops were inserted. This changed the moisture content of the specimens but since the earlier tests indicated that the effect of moisture is very small this effect was negligible. The specimens were not dried and as a measure of their moisture contents the dew points at packing are given (Fig. 35). Unbalance was controlled and was found to be uniform, oscillating around zero unbalance with very little amplitude. The guard power circuit was operated as before. The power readings were taken by a voltmeter-ammeter set. The same potentiometer was used for thermocouple emf measurement.

The results of these tests are given in Fig. 35.

4. Styrofoam

One test was made on styrofoam. No stops were used. The material was found to compress 0.5 mm under a force of 35 lb. In normal usage it is very unlikely that the styrofoam would be subjected to pressures higher than this; therefore the top cold plate being approximately 30 lb in weight no weight was used on top of the apparatus. This caused different compression of the two specimens but the change in density for the lower specimen being negligible (0.25 mm more compression, the thickness being ~30 mm) any effects of this were considered negligible. Thickness measurements were made on the apparatus immediately after the test.

At packing, dew point was 50.5° F, with 60% relative humidity. All the operation parameters were as in the previous three tests.

The test gave the value of k as 0.27 at a mean temperature of 57° F and at a density of 0.956 lb/ft^3.

5. Corkboard

The corkboard used had been the standard insulating material for low temperature applications before the advent of styrofoam and glass wool in Turkey. This corkboard is manufactured in a small shop at a rate of about 50 slabs per day and since it is not mass produced the properties may show fluctuations. The specimens as purchased were rather non-uniform in thickness and the surfaces were not flat. After considerable sandpapering the faces were made flat. However, uniform thickness was difficult to obtain. It was thought that in usage the material is rather non-uniform anyway, therefore the determination of k on a piece as it is used would be more indicative of the true insulating value. Accordingly, the test was run on flat but of variable thickness specimens.

The test thicknesses were measured on the appararus and averaged. Density was 13.1 lb/ft^3.

In order to minimize errors due to surface resistance a weight of 13 kilos was placed on the apparatus. The deflection curve of this cork indicated that the deflection difference between the top and bottom specimens would be about 0.12 mm ; thus any effects are negligible.

All other operation parameters were as before.

The value of k calculated from the test data was 0.29 at a mean temperature of 57° F, at a density of 13.1 lb/ft^3.

E. Discussion of Results

The results of the tests on k vs. mean temperature are plotted in Fig. 34 below. Also included are the two points obtained from the dry tests. One point, which was obtained under conditions leading to a significant uncertainty is not included in the figure. In this test room temperature was higher than hot plate temperature.

The tests conducted indicate one thing clearly and that is that the conductivity of Izocam does not vary significantly with moisture in the range of the tests. This fact is also stated in Ref. 5.

The value of the manufacturer appears to be correct for low temperature applications, which is usually the case with this kind of Izocam (Izocam-ITK).

The increase of the conductivity with mean temperature was found, however, to be steeper than the values of all the other experimenters. For comparison, Fig. 36 is presented below on p. 71. The differences may be due to the method of manufacture of the material. In the case of the

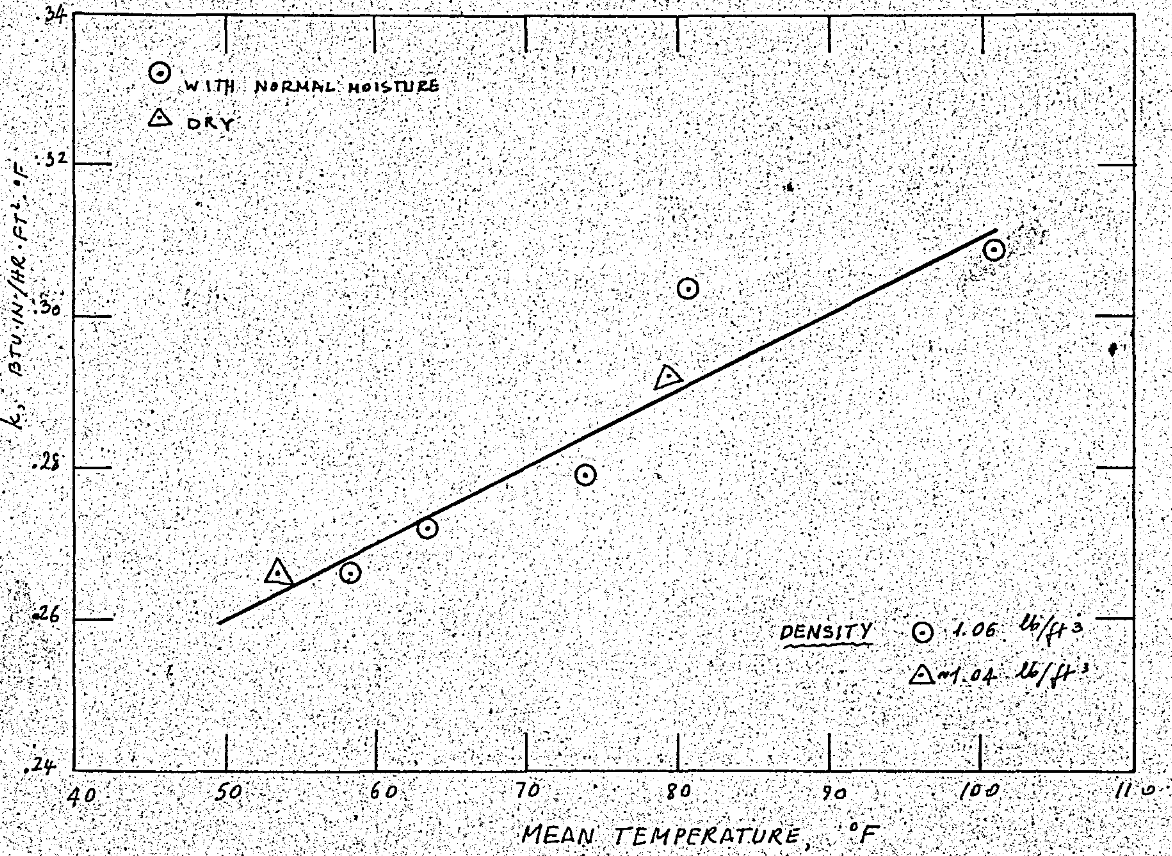
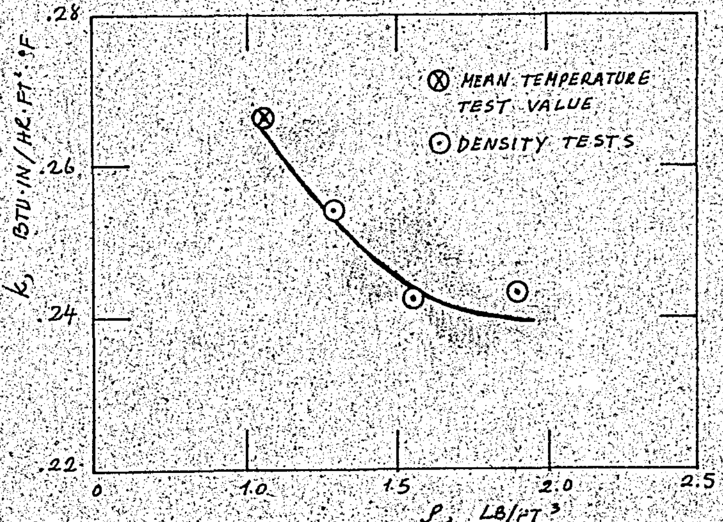


Fig. 34. IZOCAM: k. vs. mean temperature.



ρ	Mean T	Dew Pt.
1.06	58.0°F	43°F
1.29	58.4°F	50°F
1.56	57.9°F	51°F
1.90	58.4°F	57°F

Fig. 35. IZOCAM: k.vs. density.

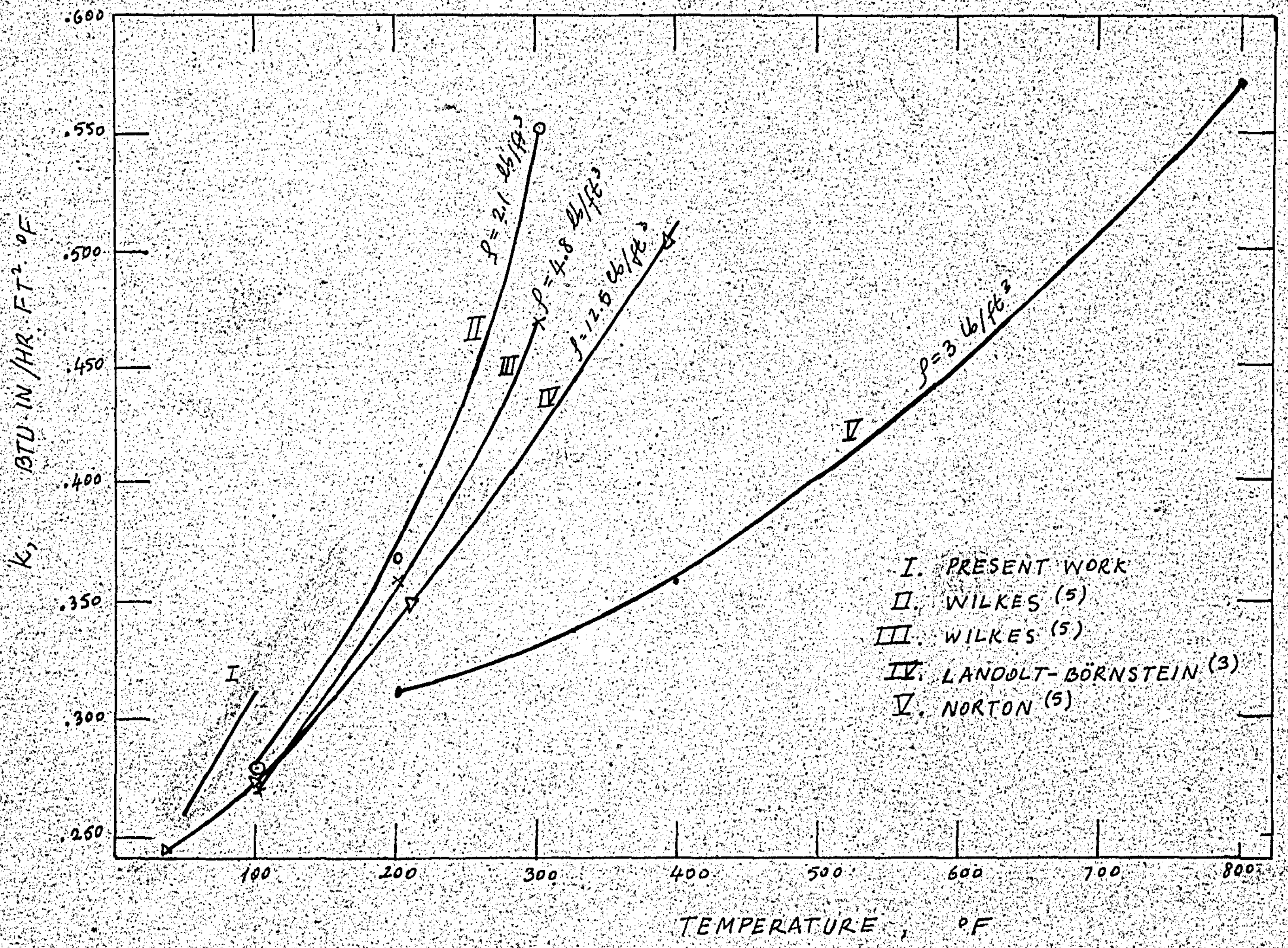


Fig. 36. Thermal Conductivity vs. Mean Temperature for Glass Wool and Izocam.

present tests the existence of bakelite as a construction material in the Izocam may have made a difference.

The scatter in the data of Fig. 34 amounts to about ∓ 2% , except for one point which is about 4% high and may be due to measurement errors.

Variation with density, which is plotted in Fig. 35,* clearly shows a decreasing trend as the density is increased from 1 to 2 lb/ft^3. The curve appears to pass through a minimum around 2 lb/ft^3 density, however with the data points obtained this result is not conclusive and more data points are necessary to reach a definite conclusion.

The values found for styrofoam and corkboard compare favorably with the available information on these materials. The manufacturer's value for styrofoam is 0.266 as opposed to the experimental value of 0.27 Btu-in/hr-ft^2-°F. For corkboard values gathered from the literature are around 0.30 Btu-in/hr-ft^2-°F,(3,5) and the experimental value is 0.29 Btu-in/hr-ft^2-°F.

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* With the exception of one doubtful point, for which room temperature was higher than hot plate temperature.

IV. CONCLUSIONS

A. The Equipment

The overall performance of the apparatus is satisfactory. The thermal conductivity of Izocam and styrofoam compare well with the values given by the manufacturers and the value for cork is close to the values available in the literature.

Accuracy of the apparatus may suffer at low mean temperatures because the temperature difference between plates has to be small since the coolant temperature is about 50 °F. This enlarges the effects of slight unbalances. Also at low mean temperatures the room temperature may be close to the hot plate temperature which introduces uncertainty about errors. The recommendations for this deficiency is using ice or some other means to further cool the water temperature, or, if possible to run the apparatus at night when room temperature is low.

No theoretical error corrections for the apparatus are necessary if room temperature is substantially lower than the hot plate temperature, if there is no unbalance, and if the specimen is about one inch thick. If there is unbalance, or if the sample thickness is other than one inch the errors can be estimated using the theory given on pp. 31-40. However no accurate estimation of error is possible if room temperature is close to that of the hot plate temperature.

Equilibrium time for the apparatus can be reduced considerably if constant water temperature is maintained.

In the testing of high k materials a large amount of heat must be supplied to the apparatus in order to obtain a good temperature difference between the plates. This heat upsets the uniformity of temperature on the cold plate, making it impossible to obtain accurate values. This limitation can be eliminated if the water flow rate can be increased.

B. Izocam-ITK*

The value given by the manufacturer is good for the range of mean temperatures between 50-60 °F. However the k vs. mean temperature curve rises rather sharply and the insulating value is sharply reduced at elevated temperatures.

No effect of normal amount of moisture on the k of Izocam was visible.

As the density of Izocam is increased from 1 lb/ft^3 to 2 lb/ft^3 k value reduces sharply. The appearance of the curve is suggestive of a minimum around 2 lb/ft^3 but the data obtained are not conclusive at this point.

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* ITK denotes the type of product, as given by the manufacturer.

APPENDIX A : INSTRUMENTS USED

1. Volt Potentiometer

Manufacturer : Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia 44, Pennsylvania.

Model : 8687

Serial No. : 1647111

Range : 0 to 1.601 and 0 to 0.1601 volt (two scales).

Accuracy : ∓(0.05% of reading + 3 V) for the small scale, and ∓(0.05% of reading + 30 V) for the big scale

2. Mirrored Galvanometer

Manufacturer : Leeds & Northrup Co., 4901 Stenton Ave., Philadelphia 44, Pennsylvania

Patent No. : 2285 G

Serial No. : 1576882

3. Regulated D.C. Power Supply

Manufacturer : Heath Co., Benton Harbor, Mich.

Model : PS-4

Inventory No. : 3034

Range : 0 to 150 and 0 to 400 volts on the built in voltmeter, 0 to 150 milliamperes on the built in ammeter

4. Ammeter-Voltmeter Set

Manufacturer : Hartmann & Braun

Model : Multavi II, GA 668

Serial No. : 1803062

Voltage Range : 0 to 6, 0 to 30, 0 to 150, 0 to 600 volts

Ampere Range : 0 to 0.003, 0 to 0.015, 0 to 0.06, 0 to 0.3, 0 to 1.5, 0 to 6 amperes

Smallest Scale Divisions : 0.5 volts on the 30 V scale and 0.05 amperes on the 1.5 ampere scale

Internal Resistances : For 0.3 ampere scale 4Ω, for 30 V scale 10000

5. A.C. Ammeter

Manufacturer : Triplet Elec. Instr. Co., Bluffton, Ohio

Model : 430 C

Inventory No. : 9357

Range : 500 milliamperes

Smallest Scale Divisions : 10 milliamperes

Internal Resistance : 1.6 ohms

6. A.C. Wattmeter

Manufacturer : Weston Elec. Instr. Corp., Newark, N.J.

Model : 432

Serial No. : 18442

Range : 0 to 50, 0 to 100, 0 to 200 watts

Smallest Scale Divisions : 0.5 watts on the 50 watt scale

Internal Resistances : For the voltage coil 14688 ohms up to 250 V, and 7344 ohms up to 125 V

7. Variable Autotransformers

Manufacturer : The Superior Electric Co., Bristol, Conn.

Type : 116 B

Frequency Range : 50/60 cycles

Phase : 1

Input Voltage : 120 V

Output Voltage : 0 to 140 V

Maximum Amperes : 10

Maximum Capacity : 1.4 KVA

8. Voltage Stabilizer

Manufacturer : General Electric Co., Fort Wayne, Indiana

Model : 9T91Y7158

Cycles : 50

Capacity : 0.5 KVA.

Serial No. : Har. Filt.

Input Voltage : 95 to 130, 175 to 235, 190 to 260 volts

Output Voltage : 118 and 236 volts

9. Rheostat

Range : 40 ohms, 3.2 amperes

10. Rheostat

Range : 340 ohms, 1.12 amperes

11. Phototube

Manufacturer : Pressler, Leipzig

12. Sling Psychrometer

Manufacturer : The Welch Scientific Co., 1515 Sedgwick St. Chicago

Inventory No. : 879

Range : 0 to 120 °F

Smallest Division : 0.5 °F

APPENDIX B : TEST DATA

In all of the data given below time is in hours, room temperature and water temperature are in degrees F, hot plate and cold plate thermocouple temperatures are in millivolts, power is in watts.

The test data are presented in the order that they are given in the section "Test Made and Results".

A. IZOCAM : k vs. Mean Temperature

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER
			TOP	BOTTOM	TOP	BOTTOM	
0.30	69.0	49.1	.995	.979	.486	.485	2.1
1.05	69.0	49.2	.995	.979	.486	.485	2.1
1.55	69.0	49.0	.995	.979	.486	.485	2.1
3.05	69.0	49.0	.995	.980	.486	.486	2.1

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER
			TOP	BOTTOM	TOP	BOTTOM	
17.45	57.5	47.8	1.320	1.306	.466	.464	3.8
18.15	57.5	47.8	1.320	1.305	.464	.464	3.8
18.45	57.5	47.8	1.319	1.306	.467	.461	3.8
19.10	57.5	47.8	1.324	1.306	.467	.464	3.8

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER
			TOP	BOTTOM	TOP	BOTTOM	
23.10	58.6	48.1	2.281	2.244	.515	.485	8.1
23.40	58.6	48.1	2.287	2.245	.512	.485	8.1
24.10	58.6	48.0	2.291	2.250	.511	.485	8.1
24.40	58.6	48.3	2.295	2.250	.515	.486	8.1

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
16.25	59.0	50.7	.936	.944	.541	.536	---	.1455
17.00	59.0	50.6	.940	.944	.540	.534	---	.1455
17.30	58.5	50.6	.940	.945	.540	.534	---	.1455
18.00	58.5	50.6	.940	.945	.540	.534	11.2	.1455

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
13.05	69.0	51.4	1.809	1.825	.586	.570	19.0	---
13.45	69.0	51.3	1.810	1.825	.585	.572	19.0	---
14.15	69.5	51.4	1.806	1.825	.583	.572	19.0	---
14.45	69.5	51.3	1.806	1.825	.583	.571	19.0	.245

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
24.50	67.5	49.2	3.395	3.380	.590	.568	30.0	---
1.20	67.4	49.2	3.396	3.380	.589	.570	30.0	---
1.50	67.1	49.2	3.395	3.380	.589	.572	30.0	---
2.15	67.1	49.2	3.396	3.380	.590	.572	30.0	.405

B. IZOCAM : k vs. Moisture

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER
			TOP	BOTTOM	TOP	BOTTOM	
18.15	60.0	48.6	.876	.864	.476	.476	1.75
18.45	60.0	48.8	.877	.865	.478	.477	1.75
19.15	60.0	48.7	.877	.864	.480	.477	1.75
19.45	60.0	48.7	.877	.865	.480	.480	1.75

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER
			TOP	BOTTOM	TOP	BOTTOM	
24.45	59.6	48.3	2.234	2.174	.515	.496	7.6
1.15	59.6	48.3	2.224	2.164	.514	.490	7.6
1.45	59.6	48.3	2.220	2.160	.515	.490	7.6
2.15	59.6	48.3	2.220	2.160	.515	.490	7.6

C. IZOCAM : k vs. Density

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
3.30	61.0	48.6	1.032	1.018	.465	.465	13.7	---
4.00	61.0	48.6	1.032	1.019	.465	.465	13.7	---
4.30	60.5	48.6	1.030	1.018	.465	.464	13.7	---
5.00	60.5	48.6	1.031	1.018	.465	.65	13.7	.177

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
3.00	61.6	48.6	.974	.970	.485	.485	13.6	---
3.30	61.6	48.6	.974	.970	.485	.485	13.6	---
4.00	61.6	48.6	.974	.974	.485	.485	13.6	---
4.30	61.6	48.6	.974	.974	.485	.485	13.6	1.77

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
5.00	65.5	49.4	.974	.970	.509	.509	---	.1985
5.30	65.5	49.4	.974	.970	.509	.509	---	.1985
6.00	65.3	49.4	.974	.970	.510	.510	---	.1985
6.30	65.1	49.6	.974	.970	.510	.510	15.45	.1985

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
16.30	70.2	48.8	.850	.850	.487	.487	11.95	---
17.00	70.2	48.6	.848	.849	.485	.485	11.95	---
17.30	70.0	48.6	.849	.849	.486	.486	11.95	---
18.00	70.0	48.6	.850	.850	.485	.485	11.95	.155

C. Styrofoam

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
17.00	64.5	49.3	.920	.916	.493	.493	9.95	---
17.30	64.3	49.3	.920	.920	.493	.493	9.95	---
18.00	64.3	49.3	.920	.920	.493	.493	9.95	---
18.30	64.3	49.3	.920	.920	.493	.493	9.93	.1305

D. Cork

TIME	ROOM T	WATER T	HOT PLATE T		COLD PLATE T		POWER	
			TOP	BOTTOM	TOP	BOTTOM	VOLT.	AMP.
4.10	67.0	50.2	.925	.920	.426	.516	---	.152
4.30	66.8	50.2	.925	.924	.429	.515	---	.152
5.00	66.8	50.2	.925	.923	.427	.515	---	.152
5.30	66.8	50.2	.925	.924	.428	.515	11.7	.152

APPENDIX C : A SAMPLE CALCULATION

The raw data is first used to obtain a k value from the one directional heat flow equation, which is later corrected by certain correction factors. These factors had to be employed since the internal resistances of the instruments affect the readings. Since in different tests different measuring instruments were used the correction factors are different. Below the values of these factors are given.

When there is a voltmeter in the circuit during operation and an ammeter is put in later, taking out the voltmeter, it can be found that the correction factor, by which the readings of the instruments must be multiplied is $(R + r)/R$, where r is the internal resistance of the ammeter, and R is the resistance of the load. In the measurements two ammeters were used, with $r = 4$ and $1.6\ \Omega$. The load resistance was 73.6Ω. Therefore the correction factors are 1.055 and 1.02, respectively.

When an ammeter is in the circuit during operation, and later the ammeter is taken out and a voltmeter is placed in it can be found that the correction factor is $R/(R + r)$. With the previous values for R and r the factors are 0.948 and 0.978. In these calculations any effect of the internal resistance of the voltmeter was neglected since its internal resistance was quite large.

The values taken on the wattmeter had to be corrected because it was discovered that it measured wrong. A calibration was made using the voltmeter-ammeter set of the measurements. The resulting curve is below.

Another correction is necessary for the lead wire resistance. The lead wires from the measuring instruments to the main heater windings are 0.4Ω. The heater itself being 73.2Ω the correction factor is 0.9946.

After the measurement corrections the thoretical corrections are made, the values for which can be found on pp. 22-27.

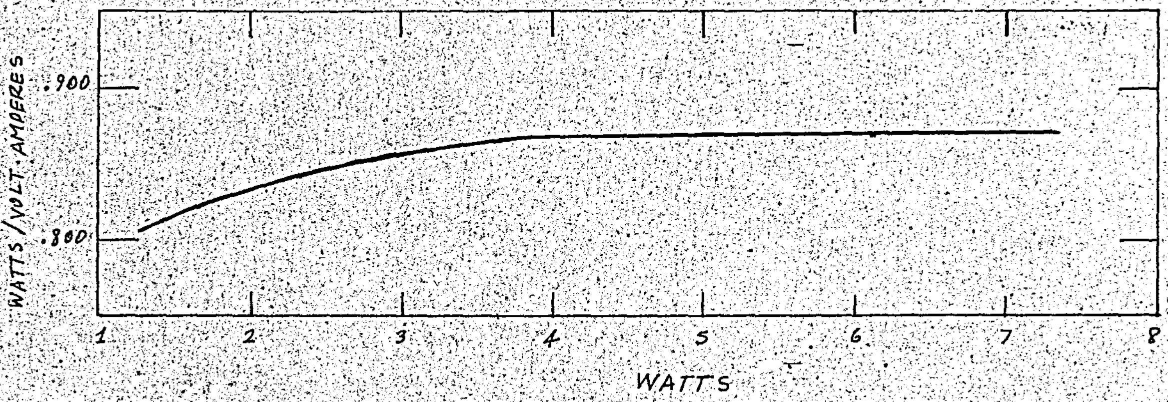

Fig. 37. Correction factor for wattmeter readings.

A sample calculation for ρ= 1.29 lb/ft^3 undried Izocam is presented below :

From Appendix B we have

Average top hot plate temperature	1.031 mV ($\mp$ 3μV)	68.6 °F ($\mp$0.1)
" " cold " "	.465 mV "	48.5 °F "
" bottom hot " "	1.018 mV "	67.9 °F "
" " cold " "	.464 mV "	48.5 °F "

Mean temperature of the specimens, from above, is 58.4 °F.

Top side ΔT = 20.1 °F

Bottom side ΔT = 19.4 °F

Top side Δx = 0.803"

Bottom side Δx = 0.804"

Top side (ΔT/Δx) = 25.0 °F/in.

Bottom side (ΔT/Δx) = 24.1 °F/in.

Average (ΔT/Δx) = 24.6 °F/in.

Total power = (13.7)(0.177)(3.415) = 8.27 Btu/hr

Power/2 = 4.14 Btu/hr

Test area = 100/144 ft^2

k = (4.14)(1.44)/(24.6) = .242 Btu-in/hr-ft^2-°F.

The voltmeter was in the circuit during the measurements, the ammeter being the ammeter of the voltmeter-ammeter set, therefore the power correction factor is 1.055. Then

k = .255

After correction for the lead wire resistance, by the factor 0.9946

k = .254

This value is subject to theotetical error correction.

The gap error is -1.07 % (p. 22).

The edge heat loss error is 0.875 % (p. 22).

No unbalance error since balance was obtained.

Total theoretical error is -0.195 % , which gives a correction beyond the accuracy range of the value, therefore is negligible.

Thus the value is k = 0.254 Btu-in/hr-ft^2-°F.

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