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THERMAL CONDUCTIVITY OF BRAIDED SUPERCONDUCTOR SYSTEMS*

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ABSTRACT

Heat transfer within a superconducting matrix as in magnet coils is of importance to magnet designers. This paper describes a series of experiments designed to give engineering values of the thermal conductivity within two heterogeneous braided superconductor systems. The systems tested and the experimental procedure are described. The results are presented along with a comparison to a mathematical model.

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INTRODUCTION

A program to measure the thermal conductivity of braided superconductor in several epoxy supported coil forms has been in progress for the last two years. This paper covers only this portion of the program which also included determination of baffling on heat transfer and the surface coefficients for both liquid and supercritical helium.

The apparent or overall thermal conductivity of four systems, has been measured parallel and perpendicular to the width of the braided conductor. The experimental apparatus and procedure is described and the reduced experimental thermal conductivity presented for both directions at various temperatures. A mathematical model using the solid conduction equation is presented for comparison.

Experimental Equipment and Instrumentation

A. System Configuration

In this program of thermal measurements, four systems were considered, namely:

1. Superconducting braid in a reinforcing matrix of clear epoxy.

2. Copper braid similarly reinforced for comparison of thermal properties with (1) above.

3. Copper braid in a matrix of aluminum powder-filled epoxy for gauging the effectiveness of high-conductivity fillers in improving overall thermal characteristics of the structure.

4. Superconducting braid in a matrix of silver-tin eutectic (presently under development by A.J McInturff, et al.).

B. Thermal Test Sample Construction

In order that test results might be meaningful to the current dipole prototype construction program, the superconducting braid used in the above systems was spared from the program inventory. Physical features of the superconducting braid, i.e., wire diameter, lead angle of weave, etc., were duplicated in the copper braid to effect a direct comparison with systems using the superconducting counterpart.

Each of the systems described above find form in a two-layered assembly of pancake-type coils of braid. The coil layers were formed by wrapping the braid on a motor-driven spool which aligned the turns and sized the width of the loose braid.

Coils (1) and (2) above were vacuum impregnated with a mixture of Epon 815 Resin and Epon U Curing Agent. (Miller-Stephenson Chemical Co.) In the process, the winding assembly served also as a potting fixture.

Collaring the outer diameter and removing one of the faceplates of the spool, the epoxy was admitted edgewise to the braid. Eventual sectioning of the test coil showed that thorough penetration of the epoxy had taken place in the interstices.

Epon 815 and U were used also for the filled epoxy system. The aluminum powder filler introduced constituted 37 volumetric percent of epoxy-filler mixture. Higher concentrations of filler produced mixtures too stiff for what was considered to be good wetting of the braid. It also made it difficult to attain the same packing factor in the turns of braid as that of the unfilled system. The coil pancakes were laid up wet to insure uniform distribution of the filler throughout the matrix.

The half-coil blanks of the eutectic/superconductor braid were wound in a bifilar fashion with an interleaving of 0.003-in. thick, B-stage epoxy-loaded glass tape between turns. This system was analyzed in anticipation of a working dipole configuration which has yet to be finalized. However, it is believed that its thermal properties will be a reasonable representation of that found in the end product.

Each coil half was wound and bonded individually. After curing, the annular surfaces of each were machined to form blanks 5/8-in. thick. Matching coil halves were bonded together with epoxy. The outer and inner diameters of the monolith were then machined to form a test specimen with 5½-in. o.d. X 3-in. i.d. X 1¼-in. thick.

C. Specimen Carrier Assembly

In determining thermal conductivity, the classic approach was used; heating one surface of the specimen electrically, cooling the opposing parallel surface and measuring the thermal gradient between the two at steady state conditions (adjoining surfaces being insulated).

Thermal conductivity both normal and parallel to the braid was investigated with the use of the Test Coil Assemblies I and II respectively

(Figs. 1 and 2). The heating unit in both assemblies was a commercial item ordered from stock.

In Assembly I, a 500 W, 240 V ring heater was used, having an inner and outer diameter matching that of the test specimen. A 3/16-in. thick copper plate was interposed between the specimen and heating unit to uniformly distribute the heat over the transferring surface. The plate was soldered to the heater sheath to become an integral part with it and then machined flat to assure intimate contact with the test specimen.

With the exception of the center plug, which was fabricated of glass-bonded mica (Mykroy), the main housing components were machined from acrylic stock. The insulating effect of these parts was supplemented by overlays of polystyrene foam (Styrofoam).

In addition to their thermal insulating properties, the materials were selected on the basis of difference in inherent expansivity which was used advantageously to effect sustained sealing of insulated surfaces. "Mobilite" lubricating grease was introduced into a 20 mil clearance separating cylindrical interfaces of housing and specimen. Because of the relative expansivities of the mating components this clearance reduced in cool down. It was found that the grease sealant had the ability to retain enough plasticity throughout most of the temperature range of cool down to allow the excess formed to redistribute and flow out of confined areas before destructive stresses could generate.

The design concepts of Assembly II essentially followed along the same lines as the above. As a heat source an 800 W, 240 V band heater was clamped to the outside cylindrical surface of the test specimen, overlapping it slightly.

D. Temperature Sensing System

For measurement of temperature, five thermocouples were arrayed as shown in Figs. 1 and 2 over the cross-sectional area of each test specimen. The thermocouple harnesses were made of 0.005 mil Chromel and Au 0.07 at. % Fe wire. The junction of each thermocouple was formed by spiraling several closely-packed wraps of the Au wire about the Chromel and soldering the junction by immersing in a pool of Indium Alloy #1 (250°F melting temperature). Thermocouple size was minimized by cutting off all but about three turns of wire forming the junction.

The thermocouple monitoring surface temperatures were bonded in place with epoxy. Internally placed thermocouples were implanted by drilling 0.020-in. diam. holes from one annular surface to the interface of the coil halves into which the thermocouple was bottomed. Prior to insertion, each of these thermocouples were encapsulated in a 0.018-in. diam. core of epoxy 5/8-in. long. The core assembly was formed by inserting the joined thermocouple wires into a casing of Teflon tubing into which epoxy was drawn. Following curing, the excess epoxy-filled tubing extending past the junction was severed and the Teflon casing was removed. Being equal in length to the depth of the drilled hole, the length of the core served to indicate any hanging up of the thermocouple on insertion, and gave assurance as to its correct positioning. By gathering and stiffening the wires, the core also made insertion easier and with a coating of adhesive for bonding in place, provided complete filling of the drilled hole.

A null detector microvoltmeter was used to measure in microvolts, the temperature difference between each of the five thermocouple sites and the helium bath. A low resistance rotary thermocouple switch was introduced into the circuit to facilitate taking of data. Supplementary remarks describing the instrumentation of this system may be found in Informal Note CMS-26 where application was also made.

E. Test Coil Assembly Support Fixture

Some details of the fixture for suspending the test coil assembly in the helium bath are shown in Fig. 3. The fixture basically consists of the coil supporting, centrally located tube, surrounded by four equally spaced tubes providing access for leads to the coil assembly and helium to the dewar. Thin-walled tubing (0.015) was used to minimize heat leakage. Three baffle stages of acrylic-overlaid polystyrene foam joined the tubes into a rigid assembly.

One of the access tubes it will be noted is terminated with a heat sink which serves to prevent the reference junction from being influenced by any outlying source of heat. The heat sink is comprised of two copper blocks between which the reference junction is clamped.

Transition of the thermocouple wires to high purity 0.015-in. diam. copper lead wire is made with soldered connections at the phenolic terminal board capping the heat sink. The lead wires are spooled on to the terminal board to assure adequate tempering. A lead brought in from outside the dewar constitutes a finite heat leak which if allowed to proceed unimpeded to the thermocouple junction, could give rise to a significant error in measurement. This effect can be minimized by tempering, whereby increasing the length of submerged lead wire, most of the heat is imparted to the cryogen before reaching the thermocouple.

Experimental Procedure

Prior to immersion into the liquid helium, the test assembly was thoroughly precooled in a bath of liquid nitrogen. The helium dewar was prefilled with enough liquid to produce a head of 4 in. over the top of the submerged coil assembly. Liquid level soundings and additions, when required, were made via the transfer tube to maintain complete submersion throughout each run.

With the assembly at bath temperature, null detector reading of all thermocouples was taken for application as an index correction to subsequent readings. Power was then applied to the heater in 50 MV increments to a maximum of 300 MV. The output of all thermocouples at each increment was recorded when steady state conditions were arrived at. For each voltage increment a corresponding current reading was recorded for computation of heat flux. After final readings were taken the specimen was allowed to cool to bath temperature and the procedure repeated for a second time.

Discussion of Experimental Results

The raw temperature data for a given thermocouple, for successive tests at the same heat flux, did not vary more than ± 2.5%. However, there were variations of as much as 25% between adjacent thermocouples at the coil midplane. This gave cause for concern until the raw data was plotted, which showed that the relationship between adjacent thermocouples, was always a constant percentage regardless of the heat flux. The conclusion from this was that the thermocouples were reading correctly, but that a placement error was accounting for the variation.

A two-layer test specimen was chosen for the course of this investigation, as opposed to a single coil of reinforced braid, in order to lessen the effect of thermocouple placement error and to improve the resolution of the temperature distribution, by increasing the cross-sectional area. However, the interface of this configuration produced a thermal gradient between coil halves that could not be disregarded, being clearly reflected in the temperature readings. With the acquisition of data completed, each coil was sectioned and ground along the radius on which the thermocouples were placed, exposing the junction. In addition to providing precise information on the thermocouple position, the section also yielded excellent definition of the interface separating the two coils. Interface thickness and thermocouple position were measured with the use of a Gaertner toolmaker's microscope. A 30X optical system was employed to make the measurements to 0.001 in. The thermocouple coordinate measurements were made to be the centroid of each junction.

With the interface thickness measured and the thermal conductivity of the epoxy known from published data, the thermal gradient across it could be determined for each heat flux. This gradient was applied as a correction to the gradient across a given coil half, taking into account the actual position of the thermocouple junctions and the interface thickness. With the application of this correction, agreement between the calculated values of conductivity for the upper and lower halves was greatly improved. Some scatter is still present in the plotted data in spite of the corrections. This is not altogether unexpected in view of the fact that the specimens are of a heterogeneous nature having a complex heat transfer mechanism. The actual heat flux, as determined by the measured heater power, was corrected for losses through the shields before the thermal conductivity calculations were made.

The curves of Fig. 4 reflect the average conductivity over the temperature range shown. A change in the apparent thermal conductivity with temperature is undoubtedly a reality but is obscured by the scatter. It will be noted that the scattering is especially pronounced with the eutectic filled braid. As may be readily observed from the curves, the eutectic greatly enhances the thermal conductivity of the system. The material used was a first effort product and the interstices were not uniformly filled, which gives a variable cross section for heat transfer. The results speak for themselves and point out clearly how poor a heat conductor a superconductor is. Using a filled epoxy offers about a 25% increase over the unfilled system. This improvement is not so significant as to conclusively justify its use since it also complicates coil fabrication. The superiority of the eutectic fill from a heat transfer standpoint is clearly evidenced.

In contrast to the conductivity parallel to the braid, the results of heat flow perpendicular to the braid are shown on Fig. 5. As would be predicted the thermal conductivity is an order of magnitude lower and any advantages of filled epoxy is clearly shown. The conclusion must be drawn that there is little value, from a cooling standpoint, to be gained from cooling surfaces parallel to the braid. There is an obvious increase in thermal conductivity with temperature. At least a portion of this is attributed to the fact that there is some conduction circumferentially due to the way the braid is wound in the test coils.

Mathematical Check of Experimental Results

An effort has been made to verify the experimental results by straightforward calculations. Since the copper coil with unfilled epoxy had materials about which the most data is published, it was tried first. Equations were set up for conduction parallel to the width of the braid using the literature values of thermal conductivity and the necessary geometric factors. In this case four equations were written:

1. Heat flow along the width of the braid accounting for the amount of copper and epoxy in the path.

2. Heat flow through the epoxy between layers of braid.

3. Heat flow along the length of the copper conductors from one side of the braid to the other.

4. Total heat flow which contains the unknown thermal conductivity term.

Setting the sum of the first three equal to the last, and solving for the unknown thermal conductivity, a calculated apparent thermal conductivity was found equal to 0.043 W/cm-K. The average thermal conductivity determined experimentally was 0.0423 W/cm-K. The agreement is almost too good but does give confidence in the experimental results. The same procedure was followed for the coil containing superconductor and epoxy and the calculated value agreed within 10% with the measured value. When the same procedure was tried on the eutectic filled superconductor coil the disagreement was almost 50% higher for the calculated value. Two reasons for this are apparent, (1) the eutectic was assumed to be a constant thickness which is not true, and (2) the thermal conductivity of the eutectic was calculated using the Lorentz ratio since no published data exists at these temperatures. In this system the heat flow across the width of the braid dominates the result so small unknowns will cause large errors.

Conclusions

A number of valid conclusions can be made from these results:

1. The amount of plastic in the system is the dominant factor in lowering of the thermal conductivity.

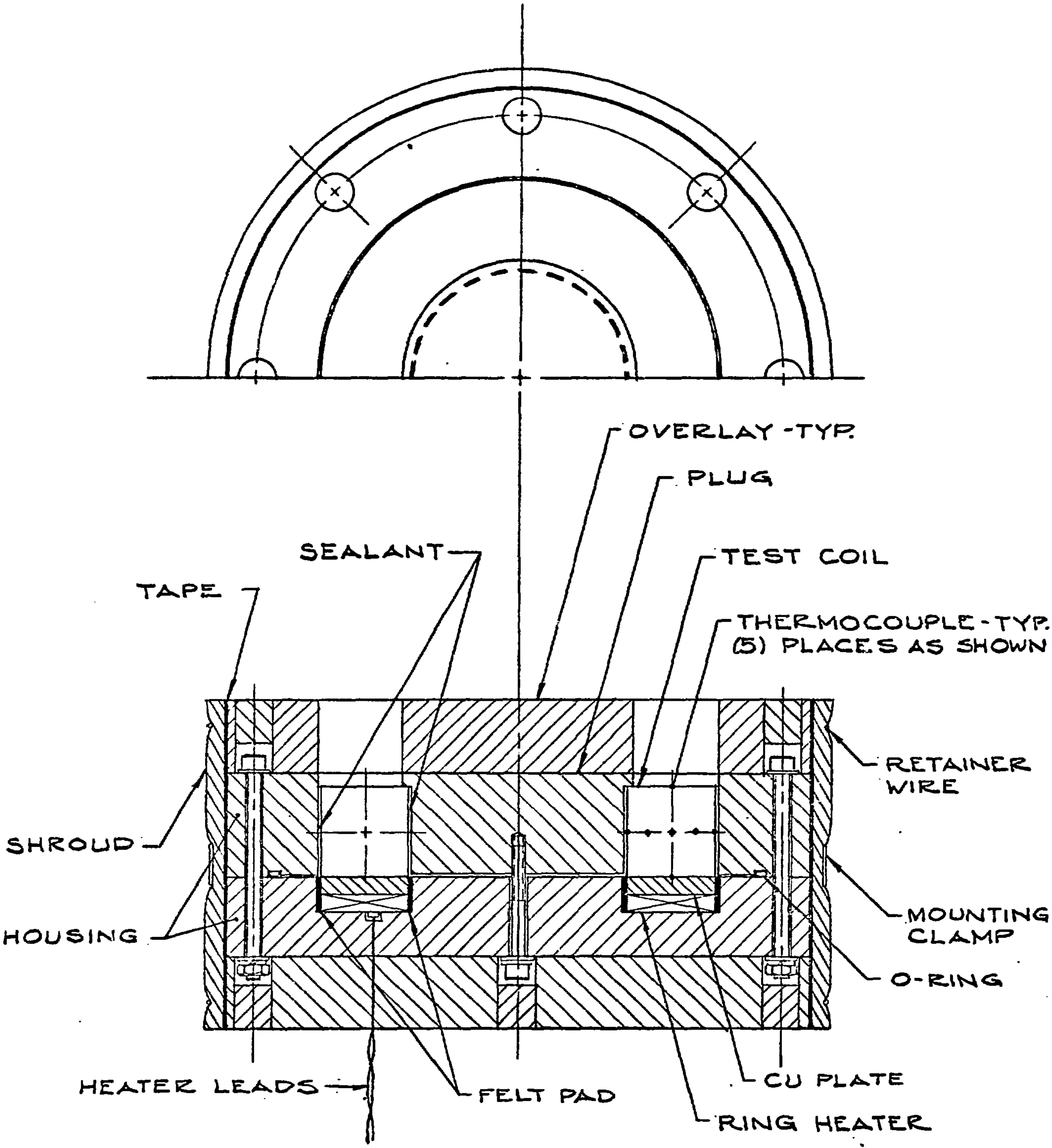
2. Any metallic filler (other than superconductor) will enhance the thermal conductivity of the system.

3. The amount of copper in a superconducting wire and any other normal metallic material in the braided matrix are the dominant factors affecting the thermal conductivity.

4. The pitch length of the braid will also determine the effective thermal conductivity in a fully insulated matrix, since the heat flow is primarily along the length of the individual wires in this system.

5. If the thermal properties of each of the components in a given system are well known individually, it is possible to calculate the apparent thermal conductivity to the accuracy required for most purposes.

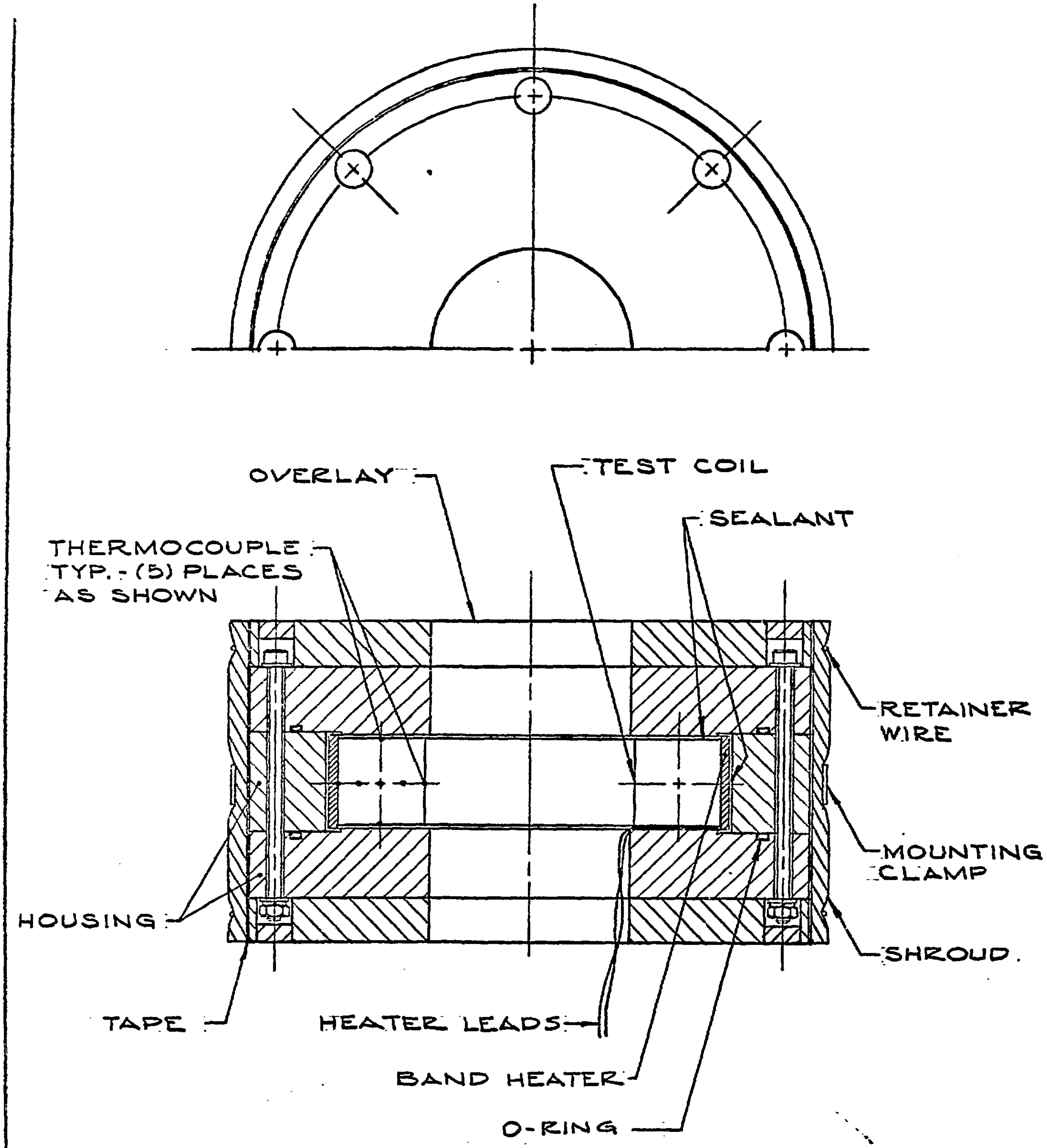
6. Cooling applied to a surface parallel to the width of the braid is of small value.



TEST COIL ASS'Y - I

SCALE: HALF

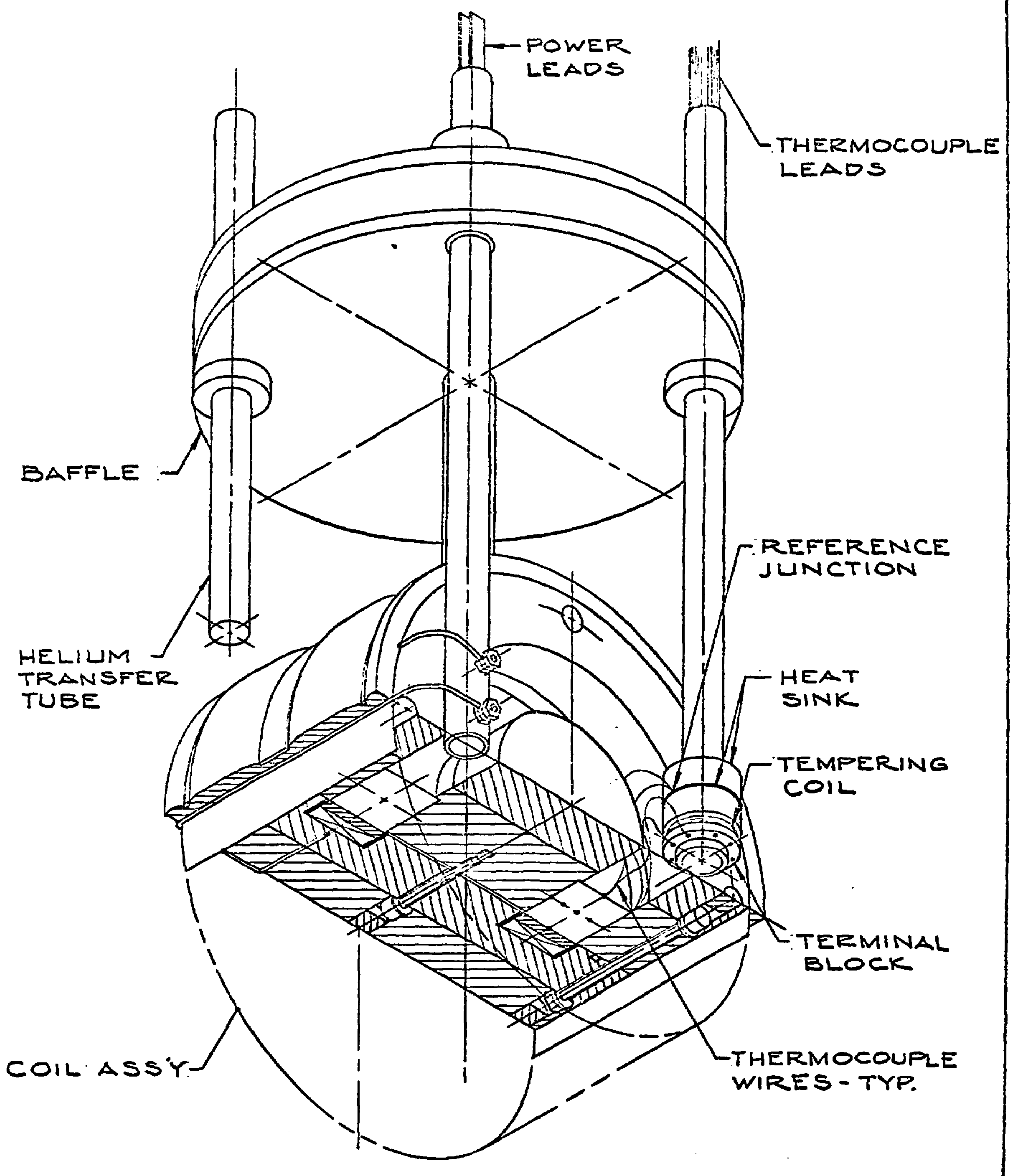
FIG. 1



TEST COIL ASS'Y - II

SCALE: HALF

FIG. 2



COIL SUPPORT DETAIL

SCALE : HALF

FIG. 3

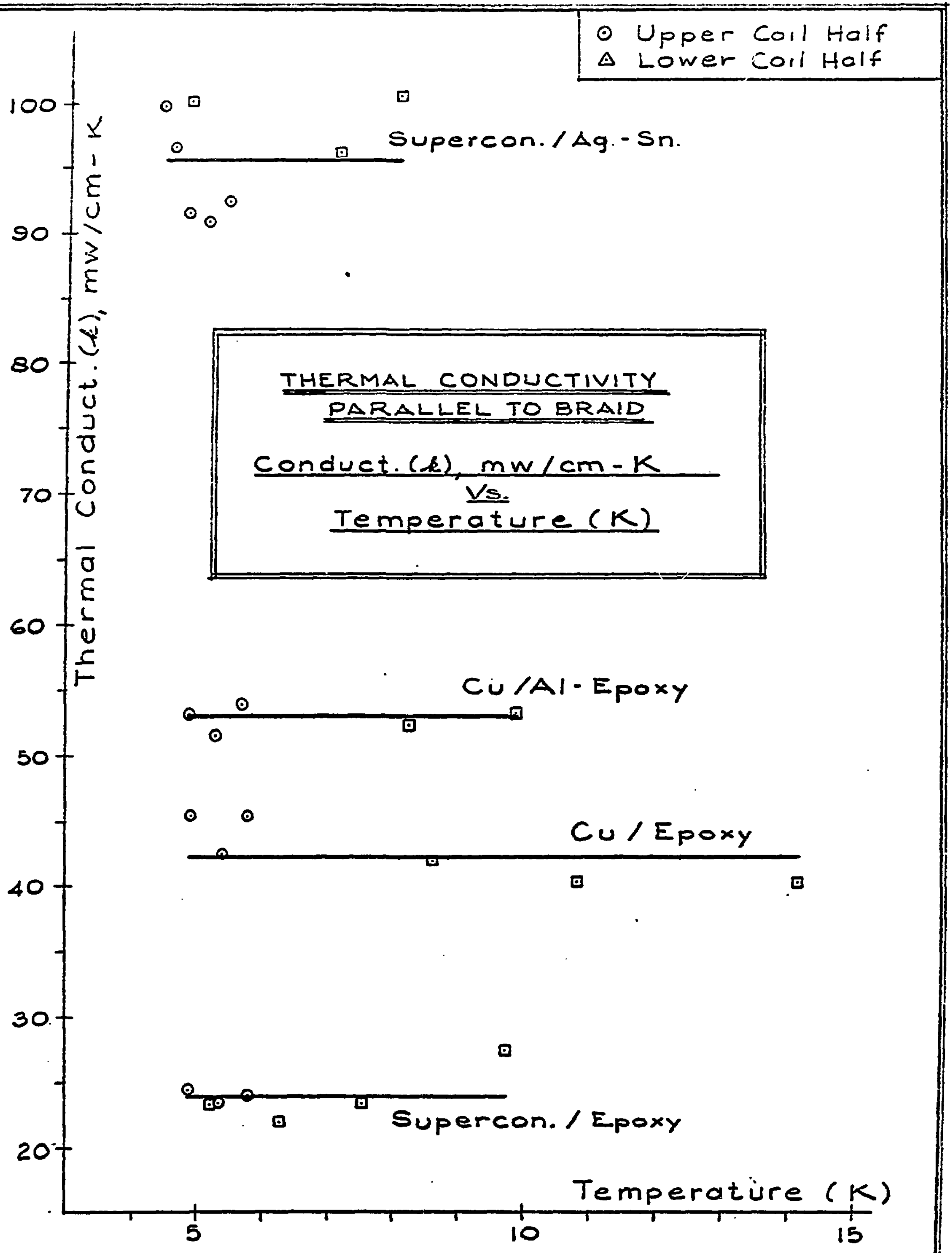
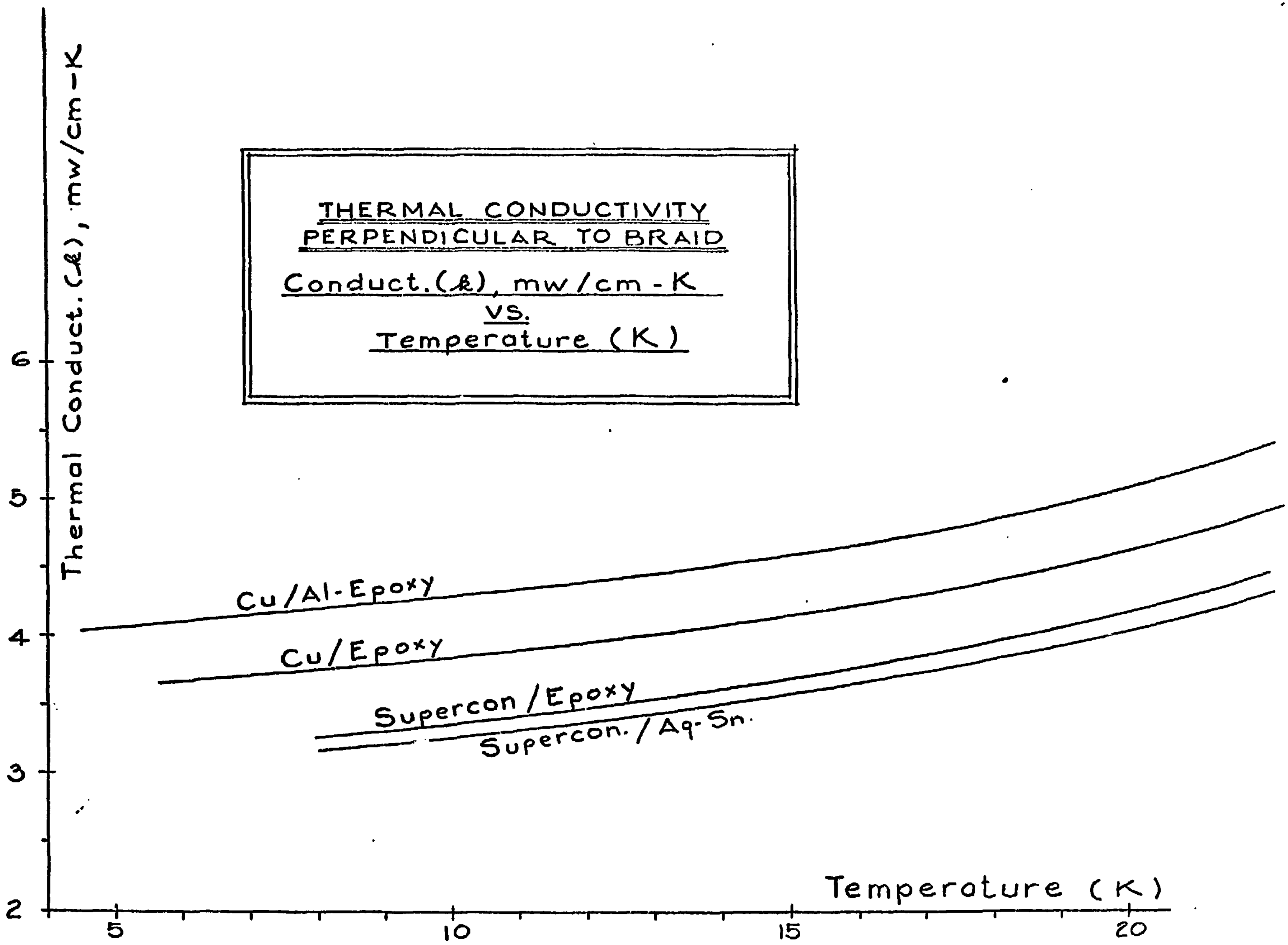

⊙ Upper Coil Half
△ Lower Coil Half
THERMAL CONDUCTIVITY
PARALLEL TO BRAID
Conduct. (k), mw/cm-K
Vs.
Temperature (K)
Thermal Conduct. (k), mw/cm-K
100
90
80
70
60
50
40
30
20
Supercon./Ag.-Sn.
Cu/Al-Epoxy
Cu/Epoxy
Supercon./Epoxy
Temperature (K)
5
10
15

FIG. 4



THERMAL CONDUCTIVITY PERPENDICULAR TO BRAID

Conduct. (k), mw/cm-K vs. Temperature (K)

FIG. 5