THE THERMAL CONDUCTIVITY OF MAGNESIUM BETWEEN ONE AND FOUR DEGREES KELVIN

by

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<u>ABSTRACT OF THESIS</u>

The Thermal Conductivity of Magnesium between One and Four Degrees Kelvin

By: Eugene G. Sharkoff

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The thermal conductivity of magnesium was measured at temperatures between 1.25 and 4.7 degrees Kelvin. A normal metal has a thermal conductivity which is directly porportional to the absolute temperature. Measurements on a sample of magnesium which was known to have an electrical resistance minimum showed a slight decrease over the values which would be expected from a normal metal. The values were noticeably lower than those anticipated in a normal metal at a temperature of 1.25 degrees Kelvin, and approached normal values until the temperature was approximately two degrees. Normal linear behavior was found between two and four degrees Kelvin. The normal thermal conductivity for the sample measured was found to be 0.082 watts per centimeter-degree per degree Kelvin. The departure from normality at the lower temperatures measured was in the same direction as that which one would expect if the phenomenon which causes the electrical resistance minimum were to affect the thermal conductivity of a material in the same way that it affects the electrical conductivity.

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INTRODUCTION

Measurement of the thermal conductivity of Magnesium is important as an aid to understanding the phenomenon which produces an electrical resistance minimum in magnesium. This electrical resistance minimum effect was found to be dependant to a large extent on the amount of manganese impurity present in the samples measured by H. E. Rorschach[1].

In normal metals, in the helium range of temperatures, lattice site scattering has become negligible. One would expect that impurity scattering of the electrons which conduct both the heat and the electricity would be independant of temperature, since the impurities are fixed, and their scattering cross section should be approximately constant. If these assumptions are true for a normal metal, then the electrical resistivity should be a constant, and by Sondheimer's prediction[2] that $L = \frac{K}{\sigma T}$ holds at temperatures much lower than the debye temperature provided L is higher than its usual value, $\frac{\pi^2}{3}\left(\frac{k}{e}\right)^2$ we arrive at the conclusion that for a normal metal, the thermal conductivity should be proportional to the first power of the temperature. Experiments on the thermal conductivity of copper[3] and aluminum[4], give this temperature dependance for the thermal conductivity. Since the resistance minimum in magnesium has been shown to be an impurity effect, one can only assume that the scattering cross-section of the manganese impurity, is temperature dependant in such a way as to increase the cross-section with decreasing temperature. This increase in cross-section should show up in thermal conductivity measurements as an additional decrease in the conductivity over that proportional to T as the temperature is lowered.

Historically, C. H. Lees[5] worked out the techniques for measuring thermal conductivities at low temperatures, in 1908, and actually made measurements of several metals down to 83^{o} K. Lees used platinum thermometers to determine the temperature gradient along a rod through which a known amount of heat was flowing.

Schott[6] and Gruneisen[7] used thermocouples as thermometers to make measurements in the liquid hydrogen range of temperatures. de Haas[8] used a single helium gas thermometer, and a known bath temperature to carry the measurements to the liquid helium range of temperatures, in 1934 and later.

The technique first used by de Haas has since been improved by the use of two thermometers inside the calorimeter which eliminates the errors introduced by the temperature drop at the interface between the sample and the bath.

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DESCRIPTION OF APPARATUS AND METHOD OF MEASUREMENT

A sample of magnesium approximately six inches long was machined to a diameter of .140 inches for about four inches along its center, leaving an enlarged portion on each end. One end was drilled and tapped to receive a 10 - 32 screw. The other enlarged portion was used to support a non-inductively wound constantan heater of approximately 110 ohms resistance. Cigarette paper was used to insulate the heater from the magnesium rod. Two lead rings were next cast around the smaller diameter portion of the sample, using a two-piece graphite crucible which fitted tightly around the magnesium rod. Casting the rings around the magnesium rod gave a shrink-fit to the rings. Since lead has a higher coefficient of thermal expansion than does magnesium, as the temperature was lowered, the rings gripped the sample more tightly, giving excellent thermal contact with the sample.

Two 100 ohm Allen-Bradley carbon composition resistors were then soldered to the lead rings. Differential contraction again aided in giving good thermal contact between the rings and the resistor leads. Allen-Bradley resistors were used because other experimentors have found that the leads remain in good thermal and electrical contact with the carbon composition at all temperatures used in this experiment.

The Calorimeter used to evacuate the space around the Mg. sample was made of Kovar-sealing glass with a Kovar cup at the bottom, and a five-lead press at the top. A pumping lead was taken from the top of the calorimeter which lead to a two-stage oil diffusion pump which worked in conjunction with a Cenco Megavac forepump.

A copper screw was inserted in the Kovar cup at the bottom of the Calorimeter, and the sample was screwed onto the screw. Differential contraction again insured good thermal contact. The leads from the resistors and the heater were number 44 copper wire, at least four inches long. Leads of this size give a very small heat leak from the sample while providing good electrical contact.

An A - C bridge excited by a 33 cps stabilized oscillator, was used in a null measurement to indicate either the resistance of the lower resistor, or the ratio of the upper resistor to the lower. These measurements gave the temperature of the lower end of the sample, and the temperature difference along the rod between the two resistors, which in turn gave the thermal conductivity when a known amount of heat was put into the heater at the top of the sample. The output of the bridge was put into a step-up transformer, then into a frequency selective amplified, with a gain of about 20,000, and then into a cathode ray oscilloscope which was used as a null detector. The noise level at the oscilloscope corresponded to an input at the bridge of about one microvolt.

The frequency selective amplifier was a standard piece of equipment in the low temperature laboratory which uses three stages of amplification, each of which has a twin tee network in the feedback path.

Temperature regulation was obtained by the use of a barostat pressure regulator which is also a standard piece of equipment. It was useful in the range between 1.6 and 4.0 degrees K. Below 1.6 degrees, the pump was set and the system was allowed to come to equilibrium before taking a measurement.

It was found that a pressure of less than 5×10^{-6} mm of Hg was needed in the calorimeter in order to prevent heat flow along the gas in the calorimeter from affecting the apparent thermal conductivity of the sample.

A Cenco Hypervac pump was used to pump on the helium bath surrounding the calorimeter for temperatures down to 1.6 degrees K, and a Kinney model DVD 8810 pump was used to reach the lowest temperatures reported.

A bottom-filling helium Dewar was used which greatly increased the efficiency with which helium was transferred. The bottom-filling Dewar makes use of the helium vapor for cooling the sample to the helium condensation point.

In order to obtain the thermal conductivity of the sample, one must know all the quantities except the thermal conductivity κ in the following equation which defines κ,

$$Q = \frac{\kappa A \Delta T}{L} \qquad \text{or} \qquad \kappa = \frac{QL}{A \Delta T} \tag{1}$$

where:

Q is the steady-state heat flowing along the sample

A is the cross-sectional area of the sample

L is the length of the sample between the two thermometers

ΔT is the temperature difference between the two thermometers

The resistors were calibrated both in the calorimeter and directly in contact with the helium bath, and were found to follow the law $\ln R = \ln R_0 + \frac{8.4}{T}$ (2)

Since we are only interested in ΔT which is small compared to T, we may differentiate, giving $\frac{dR}{R} = -\frac{8.4\,\Delta T}{T^2}$ (3)
Ignoring the negative sign, we find that $\Delta T = \frac{T^2 \Delta R}{8.4 R}$ (4)

With the bridge set-up used, we actually measured R and a quantity proportional to the ratio of the two resistors, both with and without the heat flowing through the sample. The measurement of R gives the temperature directly from equation 2 above. $\frac{\Delta R}{R}$ is obtained by dividing the difference of the two ratios by their average. We therefore have ΔT. $\frac{L}{A}$ was found to be 72.5 by measurement, and Q was determined by measuring the amount of current flowing through the 110 ohm heater. Thus the measurements taken give the thermal conductivity through very simple calculations.

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RESULTS

The thermal conductivity of magnesium was measured from 1.25 to 4.7 degrees Kelvin, and the results are shown in Figure 1 in graphical form.

The thermal conductivity of a normal metal is directly proportional to the absolute temperature at temperatures where the lattice conduction is negligible compared to the electronic conduction. Experimenters have found that lattice conduction is negligible compared to electronic conduction in the liquid helium range of temperatures. Solving the Boltzmann transport equation for the electronic thermal conductivity gives the normal metal behavior mentioned above. At 1.25 degrees, the conductivity was approximately 20% below the value to be expected from a normal metal. This result indicates that the mechanism which causes the electrical resistance minimum phenomenon to appear, acts at least qualitatively in the same manner on the thermal transport mechanism.

The scattering in the data at the lower temperature end of the experimental curve was due to a lack of sensitivity of the measuring equipment which was used. This lack of sensitivity was due to the very high internal impedance of the bridge as seen from the transformer primary. Since the impedance of the transformer primary at 33 cycles was about 2,000 ohms, and the bridge impedance varied from about 1,000 ohms to about 200,000 ohms at low temperatures, the loss in gain was enough to cause the loss in sensitivity which caused the scatter of points at the lower end of the experimental curve.

The points shown on the thermometer calibration curve are those taken on August 15 and 19, at the same time that the rest of the data was taken. It is interesting to note that the best representative curve for this data is the same as the best representative curve for those same thermometers when they were originally calibrated early in June, even though they have been used as thermometers at liquid helium temperatures at least ten separate times.

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SAMPLE CALCULATION

In order to find the thermal conductivity from the data taken during the experiment, the following things were done:

The temperature of the sample was determined from the resistance of the lower thermometer while the heat was flowing down the rod. Since the temperature difference along the rod was small compared to the absolute temperature of the sample, at all times, no appreciable error was introduced by considering the temperature of the lower thermometer that of the sample.

A quantity proportional to the ratio of the upper thermometer resistance to the lower thermometer resistance, was measured both with and without a known quantity of heat flowing through the rod. The quantity measured with the heat flowing was subtracted from the quantity measured without the heat flowing, and this number was divided by the average of the two readings. This calculation gives $\frac{dR}{R}$ which, when divided by the slope of the plot of $\ln R$ vs $\frac{1}{T}$, and multiplied by T^2, gives the temperature difference along the sample between the two thermometers.

Since the resistance of the constantan heater remains constant at 110 ohms over the temperature range covered in the experiment, the heat input to the sample was determined by measuring the current through the heater, squaring the current, and multiplying by the resistance of the heater.

The diameter of the sample between the two thermometers was .140 inches, making the area .10 square centimeters. The distance between the centers of the two lead rings was 7.25 centimeters, therefore $\frac{L}{A}$ is 72.5 cm^{-1}

K was obtained from the formula $K = \frac{L\,Q}{A\,\Delta T}$ with all the quantities known as shown above.

From the data taken on 15 August, at a sample temperature of 2.54° K, the resistance of the lower thermometer was 6,680 ohms, the quantity proportional to the ratio of the two thermometers without heat flowing, was 986.5. The quantity with 0.8 milliamperes flowing through the heater, was 955.7. The difference was 30.8, and the average, 971.1. T^2 was 6.45, and the slope of the resistance-temperature curve was 8.4. $\frac{30.8 \times 6.45}{971.1 \times 8.4} = \Delta T = .024^\circ$ K. $(0.8 \times 10^{-3})^2$ was $.64 \times 10^{-6}$. This quantity multiplied by 110 ohms gives $.704 \times 10^{-4}$ watts.

$$\frac{72.5 \times .704 \times 10^{-4}}{24 \times 10^{-3}} = .210 = \chi$$

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SUGGESTIONS FOR CONTINUED RESEARCH

The thermal conductivity of one sample of magnesium has been measured between 1.25 and 4.7 degrees Kelvin. The deviations from the behavior of a normal metal began to appear below two degrees.

In view of this fact, it would be wise to continue the investigation down to .8 or .9 degrees so that some more definite conclusions can be reached as to the correlation between the rise in electrical resistance, and the decrease in thermal conductivity with respect to the behavior expected of a normal metal.

The investigation of a series of samples including several with varying amounts of manganese impurity should be conducted to see whether or not the manganese impurity has the same quantitative effect on the thermal conductivity as it does on the electrical resistance.

Some attempt should be made to carry measurements up to the maximum in the thermal conductivity curve, or at least to the point where one first finds the electrical resistance begin to rise. This investigation might be accomplished by making a controlled poor thermal contact between the sample and the resistor. The sample could then be made to rise considerably above the bath temperature, and measurements could be extended upward in temperature.

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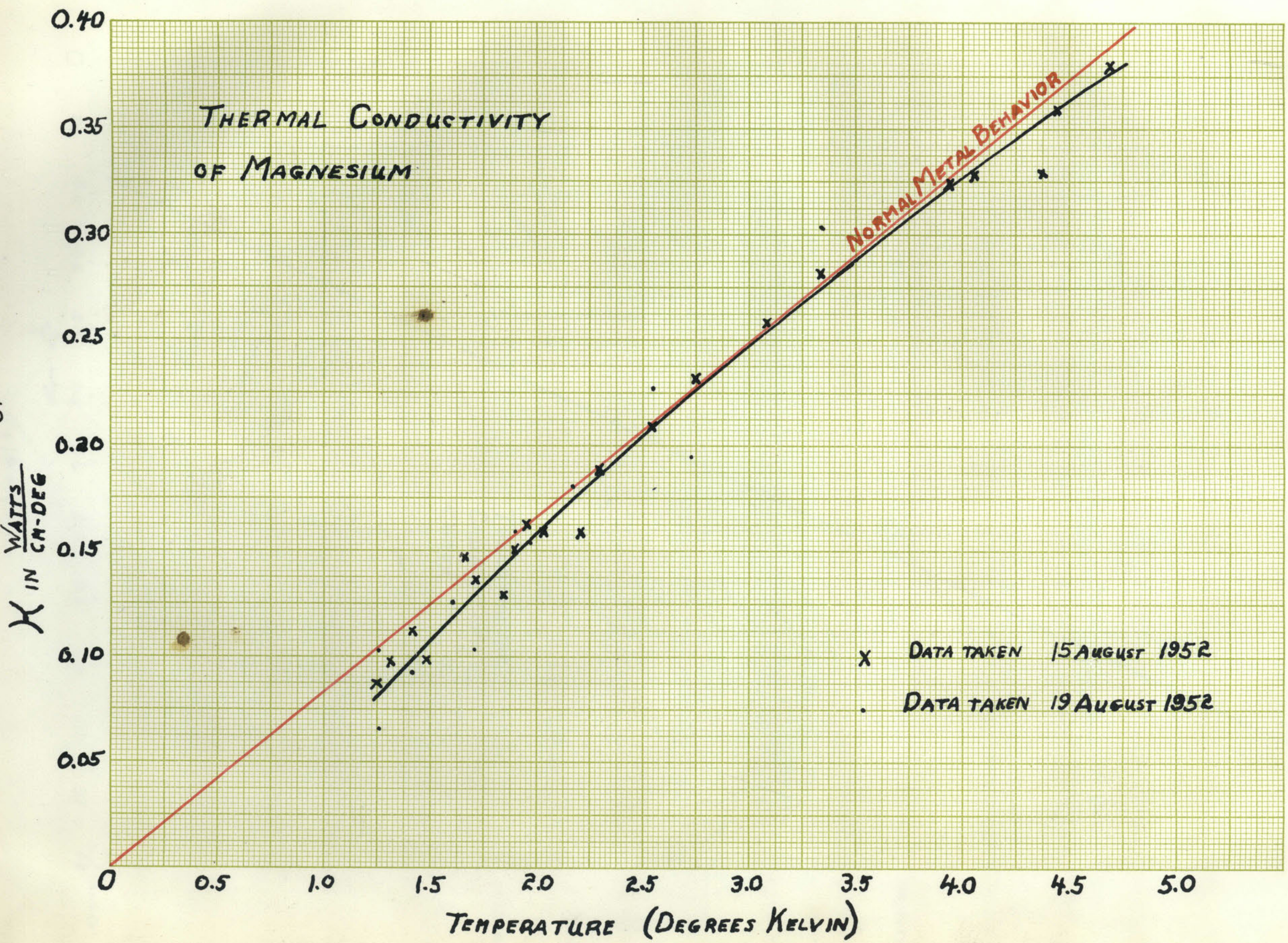
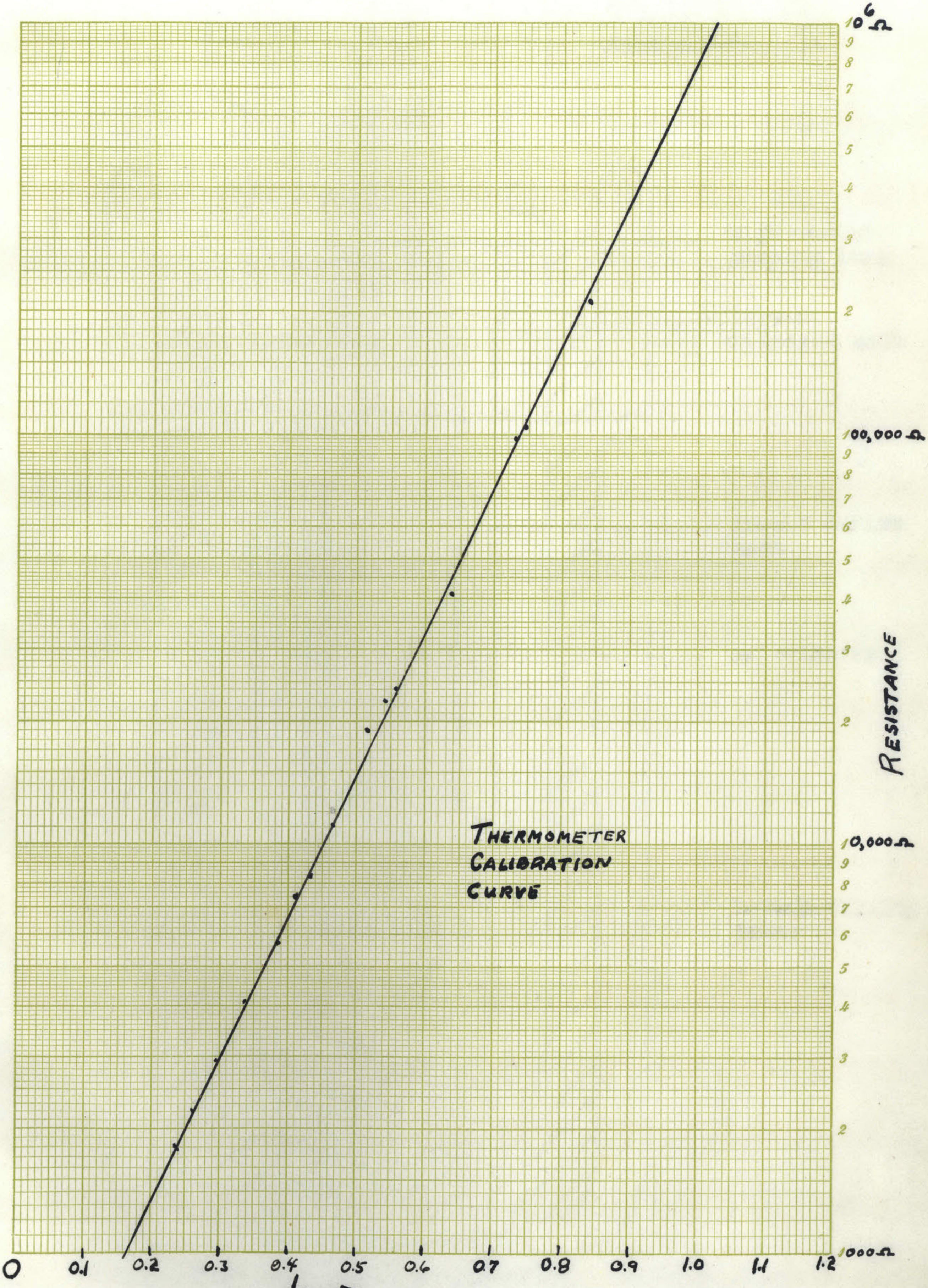

Thermal Conductivity
of Magnesium
Normal Metal Behavior
X Data taken 15 August 1952
• Data taken 19 August 1952
K in Watts / cm-deg
Temperature (Degrees Kelvin)
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

Figure 1

FIGURE 2



THERMOMETER
CALIBRATION
CURVE
RESISTANCE
$10^6 \Omega$
100,000 Ω
10,000 Ω
1000 Ω
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
$\frac{1}{T}$ →

FIGURE 3

CALORIMETER
AND DEWAR
ARRANGEMENT

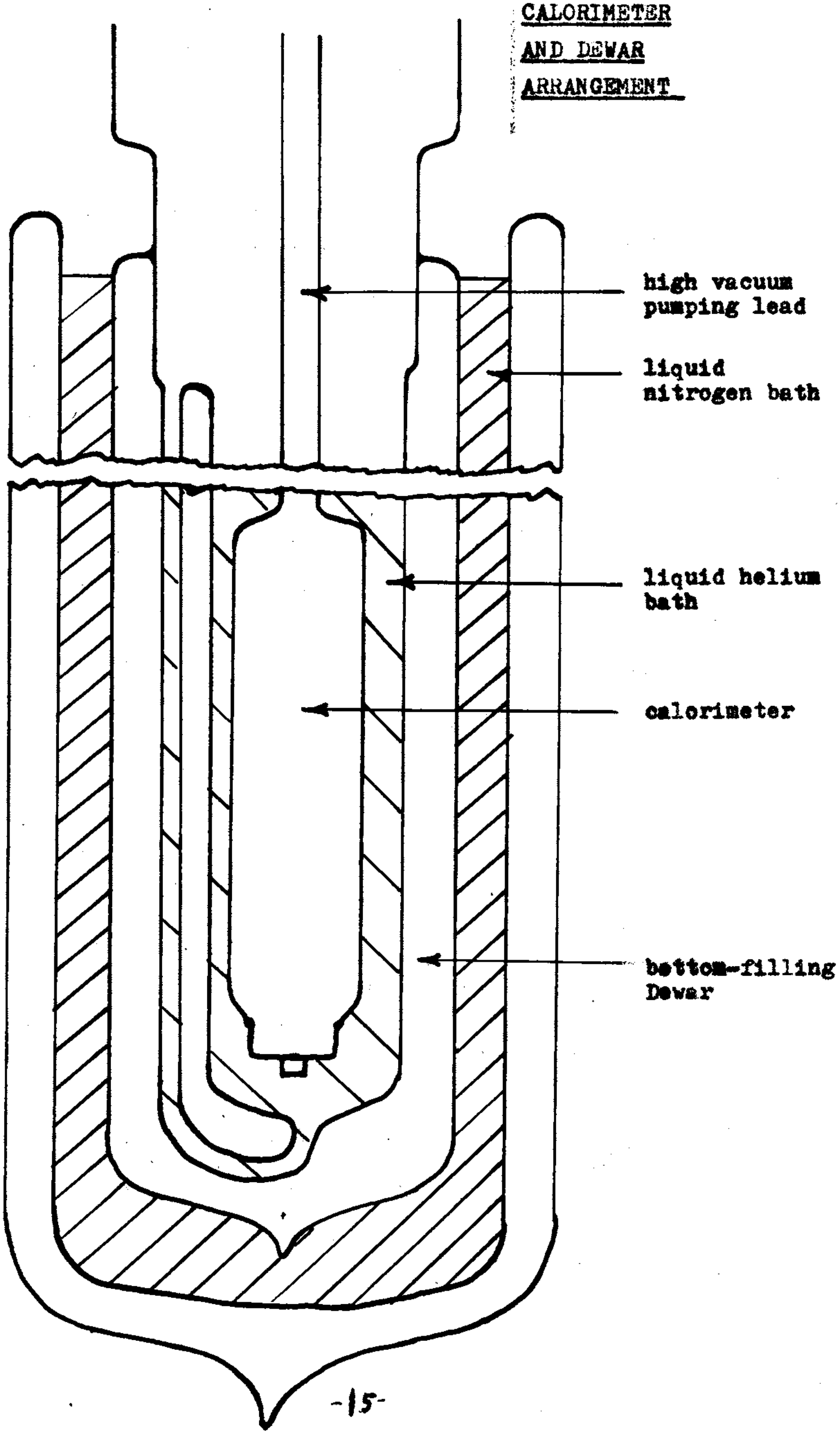
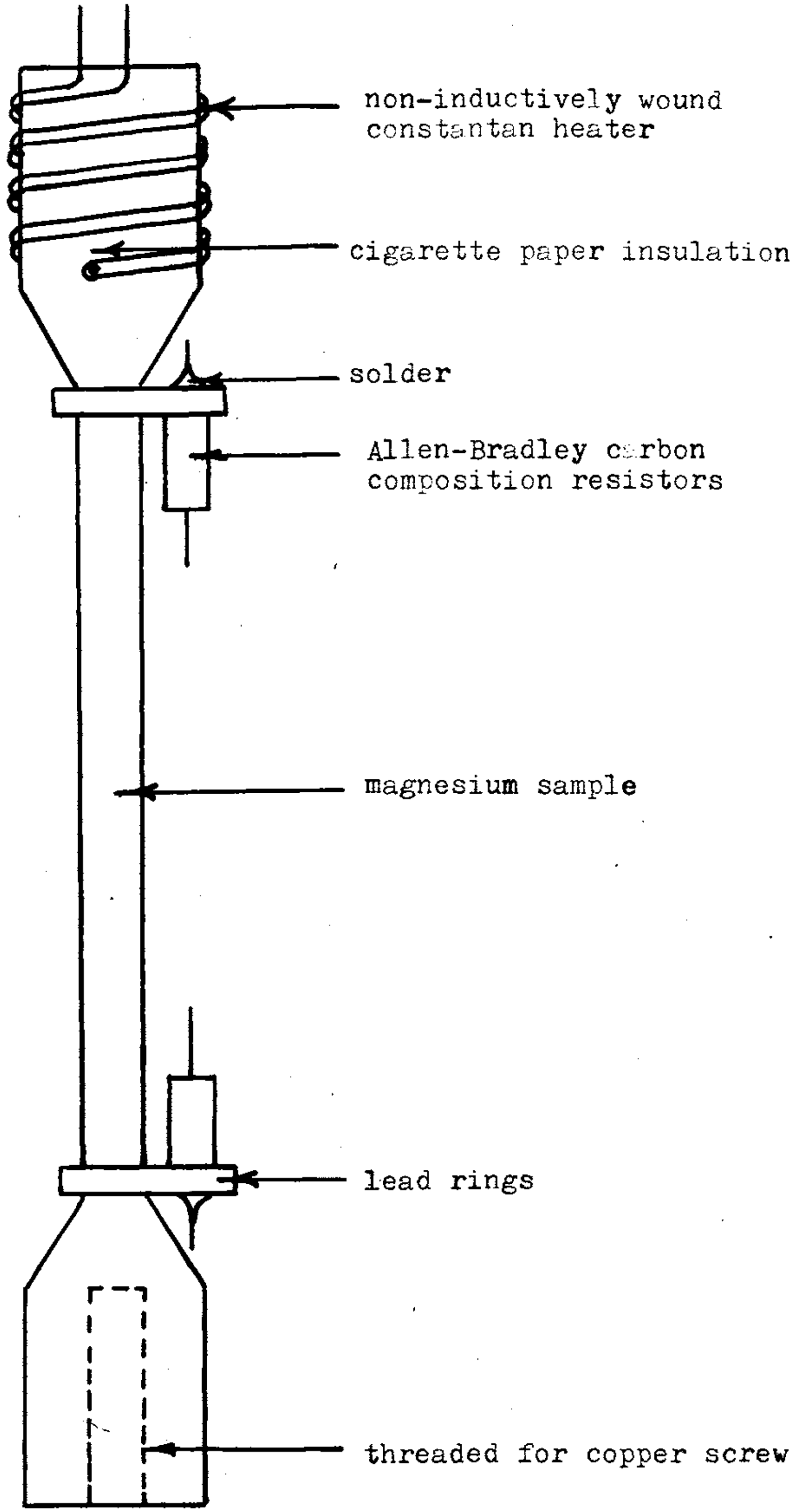


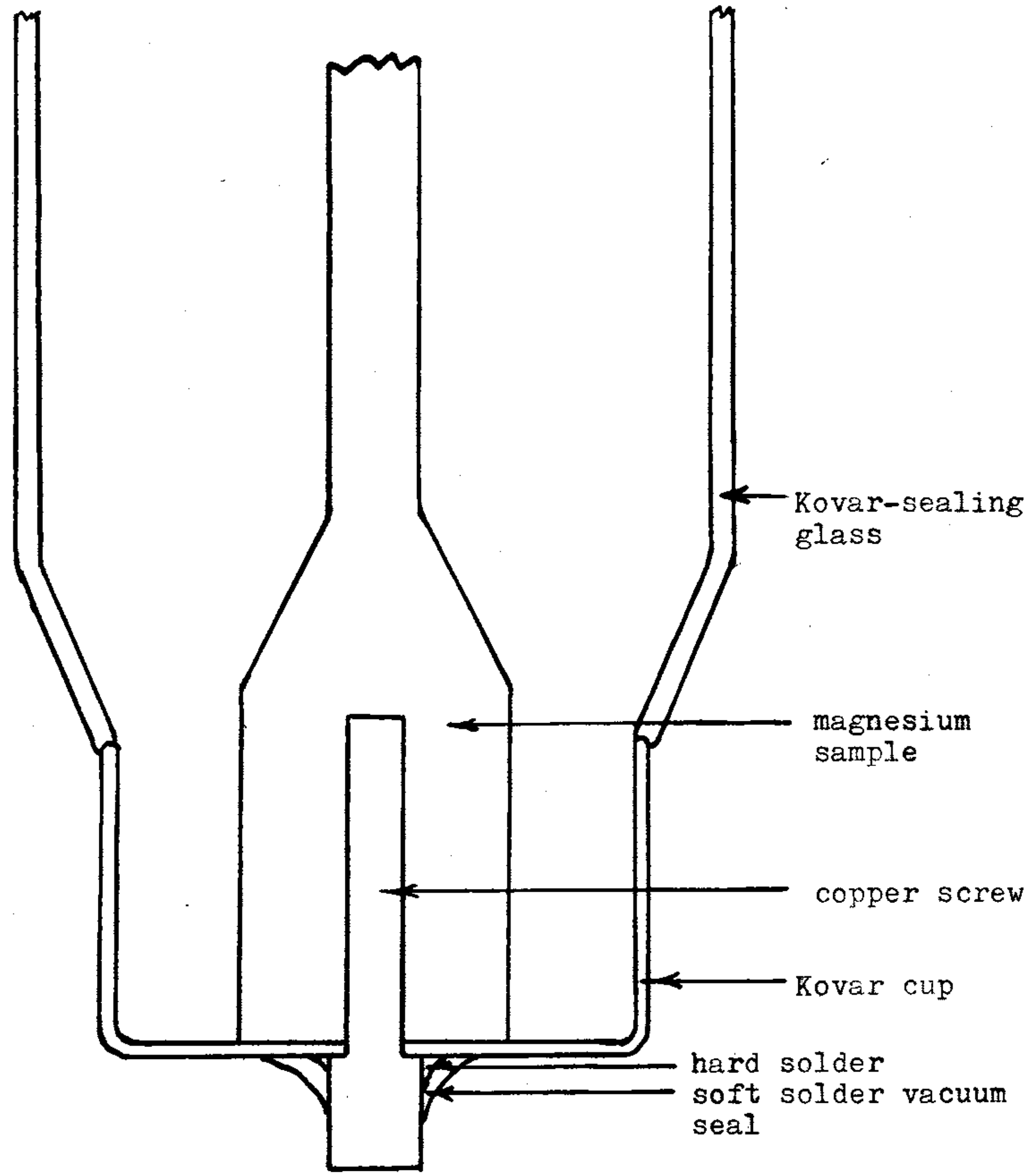
FIGURE 4



SAMPLE WITH THERMOMETERS AND

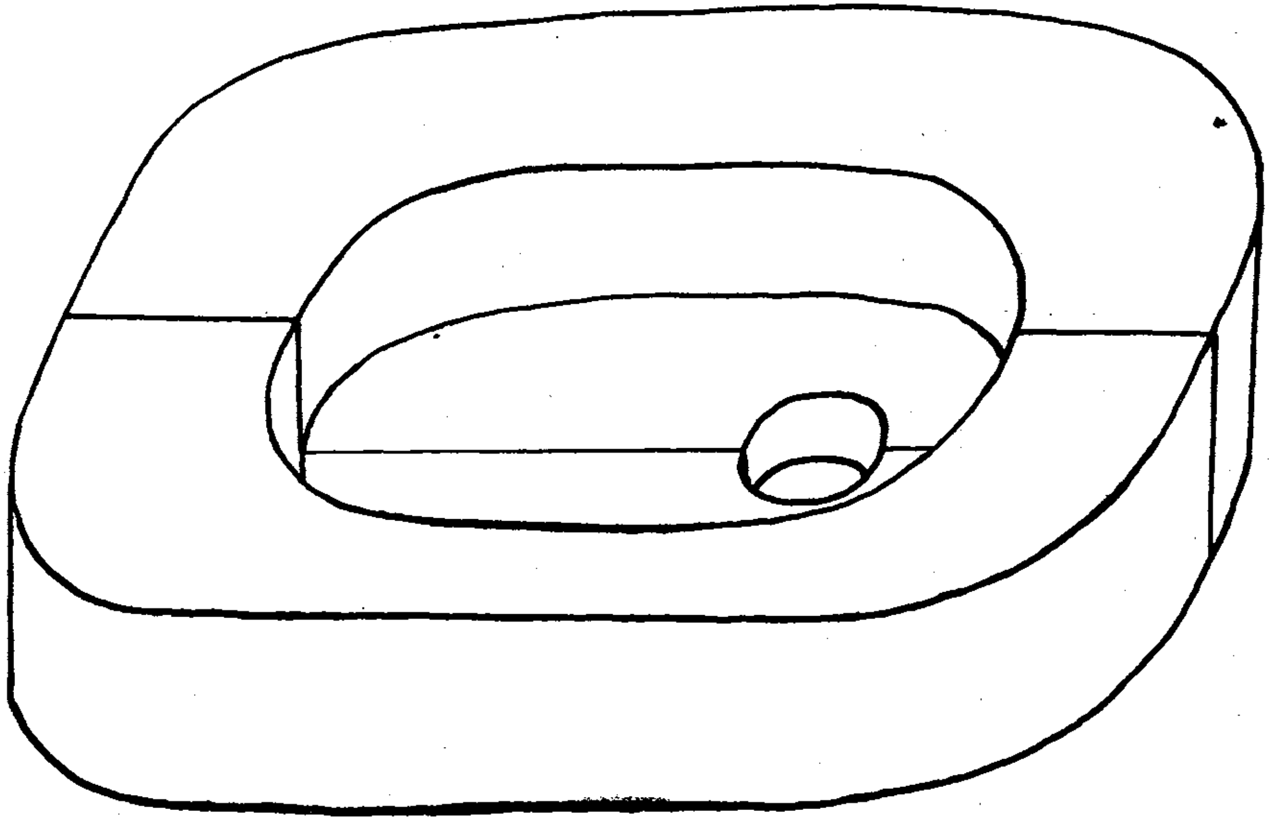
HEATER ATTACHED

FIGURE 5



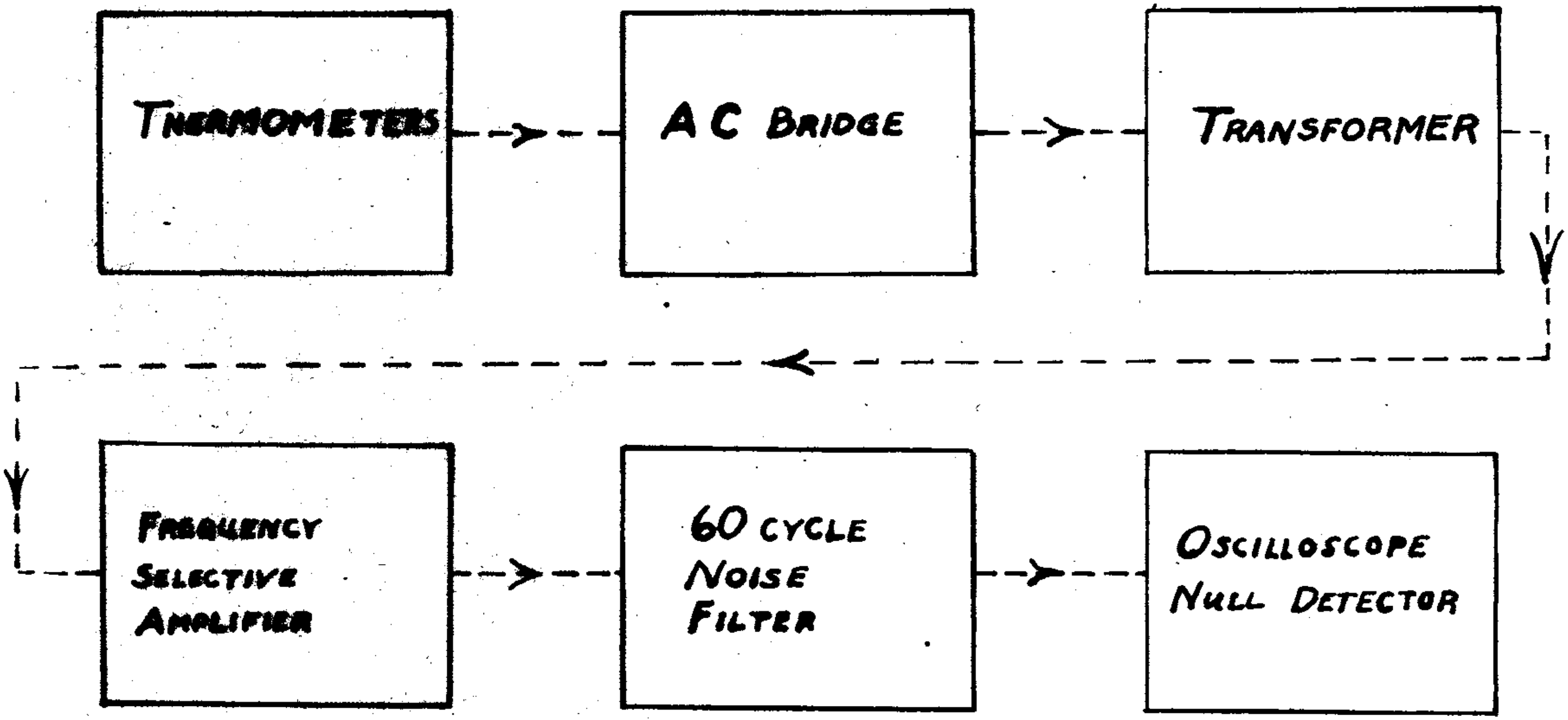
SELF-TIGHTENING JOINT FOR USE AT LOW TEMPERATURES

FIGURE 6



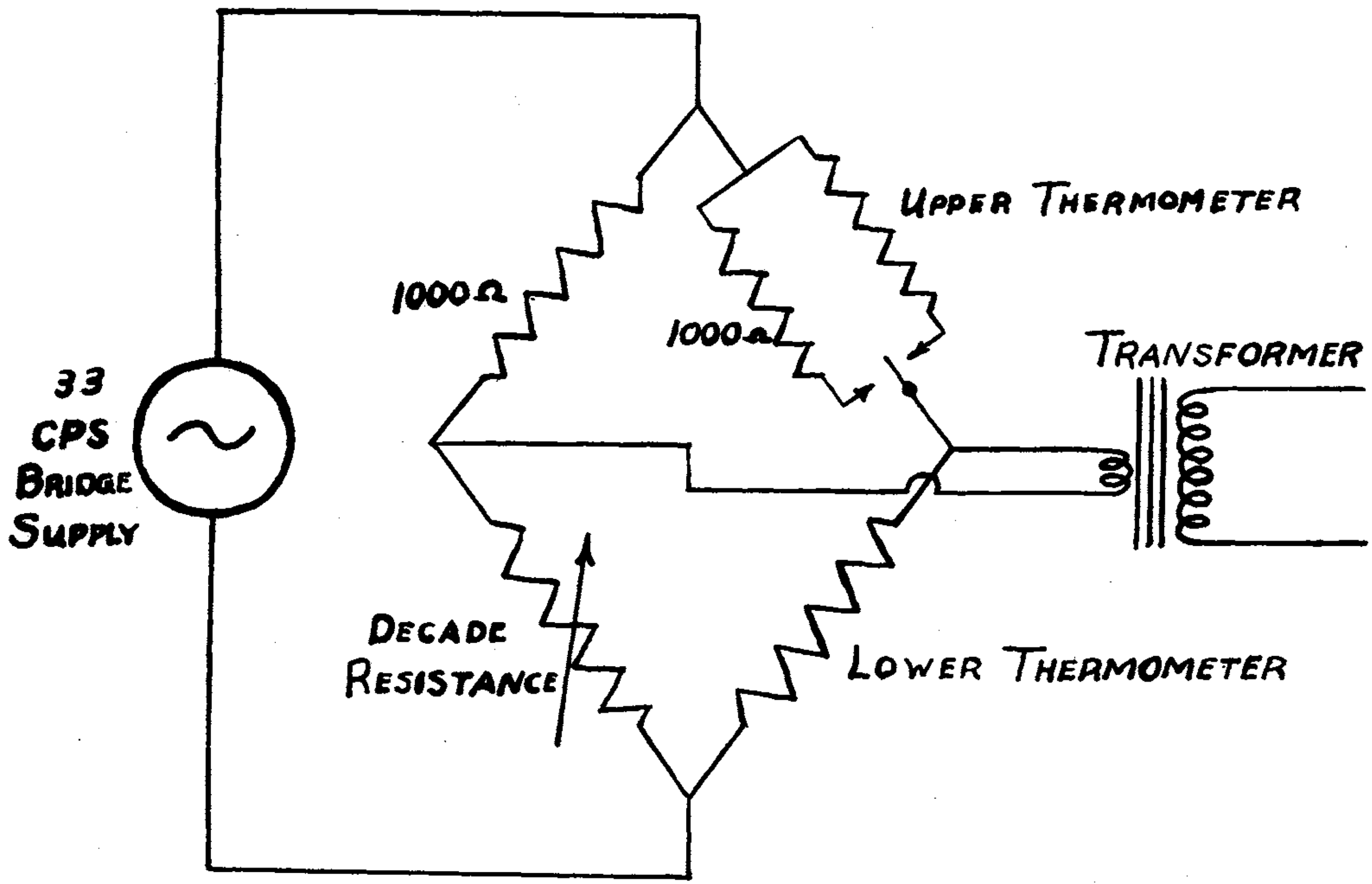
TWO-PIECE GRAPHITE CRUCIBLE

(USED TO CAST LEAD RINGS AROUND SAMPLE)



BLOCK DIAGRAM OF ELECTRONIC EQUIPMENT

FIGURE 7



A-C BRIDGE

FIGURE 8

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