EXPERIMENTAL DETERMINATION OF THE THERMAL CONDUCTIVITY OF POROUS COPPER

Thesis by

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ABSTRACT

The techniques of powder metallurgy have produced porous variations of the metals copper, steel and nickel. The proposed application of these porous metals in the sweat-cooling of jet propulsion engines demands an exact knowledge of their thermal as well as their physical properties.

This thesis presents an experimental determination of the thermal conductivity of copper as a function of porosity, and an insight into the way this conductivity depends on temperature.

The experiments were performed on a simplified version of the apparatus used by the Bureau of Standards for solid metals. Four copper specimens varying in porosity from 22 to 42 per cent were measured. The results obtained are consistent with those predicted by other investigators from entirely different considerations.

The results are summarized in two graphs. The first shows temperature versus thermal conductivity. The second gives thermal conductivity versus porosity. It is shown that porosity largely determines thermal conductivity while temperature is distinctly a second-order influence. An analytical expression for the variation of thermal conductivity with porosity is introduced, and general agreement with the experimental results is noted.

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PART I

INTRODUCTION AND SUMMARY

The thermal conductivity of porous metals is of considerable practical interest in the technique of sweat cooling. For this reason an experimental determination of the thermal conductivity of several porous metals was begun at Jet Propulsion Laboratory. Because of limitations of the equipment, only porous copper has been tested up to this time.

This study was performed on an apparatus of the type used by Van Dusen (Cf. Ref. 1) for measuring the same property in solid metals. The method was to compare two specimens, one of known conductivity, through which heat flows in series. The specimens were placed in an apparatus hereafter called the "conductometer."

Axial temperature gradients in two cylindrical rods placed firmly end to end were measured under conditions approaching thermal equilibrium. When a steady state had been attained, the heat flux, assuming no radial losses, was the same in both bars. The conductivity at any point in either bar was inversely proportional to the temperature gradient at that point. If the absolute value of the conductivity of the metal of one bar was known at some temperature within the experimental range, the thermal conductivity of the other bar could be calculated for all points at which the temperature gradient had been determined.

The experiment involved testing four copper specimens of 22, 28, 39, and 42 per cent porosities, and in addition, one wrought copper specimen, for the purpose of calibrating heat losses in the conductometer.

PART II

DESCRIPTION OF THE EQUIPMENT

Elaborate refinement of the apparatus to obtain great precision was not attempted. Figure 18 illustrates the conductometer disassembled, while Figure 19 shows the conductometer enclosed by a transite tube, or shield. This tube serves to contain powdered asbestos lagging. Referring to Figure 18, it is seen that heat from a controlled source passes through a six-inch copper specimen, then through a three-inch pure iron standard of identical cross section. A diameter of one-half inch was chosen for both standard and specimen. No attempt was made to solder the two rods since solder would flow into the spaces in the matrix of the porous copper. The lower end of the copper specimen rested on an iron cylinder with a truncated conical top. This cylinder served to guide the heat into the specimen (Cf.Fig. 20).

The pure iron standard is an integral part of the heat sink, in which cooling channels were machined. However, the use of circulating water was abandoned after it was observed that adequate temperature gradients were being obtained with no coolant flow. Six number 28 chromel-alumel thermocouples were fastened to the copper specimen, and five to the standard, in the following manner: the thermocouple wires were first welded together, then the bead was inserted in a shallow .040 inch diameter hole, and peened to insure good contact. The thermocouples were an inch apart on the specimens, and half an inch apart on the standard. The twenty-two thermocouple leads were passed to a Jones strip which was in turn connected to an eleven-position rotary selector switch. Temperatures were read directly on a model 8370 Leeds and Northrup potentiometer which was positioned on the table to the left of the rotary switch.

A short comparison between the present conductometer and that used by Van Dusen at the Bureau of Standards might well be made. The Van Dusen equipment differed chiefly in the number of refinements.

(1) In place of the transite tube there was used a tube which was stainless steel where it paralleled the specimen and nickel where it paralleled the standard. The temperature gradients along this metal tube could be matched to the temperature gradients in the specimen and standard, thus preventing heat transfer from the specimens to the outside air.

(2) A heat sink using water at constant temperature was provided.

(3) Although the Van Dusen equipment was rapidly brought up to temperature on alternating current, thermal equilibrium was maintained on a constant direct current source of electricity. The present conductometer used only the laboratory power source, which fluctuates because of the demands of other projects at the laboratory.

PART III

METHOD OF ANALYSIS

The method of analysis, briefly outlined, was as follows:

(1) The first step was to calibrate the conductometer for radial heat losses using a wrought copper specimen of known conductivity. The purpose of this calibration is to correct the slopes of the curves in Figure 3. The curves to be corrected are labeled T_{obs}, observed temperature. Absolute temperature, in the computation of thermal conductivity, is not significant; temperature gradient, °F per inch, is the important factor.

The lines labeled T_{cal} in Figure 3 have the correct slope for the particular value of junction temperature used as a reference point. The reader should not attempt to correlate the new values of absolute temperature at each thermocouple with the observed values. These new values are arbitrary and depend on which thermocouple is used as a point of reference. The amount of heat loss at each thermocouple on the standard was assumed negligible, since those thermocouples are relatively cool.

Two sets of temperature gradients resulted from this method, one determined from the potentiometer readings, and the second computed from the known thermal conductivity of the wrought copper. By comparing the first group of readings with the second group, Table I and Figure 3 were constructed. The corrections gleaned from Table I and Figure 3 were then consolidated on the conductometer calibration chart, Figure 4. The calibration chart gives a corrected curve for each run in Figures 5, 6, 7, and 8. Of each pair of lines, these lines are to the left and are labeled T_{cal}.

(2) Another set of graphs, Figures 9 through 14, was drawn giving temperature gradient versus temperature. This resulted in one curve for each specimen.

(3) The final computations, Tables 8 and 9, involved the use of Figures 1 and 2, and Figures 9 through 14 to solve the basic equation $K_c \left[\frac{\Delta T}{\Delta l}\right]_c = K_s \left[\frac{\Delta T}{\Delta l}\right]_s$ for the thermal conductivity of porous copper $K_c = K_s \dfrac{\left[\frac{\Delta T}{\Delta l}\right]_s}{\left[\frac{\Delta T}{\Delta l}\right]_c}$

In this equation,

K_s	is the thermal conductivity of the iron standard. Thermal conductivity is defined as the time rate of transfer of heat by conduction, through unit thickness, across unit area for unit difference of temperature. In this experiment, the units are: BTU $sec^{-1} \frac{in}{in^2}\ {}^oF^{-1}$ or BTU $sec^{-1}\ in^{-1}\ {}^oF^{-1}$. These values are conveniently plotted in Figure 1.
$\left[\frac{\Delta T}{\Delta l}\right]_s$	is the temperature gradient of the iron standard, and is obtained from Figure 9
$\left[\frac{\Delta T}{\Delta l}\right]_c$	is the temperature gradient of the porous copper specimen, and is obtained from Figures 11 through 14.

PART IV

EXPERIMENTAL PROCEDURE

The experimental procedure for both the wrought copper calibration rod and for the porous copper specimens (Cf. Ref. 2) was identical. The specimen was placed in the conductometer (Cf. Figure 18) between the heating coil and the standard, insuring the best possible contact at all points. The middle section of the transite tube was replaced (Cf. Figure 19), powdered asbestos was poured in, and the top section of the tube was positioned. The 110 volt power-line was connected through a micromax to the heating coil. The rheostat on the micromax was convenient for controlling the power input to the heating coil. The micromax indicated the temperature of the hottest thermocouple at all times, but the temperature controlling facilities of the micromax were not used after it was found that the switching on and off of the power prevented the conductometer from reaching thermal equilibrium.

Four hours were allowed for the system to reach thermal equilibrium. Actual thermal equilibrium was never attained because the source of power was under the influence of a variable line voltage caused by the demands of other projects at the laboratory. At the end of four hours two sets of readings were taken about fifteen minutes apart, or until the temperature drift became less than $5^{\circ}F$ over the fifteen minute period. At this time, the thermocouples were read from number one through number eleven and back again. The average temperature for each thermocouple was recorded.

In practice, runs were controlled from the hottest thermocouple, and, during one installation, six runs starting at 400, 550, 700, 850, 1000 and 1150°F would be made.

In Figures 3, 5, 6, 7, and 8 there will be noticed a discontinuity at the interface or junction between the specimen and the standard. This is merely due to high thermal resistance between the two rods, since they are not soldered. However, each temperature curve above the junction corresponds to one below.

The wrought copper test rod was fabricated from electrolytic copper, the purest commercially available, and the value of thermal conductivity for this type of copper was taken from Reference 1.

PART V

RESULTS OF EXPERIMENTS

The results of the experiments may be conveniently divided into two parts; the calibration tests, and the tests on the porous specimens.

The results of the calibration tests, Table I, conducted on a wrought copper specimen were transferred to the graph, Figure 3. The lines labeled T_{obs}, observed temperature, resulted from the potentiometer readings whereas the lines labeled T_{cal}, calibrated temperature, were calibrated from the known thermal conductivity of wrought copper, as in Table I. The necessary corrections are summarized in Figure 4, the conductometer calibration chart.

The second part of the experiment involved calibrating the observed readings made on the porous copper specimens. Both the observed and calibrated temperatures are plotted in Figures 5, 6, 7, and 8.

PART VI

ANALYSIS OF RESULTS

The basic law governing heat flow in the steady state is

$$q = KA\frac{dT}{dl} \qquad \text{where}$$

q is the quantity of heat in BTU

K is a proportionality constant called the thermal conductivity, and is a characteristic property of the solid through which the heat is flowing, in BTU $sec^{-1}\ in^{-1}\ {}^{o}F^{-1}$.

A is the area through which the heat is flowing, in square inches.

$\frac{dT}{dl}$ is the temperature gradient at a given point in the body under consideration.

If the area is taken as unity, the law becomes, $q = K\frac{dT}{dl}$.

Two features of this law are worthy of special note. First, the thermal conductivity is, by definition, merely a proportionality constant valid for a particular body under a particular set of conditions. Secondly, the basic relation involves only the temperature gradient, and not temperature directly.

The basic law may also be written

$$K_1 \left(\frac{dT}{dl}\right)_1 = K_2 \left(\frac{dT}{dl}\right)_2$$

Within experimental limits, the temperature gradient varies so slowly with distance along the specimen that no appreciable error is introduced by taking finite lengths as large as one inch. Hence the basic law can be written in the following manner, which was the form used for computation

$$K_1 \left[\frac{\Delta T}{\Delta l} \right]_1 = K_2 \left[\frac{\Delta T}{\Delta l} \right]_2$$

Using this form the computation of the thermal conductivity of porous copper was made as follows.

Since temperature gradients as a function of temperature could not be read directly from Figures 3, 5, 6, 7, and 8, separate graphs of these two functions were drawn. They are presented in Figures 9 through 14, where the temperature gradients are given as functions of the junction temperature, T_j. There is significant scatter in Figure 13, for a specimen of 39 per cent porosity, but Figure 14, for a specimen of 42 per cent porosity exhibits more consistency.

To obtain the thermal conductivity of porous copper for any porosity tested, it was necessary to solve the basic equation for K_c:

$$K_c = K_s \frac{\left[\frac{\Delta T}{\Delta l} \right]_s}{\left[\frac{\Delta T}{\Delta l} \right]_c} \qquad \text{where}$$

K_c is the thermal conductivity of the porous copper specimen, BTU sec^{-1} in^{-1} $^{\circ}\text{F}^{-1}$.

K_s is the same property for the iron standard and was obtained from Figure 1.

$\left[\frac{\Delta T}{\Delta l} \right]_s$ is the temperature gradient for the iron standard and was obtained from Figure 9.

$\left[\frac{\Delta T}{\Delta l} \right]_c$ is the temperature gradient for the porous copper specimen and was obtained from one of the Figures 11,12, 13, or 14.

Figure 10 is a presentation, in graphical form of temperature gradient versus junction temperature for the wrought copper specimen. Here the temperature gradients were first calculated from the known conductivity of wrought copper, then read directly from the graph, Figure 3. The agreement is good.

The results of the above computations were plotted in two graphs. Figure 15 presents temperature versus thermal conductivity with porosity as the parameter. Figure 16 presents thermal conductivity versus porosity with temperature as the parameter. The temperature influence was so slight, however, that no attempt was made to draw a separate line for each temperature. This concluded the experiment.

There are errors of unknown magnitude in this experimental determination. The reproducibility of these results is believed better than the absolute accuracy, so that the results obtained on these specimens, all tested by the same method, are accurate to about 10 per cent.

A listing of possible sources of error should include the following:

(1) There was appreciable radial heat loss from both specimen and standard.

(2) The system could not be maintained at thermal equilibrium because of fluctuating power supply.

(3) At higher temperatures it has been shown that the thermocouples became loosened because of unequal expansion of

the thermocouple metal and the copper. This caused observed temperatures to be lower than their true values. The seriousness of this error can be appreciated by recalling that a temperature gradient was determined as a small difference of two large numbers. One investigation showed that a one per cent error in the temperature reading caused a 15 per cent error in the temperature gradient.

(4) The type of direct reading potentiometer used could not be read in less than 5°F increments. A potentiometer accurate to 1°F would have been better for the same reason as in paragraph 3.

(5) The porous specimens of 39 and 42 per cent porosities contained cracks and discontinuities which undoubtedly disturbed the heat flow.

To sum up, the precise determination of thermal conductivity is very difficult, first because there is available no perfect thermal insulator to confine the thermal current to the path desired, and second because precise measurements of high temperatures are difficult to obtain.

The best theoretical analysis of the effect of porosity on thermal conductivity is obtained from a comparison with electrical conductivity. The fact that the ratio, for solid metals of thermal conductivity to electrical conductivity is approximately constant at room temperature was first discovered in 1853 by Wiedemann and Franz (Cf. Ref. 3). However, this ratio varies considerably with temperature. Years later, Lorentz (Cf. Ref. 3) showed that by adding a temperature factor to this ratio, the value should become an universal constant.

The proportionality between thermal conductivity and electrical conductivity established long ago for solid metals appears to hold true for porous metals. Maxwell (Cf. Ref. 4) calculated the electrical conductivity of a structure composed of spheres of one metal dispersed in another and arrived at an equation which may be written

$$K_{Ag} = K_{cu} \frac{(2K_A + K_{cu} - P_A(K_A - K_{cu})}{(2K_A + K_{cu} - 2P_A(K_A - K_{cu})} \qquad \text{where}$$

K_{Ag} is the conductivity of the aggregate, K_{cu} and K_A are respectively the conductivity of the matrix material and of the dispersed phase, and P_A is the volume fraction of the dispersed phase in the mixture. While this relation is exact only for dispersed particles of spherical shape and for relatively small values of P_A, it gives a reasonable approximation to the experimental results of this thesis.

If we take copper as the matrix and air as the dispersed phase, the electrical conductivity of the aggregate is

$$K_{Ag} = K_{cu} \frac{(1 - P_A)}{(1 + 2P_A)}$$

where the conductivity of the air is assumed negligible. This agrees generally with the experimental measurements of thermal conductivity, Figure 17. By modifying this equation, an empirical expression which fits the experimental results better can be obtained, as in the equation

$$K_{Ag} = K_{cu} \frac{(1 - P_A)}{1 + 3.5P_A}$$

These results are graphed in Figure 17.

PART VII

CONCLUSIONS

The experimental study of the thermal conductivity of porous copper has shown that:

1. The thermal conductivity is a decreasing function of porosity, falling off very rapidly for the first few per cent of porosity, and then leveling off.

2. The influence of temperature on both wrought copper and porous copper specimens is identical and almost negligible.

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TABLE I

CALIBRATION TESTS
WROUGHT COPPER - FIRST INSTALLATION

THERMO-COUPLE NO.	RUN NO. 1	2	3	4	5	6	7
11	145	190	195	210	220	234	287
10	168	222	235	255	268	294	367
9	192	260	276	304	321	355	452
8	216	299	319	355	376	420	549
7	241	330	361	403	430	480	645
6	302	421	461	520	560	603	814
5	311	438	479	540	583	630	850
4	322	453	499	562	606	656	889
3	334	467	519	583	629	682	928
2	345	484	536	606	653	708	969
1	357	503	559	631	682	742	1020

WROUGHT COPPER - SECOND INSTALLATION

	1	2	3	4	5	6	7
11	172	209	242	258	298	321	351
10	208	254	299	326	379	421	460
9	243	301	301	402	469	533	582
8	285	352	428	481	570	657	718
7	321	400	492	563	672	786	863
6	412	515	632	732	828	982	1070
5	428	536	659	761	862	1024	1116
4	442	557	684	796	901	1070	1166
3	460	579	711	825	940	1118	1218
2	478	601	739	860	981	1170	1270
1	495	630	780	900	1035	1230	1330

TABLE I (cont.)

CALIBRATION OF THE CONDUCTOMETER USING A WROUGHT COPPER SPECIMEN THE TEMPERATURE GRADIENT OF THE COPPER, $\left[\frac{\Delta T}{\Delta l}\right]_c$, IS FOUND FROM THE BASIC EQUATION, $\left[\frac{\Delta T}{\Delta l}\right]_c = \frac{K_S}{K_C}\left[\frac{\Delta T}{\Delta l}\right]_S$ WHERE K_S, K_C AND $\left[\frac{\Delta T}{\Delta l}\right]_S$ ARE KNOWN

	TEMP. AT THE JUNC.	TEMP. GRADIENT	CONDUCTIVITY OF STAND		CONDUCTIVITY OF COPPER		TEMP GRAD. OF COPPER
	T_J	$\left[\frac{\Delta T}{\Delta l}\right]_S$	K_S	$K_S\left[\frac{\Delta T}{\Delta l}\right]_S$	K_C		$\left[\frac{\Delta T}{\Delta l}\right]_C$
	°F	°F/INCH	BTU/IN/SEC/°F	BTU/IN²/SEC	BTU/IN/SEC/°F		°F/INCH
1ST INSTALLATION							
RUN NO 1	295	56	8.58	480	50.1		9.5
RUN NO 2	410	84	8.06	678	49.8		13.52
RUN NO 3	450	100	7.88	788	49.5		16.0
RUN NO 4	510	116	7.62	915	49.4		19.0
RUN NO. 5	550	130	7.44	965	49.2		20.0
RUN NO. 6	590	145	7.28	1020	49.1		22.0
RUN NO. 7	800	240	6.36	1530	48.3		30.0
2D INSTALLATION							
RUN NO. 1	235	83.0	8.85	735	49.7		15.0
RUN NO 2	280	110	8.62	950	49.4		19.0
RUN NO 3	325	141	8.45	1190	49.0		24.5
RUN NO 4	355	155	8.26	1280	48.6		27.0
RUN NO 5	385	178	8.09	1440	48.2		32.5
RUN NO 6	420	215	8.01	1720	47.7		40.0
RUN NO 7	460	230	7.84	1850	47.4		41.0

TABLE I (cont.)

CALIBRATION OF THE CONDUCTOMETER USING A WROUGHT COPPER SPECIMEN

COMPUTATION OF THE CORRECTION TERM, ΔT, FROM WHICH THE CALIBRATION CHARTS ARE CONSTRUCTED.

	THERMO-COUPLE →	6	5	4	3	2	1
		°F	°F	°F	°F	°F	°F
1ST INSTALLATION							
RUN NO 1	OBSERVED TEMP, T_{OBS}	300	311	322	333	344	355
	CALIBRATED TEMP, T_{CAL}	300	309.5	319	328.5	338	347.5
	CALIBRATION FACTOR, ΔT	—	1.5	3.0	4.5	6.0	7.5
RUN NO. 2	T_{OBS}	420	437	454	471	488	505
	T_{CAL}	420	435	450	465	480	495
	ΔT	—	2.0	4.0	6.0	8.0	10.0
RUN NO. 3	T_{OBS}	460	479	498	517	536	555
	T_{CAL}	460	476	492	508	524	540
	ΔT	—	3.0	6.0	9.0	12.0	15.0
RUN NO. 4	T_{OBS}	520	542	564	586	608	630
	T_{CAL}	520	539	558	577	596	615
	ΔT	—	3.0	6.0	9.0	12.0	15.0
RUN NO. 5	T_{OBS}	560	584	608	632	656	680
	T_{CAL}	560	580	600	620	640	660
	ΔT	—	4.0	8.0	12.0	16.0	20.0

TABLE I (cont.)

CALIBRATION OF THE CONDUCTOMETER USING A WROUGHT COPPER SPECIMEN

COMPUTATION OF THE CORRECTION TERM, ΔT, FROM WHICH THE CALIBRATION CHARTS ARE CONSTRUCTED

	THERMOCOUPLE →	6	5	4	3	2	1
2D INSTALLATION		°F	°F	°F	°F	°F	°F
RUN NO. 1	T_{OBS}	412	429	446	463	480	497
	T_{CAL}	412	427	442	457	472	487
	ΔT	—	2	4	6	8	10
RUN NO. 2	T_{OBS}	515	538	561	584	607	630
	T_{CAL}	515	534	553	572	591	610
	ΔT	—	4	8	12	16	20
RUN NO. 3	T_{OBS}	630	660	690	720	750	780
	T_{CAL}	630	655	680	705	730	755
	ΔT	—	5	10	15	20	25
RUN NO. 4	T_{OBS}	730	764	798	832	866	900
	T_{CAL}	730	757	784	811	838	865
	ΔT	—	7	14	21	28	35
RUN NO. 5	T_{OBS}	980	1030	1080	1130	1180	1230
	T_{CAL}	980	1020	1060	1100	1140	1180
	ΔT	—	10	20	30	40	50
RUN NO. 6	T_{OBS}	1070	1122	1174	1226	1278	1330
	T_{CAL}	1070	1111	1152	1193	1234	1275
	ΔT	—	11	22	33	44	55

TABLE II

READINGS FROM THE CONDUCTOMETER

SPECIMEN NO. 1 - 22% POROUS

THERMO-COUPLE NO.	RUN NO. 1	2	3	4	5	6	7
11	124	158	190	211	239	270	
10	140	186	230	260	298	339	
9	158	220	271	309	362	417	
8	175	250	313	361	428	496	
7	192	280	354	415	492	580	
6	272	402	492	615	731	865	
5	289	430	529	654	782	920	
4	308	460	570	703	838	976	
3	328	481	614	756	893	1043	
2	346	529	656	809	953	1107	
1	385	580	710	865	1010	1190	

SPECIMEN NO. 2 - 28% POROUS

	1	2	3	4	5	6	7
11	127	151	185	208	247	288	
10	147	182	221	262	307	365	
9	166	214	265	314	372	450	
8	188	245	308	372	442	555	
7	209	276	349	429	510	640	
6	272	366	453	567	658	830	
5	294	399	501	630	738	920	
4	317	433	548	692	800	995	
3	340	467	594	756	858	1070	
2	364	504	640	817	920	1150	
1	400	550	700	880	1000	1240	

TABLE II (cont.)

READINGS FROM THE CONDUCTOMETER

SPECIMEN NO. 3 - 39 % POROUS

THERMO-COUPLE NO.	RUN NO. 1	2	3	4	5	6	7	8
11	120	130	147	144	170	186	197	229
10	137	147	173	168	202	222	239	282
9	153	163	199	190	233	263	286	339
8	173	184	228	220	270	304	337	399
7	190	201	255	242	302	343	381	455
6	240	253	330	312	393	445	498	600
5	270	283	371	351	442	521	619	760
4	300	313	413	390	492	603	727	883
3	330	344	457	431	552	677	807	981
2	362	375	501	476	618	747	884	1076
1	410	420	560	540	705	845	997	1200

SPECIMEN NO. 4 - 42 % POROUS

	1	2	3	4	5	6	7	8
11	122	147	166	175	180	188	195	
10	137	169	194	208	216	226	231	
9	152	194	224	243	252	266	272	
8	170	218	257	280	290	305	310	
7	184	241	288	314	326	342	350	
6	*—	—	—	—	—	—	—	
5	300	400	469	532	562	610	670	
4	328	440	528	606	658	720	817	
3	352	474	583	672	763	842	972	
2	378	514	650	768	909	1014	1182	
1	400	558	720	860	1020	1130	1305	

* THE SHORT LENGTH OF SPECIMEN NO. 4 PERMITTED ONLY 5 THERMO-COUPLES TO BE CONNECTED.

TABLE III

TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

ARMCO IRON STANDARD

	TEMP. AT THE JUNC	TEMP GRADIENT		TEMP. AT THE JUNC.	TEMP. GRADIENT
	T_J °F	$\frac{\Delta T}{\Delta l}$ °F/INCH			
FIRST INSTALLATION	265	48	FOURTH INSTALLAT.	205	34
	365	73		220	35
	405	81		280	55
	480	106		335	64
	545	120		385	80
	645	160		430	92
	760	215		510	116
SECOND INSTALLATION	205	34	FIFTH INSTALLAT.	205	30
	310	60		260	45
	395	84		320	64
	555	130		350	70
	660	170		435	100
				510	130
THIRD INSTALLATION	230	42			
	310	62			
	390	85			
	480	105			
	570	130			
	715	170			

TABLE IV

FINAL COMPUTATION

BASIC EQN:

$$K_C\left[\frac{\Delta T}{\Delta l}\right]_C = K_S\left[\frac{\Delta T}{\Delta l}\right]_S$$

WHERE: K_C IS THE UNKNOWN CONDUCTIVITY OF COPPER
K_S IS THE KNOWN CONDUCTIVITY OF IRON
$\left[\frac{\Delta T}{\Delta l}\right]_C$, $\left[\frac{\Delta T}{\Delta l}\right]_S$ ARE KNOWN TEMP. GRADIENTS

	JUNCTION TEMP °F	CONDUCTIVITY OF STAND.	TEMP GRAD. OF STAND			CONDUCTIVITY OF COPPER	
		COPPER NO. 1 - 22 % POROUS					
	T_J	K_S	$\left[\frac{\Delta T}{\Delta l}\right]_S$	$K_S\left[\frac{\Delta T}{\Delta l}\right]_S$	$\left[\frac{\Delta T}{\Delta l}\right]_C$	K_C	
	200	9.00	31.5	288	10.0	28.8	$\times 10^{-4}$
	300	8.56	57.5	492	18.0	27.4	
	400	8.12	85.0	690	25.5	27.0	
	500	7.67	113.0	866	34.0	25.8	
	600	7.24	147.0	1063	41.0	25.8	
	700	6.80	178.0	1210	49.0	24.8	
		COPPER NO. 2 - 28 % POROUS					
	T_J	K_S	$\left[\frac{\Delta T}{\Delta l}\right]_S$	$K_S\left[\frac{\Delta T}{\Delta l}\right]_S$	$\left[\frac{\Delta T}{\Delta l}\right]_C$	K_C	
	200	9.00	31.5	288	16.0	18.0	$\times 10^{-4}$
	300	8.56	57.5	492	27.0	18.2	
	400	8.12	85.0	690	38.0	18.2	
	500	7.67	113.0	866	49.5	17.5	
	600	7.24	147.0	1063	61.0	17.4	
	700	6.80	178.0	1210	72.0	16.8	
		COPPER NO. 3 - 39 % POROUS					
	T_J	K_S	$\left[\frac{\Delta T}{\Delta l}\right]_S$	$K_S\left[\frac{\Delta T}{\Delta l}\right]_S$	$\left[\frac{\Delta T}{\Delta l}\right]_C$	K_C	
	200	9.00	31.5	288	23.0	12.5	$\times 10^{-4}$
	300	8.56	57.5	492	43.0	11.4	
	400	8.12	85.0	690	620	11.1	
	500	7.67	113.0	866	81.0	10.1	
	600	7.24	147.0	1063	100.0	10.6	
	700	6.80	178.0	1210	119.0	10.1	

TABLE IV (cont.)

FINAL COMPUTATION - CONCLUDED

	JUNCTION TEMP. °F	CONDUCTIVITY OF STAND	TEMP GRAD OF STAND			CONDUCTIVITY OF COPPER	
	T_J	K_S	$\left[\frac{\Delta T}{\Delta l}\right]_S$	$K_S\left[\frac{\Delta T}{\Delta l}\right]_S$	$\left[\frac{\Delta T}{\Delta l}\right]_C$	K_C	
		COPPER NO. 4 - 42 % POROUS					
	200	9.00	31.5	288	24.0	12.0	$\times 10^{-4}$
	300	8.56	57.5	492	45.0	10.8	
	400	8.12	85.0	690	65.0	10.6	
	500	7.67	113.0	866	85.0	10.2	
	600	7.24	147.0	1063	105.0	10.1	
	700	6.80	178.0	1210	125.0	9.7	

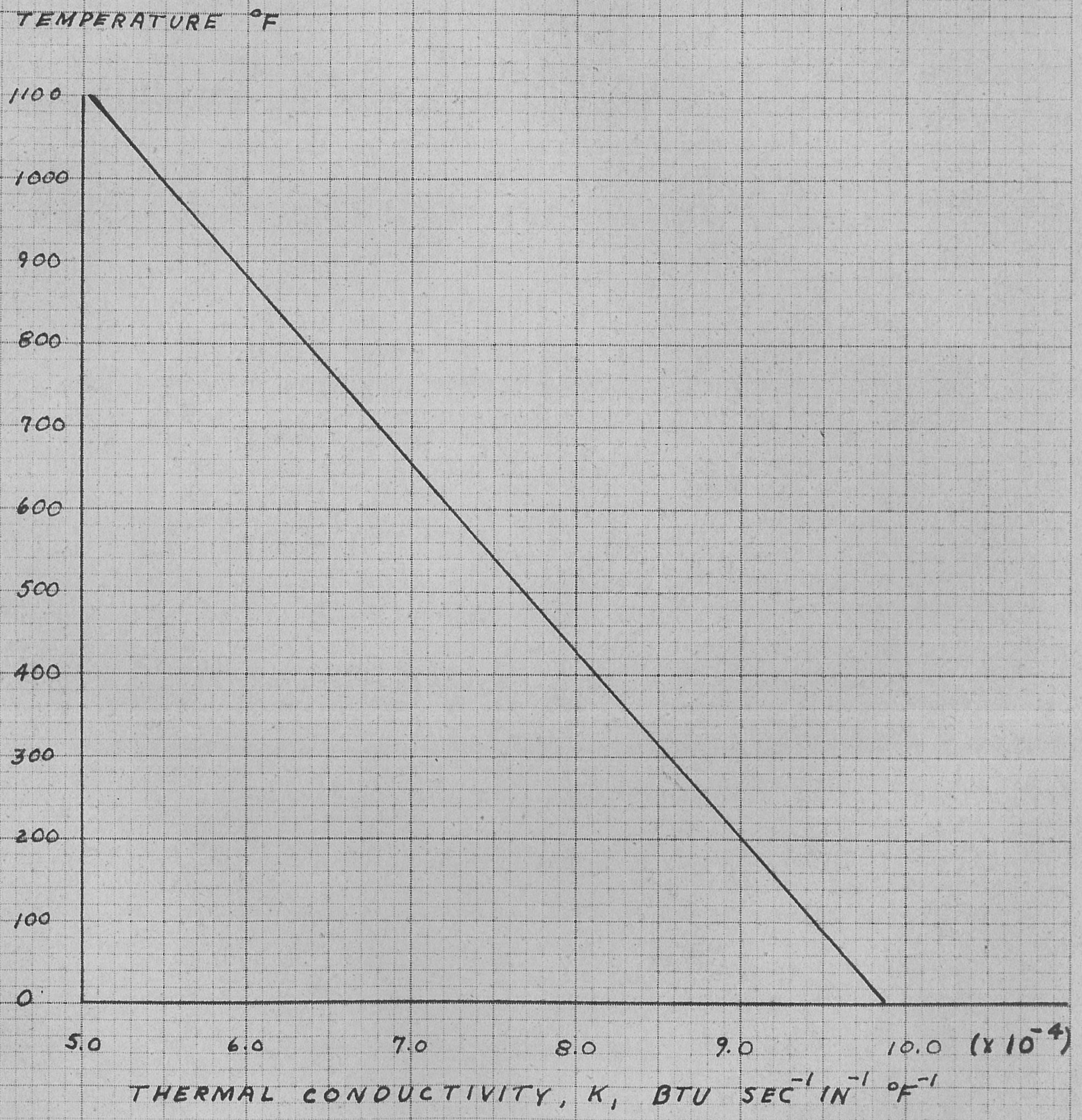
TABLE V

THERMAL CONDUCTIVITY OF POROUS COPPER COMPUTED BY MAXWELL'S LAW:

$$K = \left(\frac{1-P}{1+2P}\right) 50 \times 10^{-4}$$

WHERE K IS THE CONDUCTVITY
P IS THE POROSITY

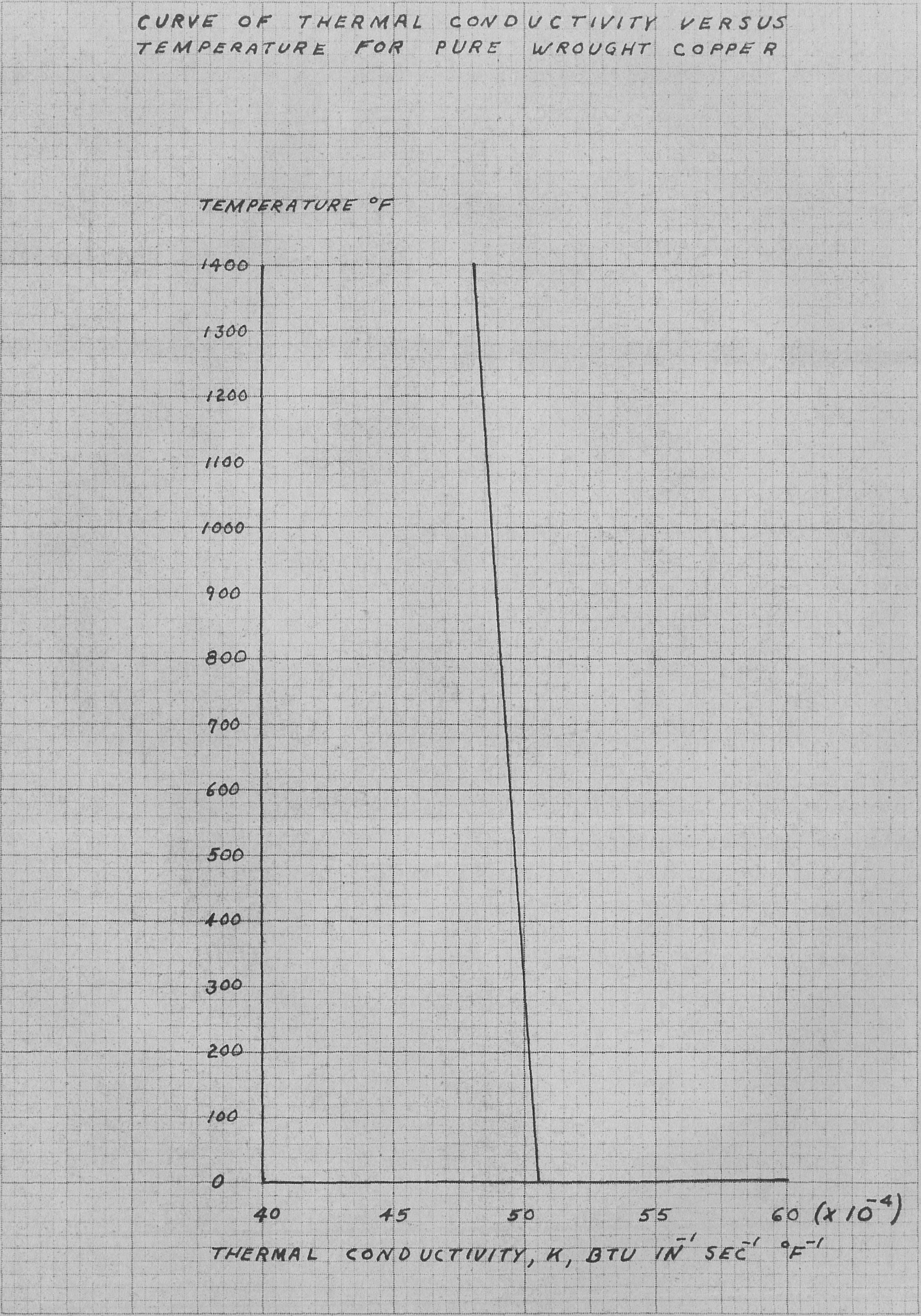
		POROSITY			THERMAL CONDUCTIVITY
		P %	1 − P	1+2P	$K \times 10^4$
1		0	1.00	1.00	50.0
2		10	0.90	1.20	37.3
3		22	0.78	1.44	27.1
4		28	0.72	1.56	23.0
5		39	0.61	1.78	17.1
6		42	0.58	1.84	15.8
7		50	0.50	2.00	12.5
8		60	0.40	2.20	9.10
9		70	0.30	2.40	6.25
10		80	0.20	2.60	3.84
11		90	0.10	2.80	1.77
12		100	0	3.0	0



CURVE OF THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR THE STANDARD METAL

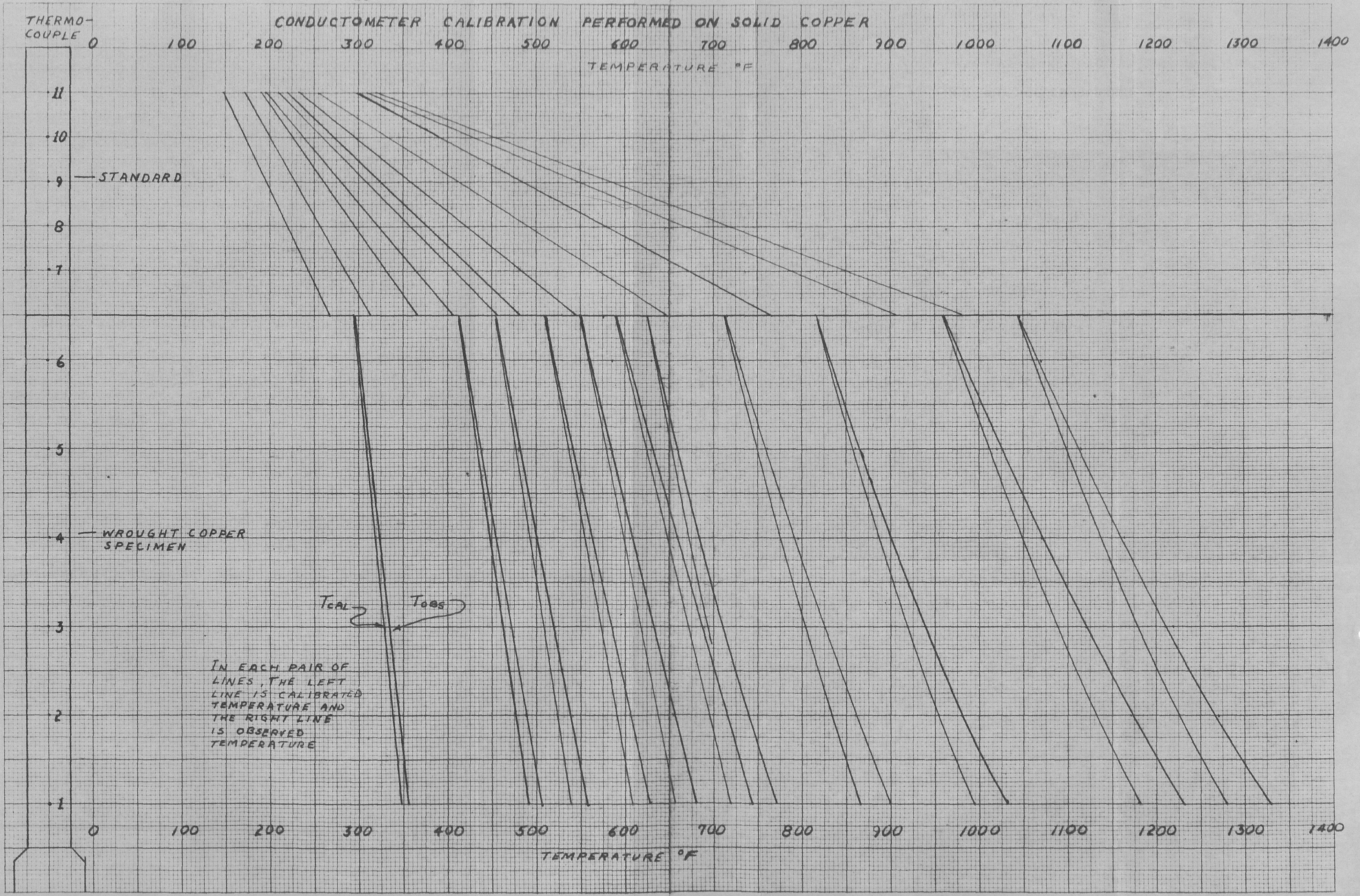
OPEN-HEARTH (PURE) IRON

FIGURE 1



CURVE OF THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR PURE WROUGHT COPPER

FIGURE 2



CONDUCTOMETER CALIBRATION PERFORMED ON SOLID COPPER

FIGURE 3

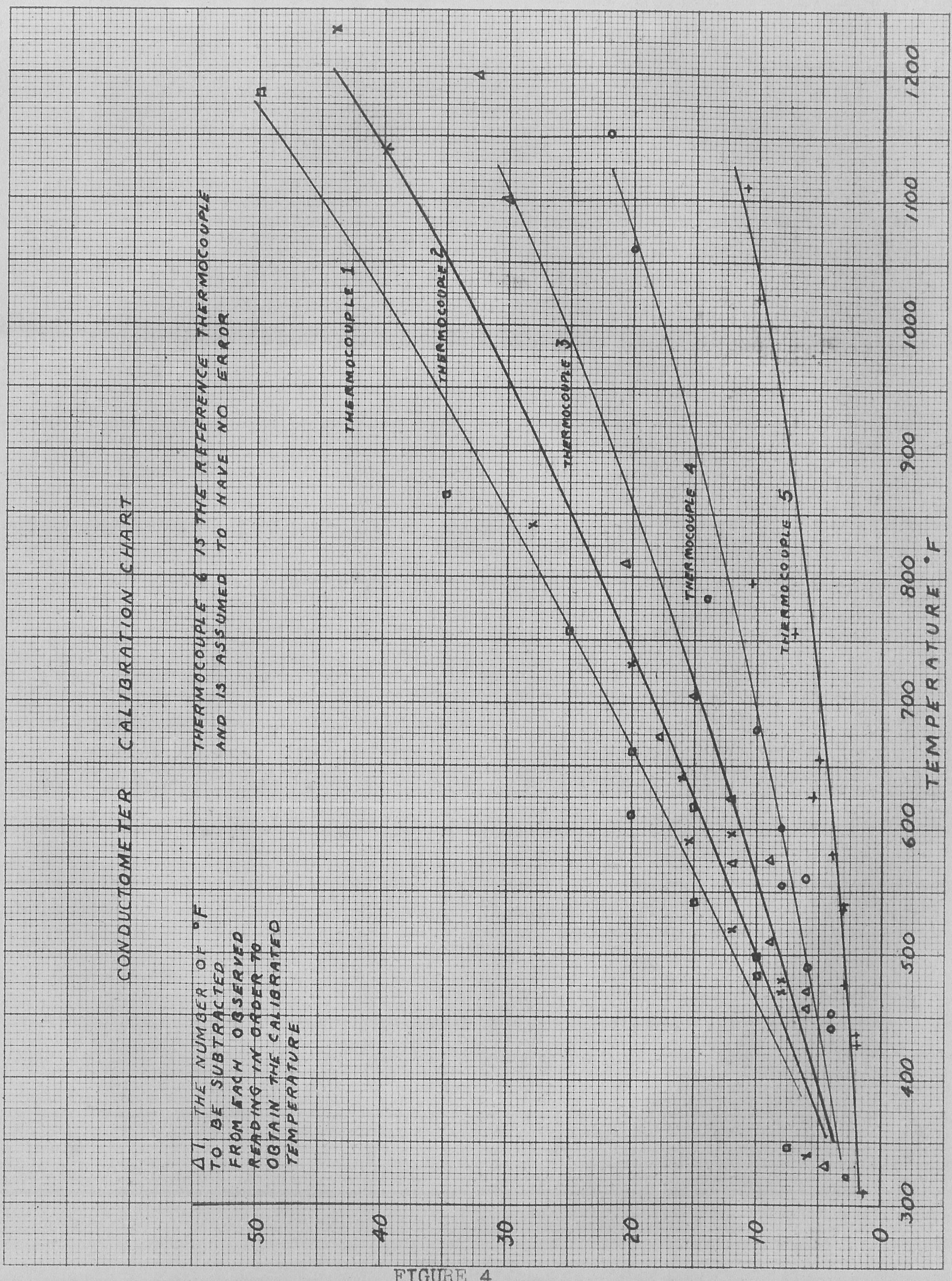

CONDUCTOMETER CALIBRATION CHART
THERMOCOUPLE 6 IS THE REFERENCE THERMOCOUPLE AND IS ASSUMED TO HAVE NO ERROR
ΔT, THE NUMBER OF °F TO BE SUBTRACTED FROM EACH OBSERVED READING IN ORDER TO OBTAIN THE CALIBRATED TEMPERATURE
THERMOCOUPLE 1
THERMOCOUPLE 2
THERMOCOUPLE 3
THERMOCOUPLE 4
THERMOCOUPLE 5
0
10
20
30
40
50
300
400
500
600
700
800
900
1000
1100
1200
TEMPERATURE °F

FIGURE 4

GRAPH OF CONDUCTOMETER READINGS - COPPER SPECIMEN NO. 1 - 22% POROUS

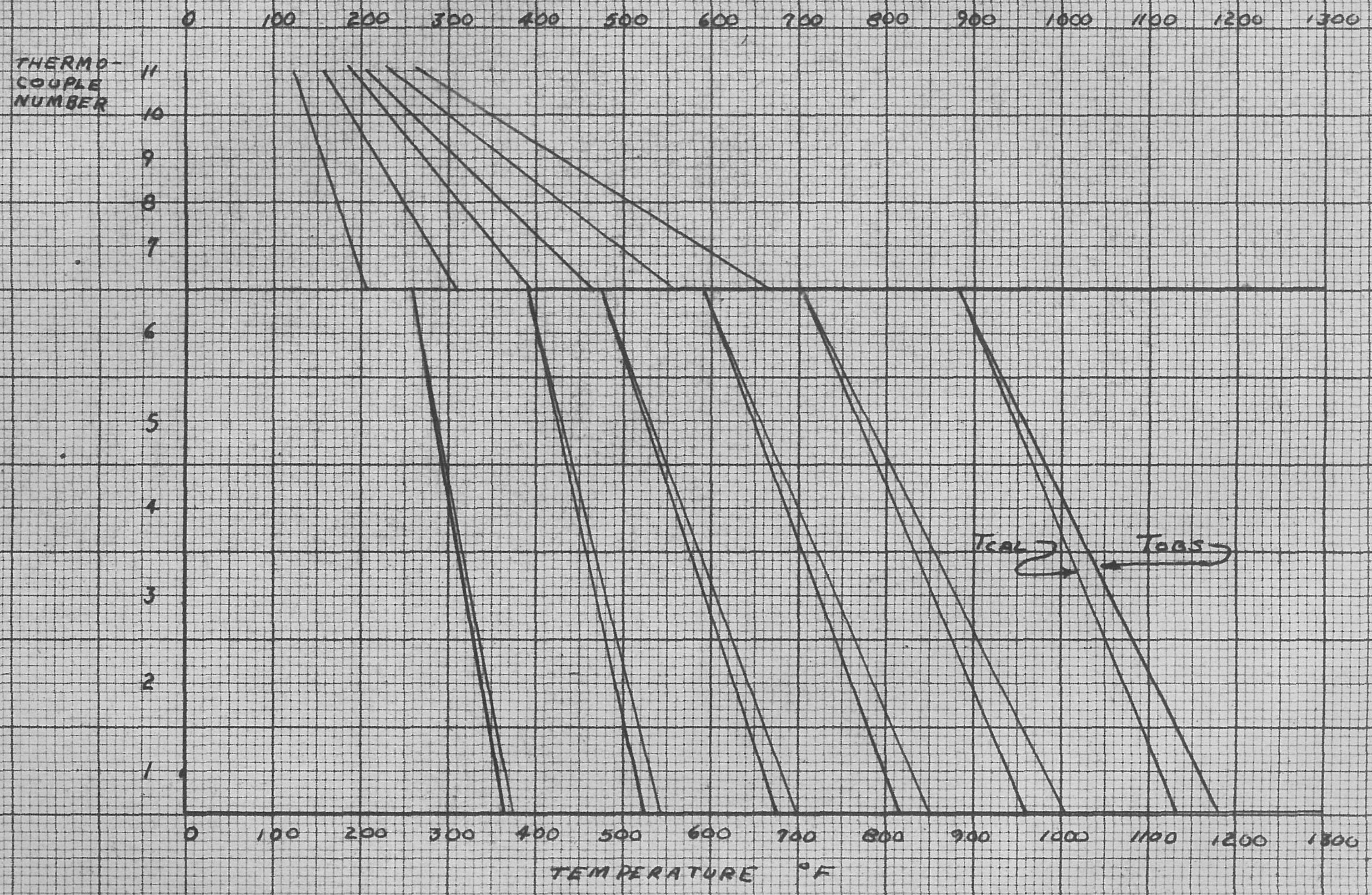


FIGURE 5

GRAPH OF CONDUCTOMETER READINGS.
COPPER SPECIMEN NO. 2 - 28% POROUS

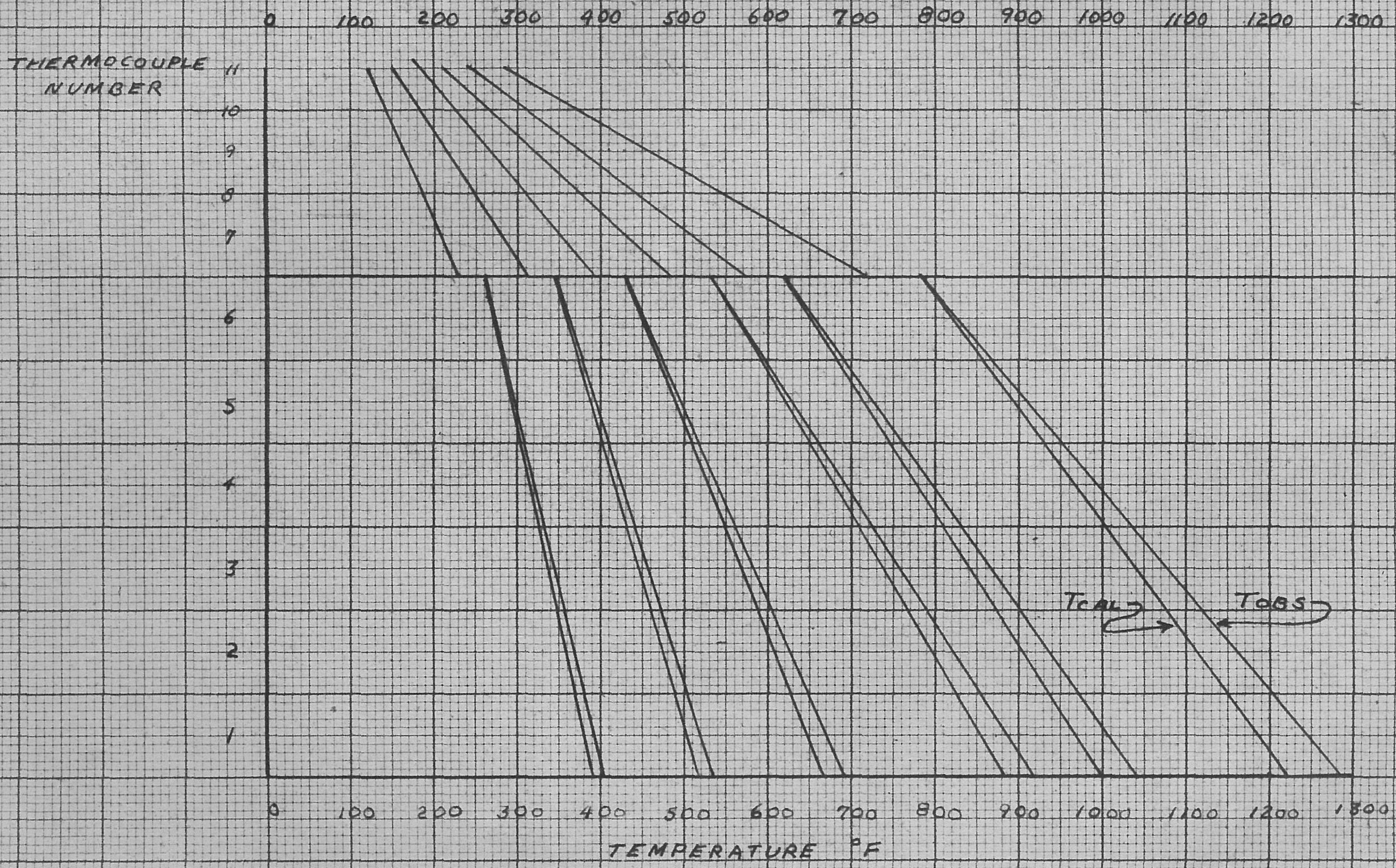


FIGURE 6

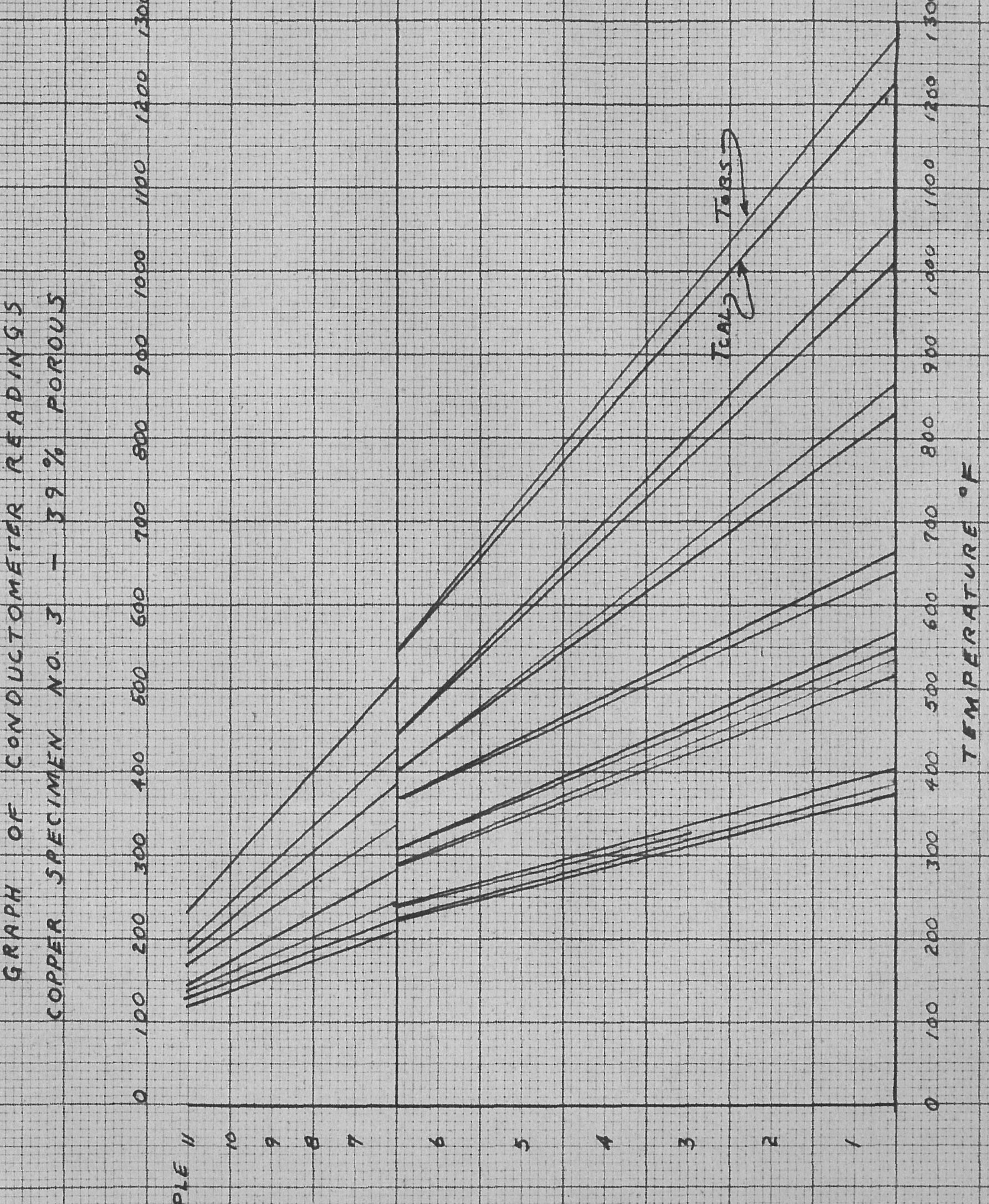
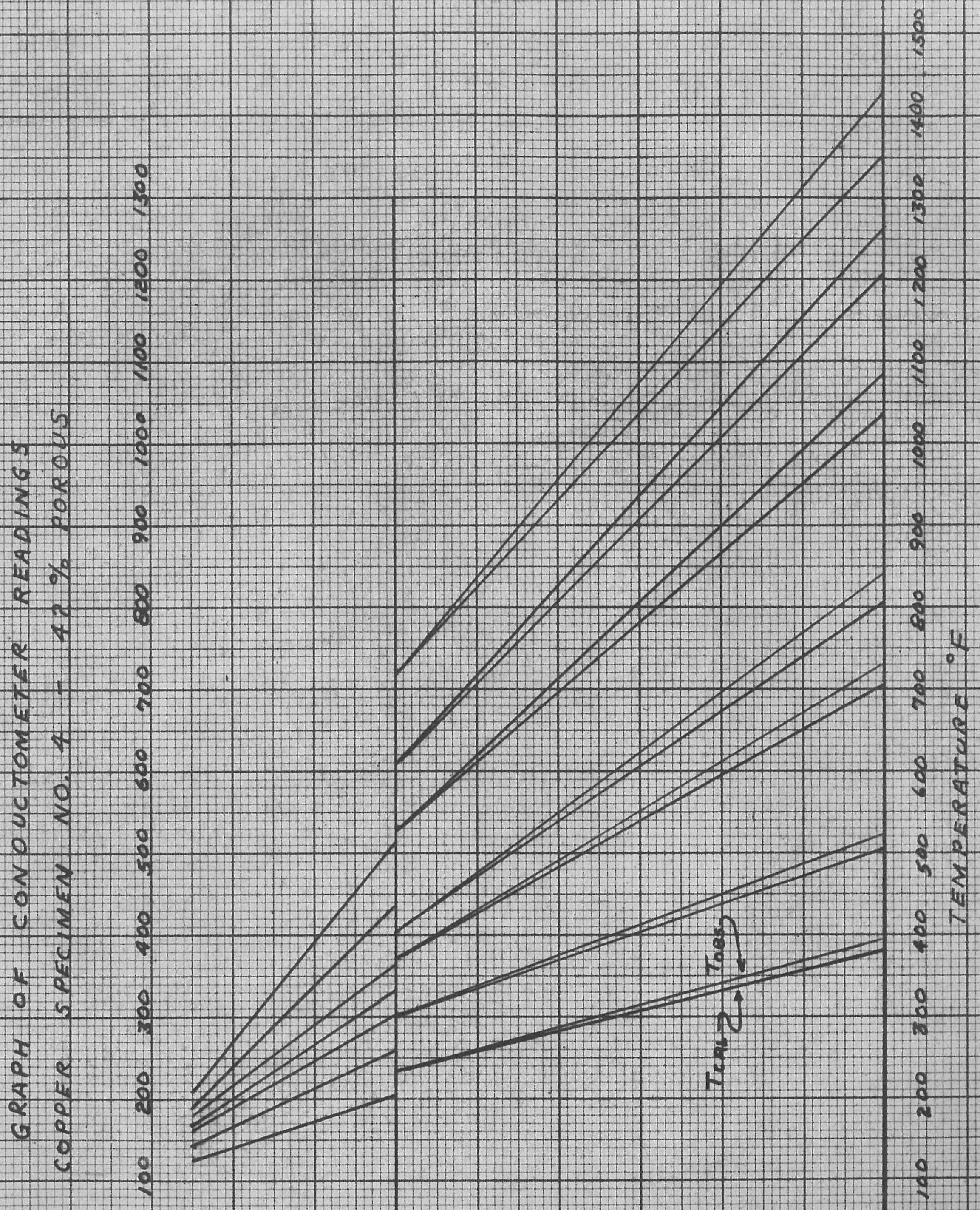

GRAPH OF CONDUCTOMETER READINGS
COPPER SPECIMEN NO. 3 — 39% POROUS
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
TEMPERATURE °F
THERMOCOUPLE NUMBER
11
10
9
8
7
6
5
4
3
2
1
T OBS
T CAL

FIGURE 7



GRAPH OF CONDUCTOMETER READINGS
COPPER SPECIMEN NO. 4 - 42 % POROUS

FIGURE 8

TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

ARMCO IRON STANDARD

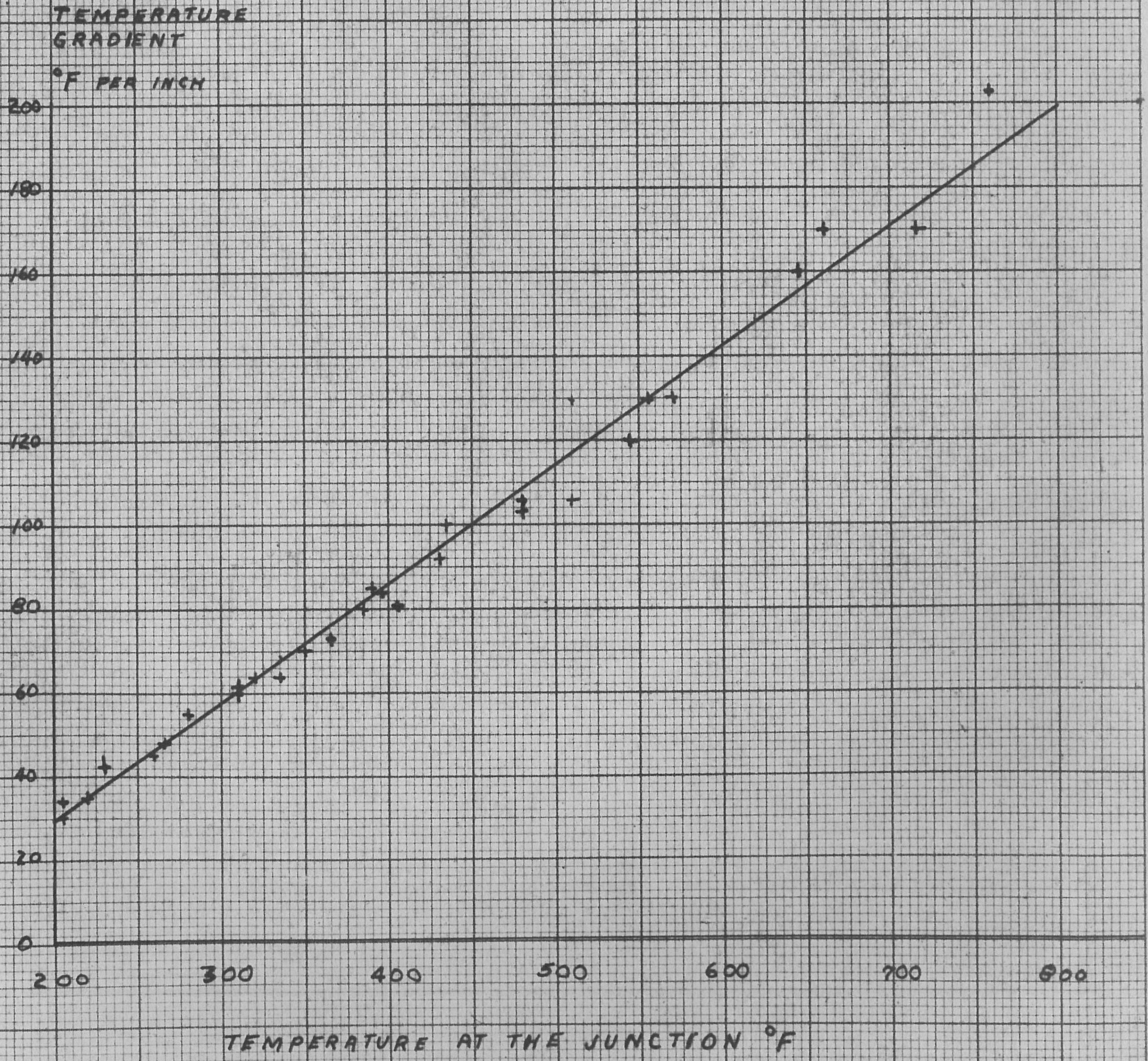


FIGURE 9

TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

WROUGHT COPPER

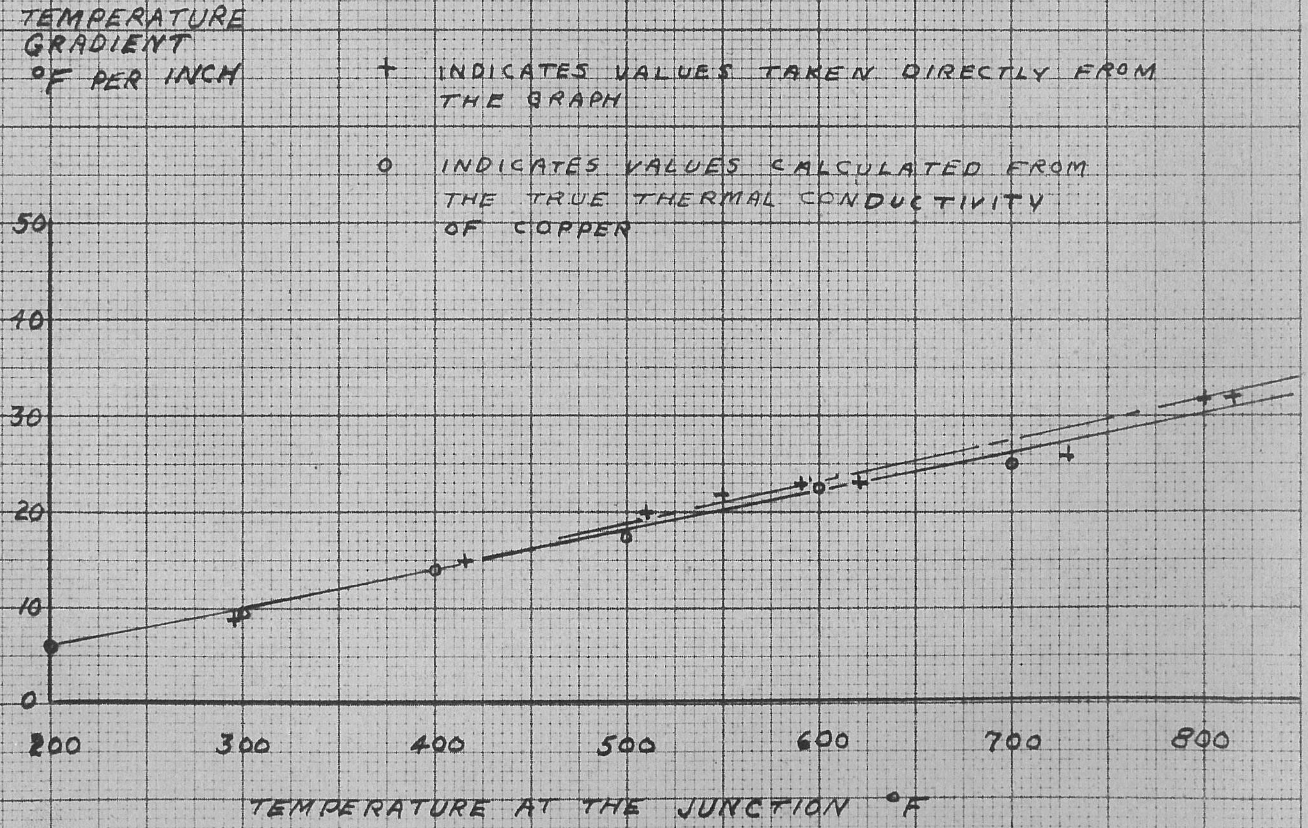


FIGURE 10

TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

COPPER SPECIMEN NUMBER 1 - 22 % POROUS

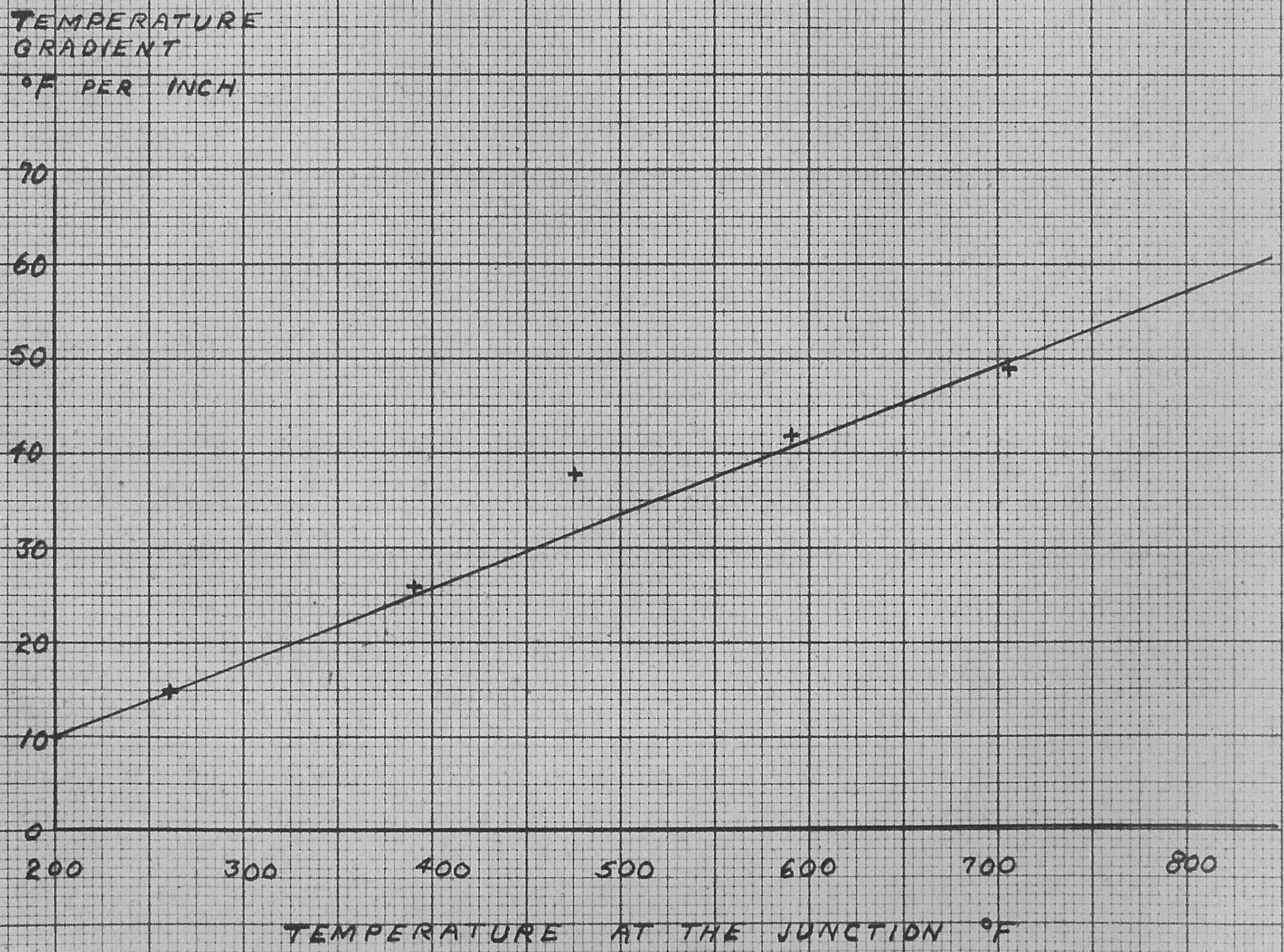
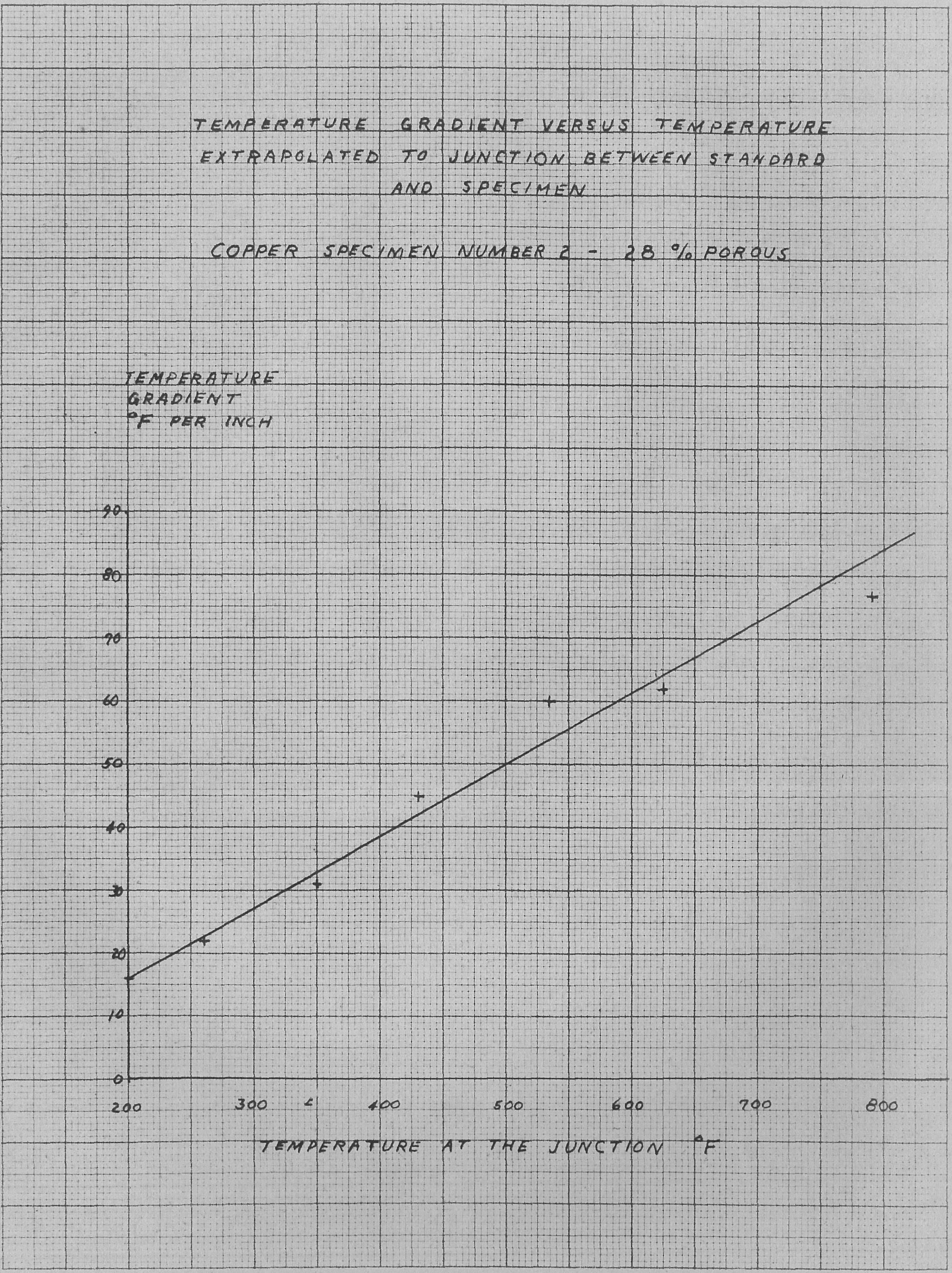


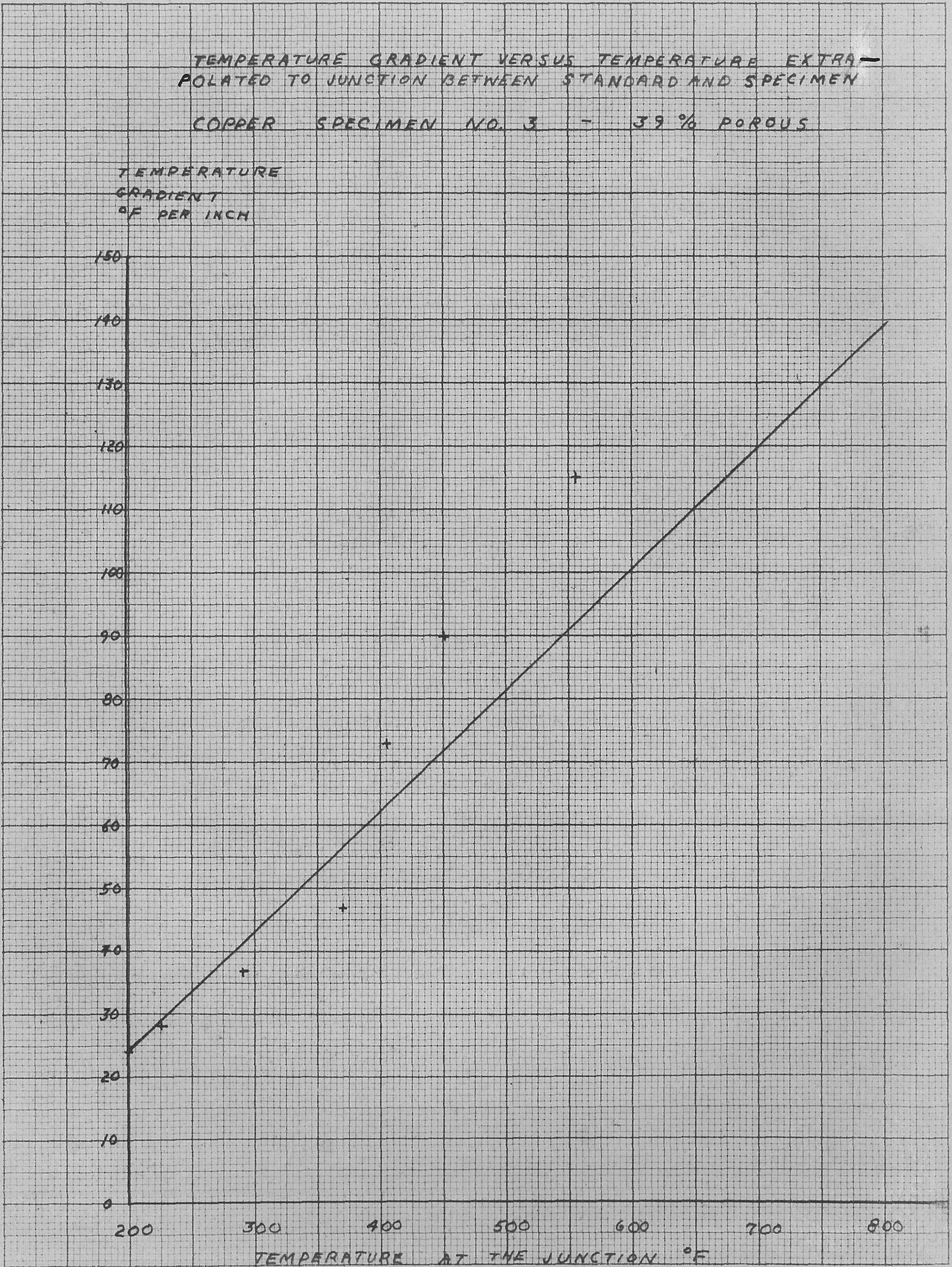
FIGURE 11



TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

COPPER SPECIMEN NUMBER 2 - 28 % POROUS

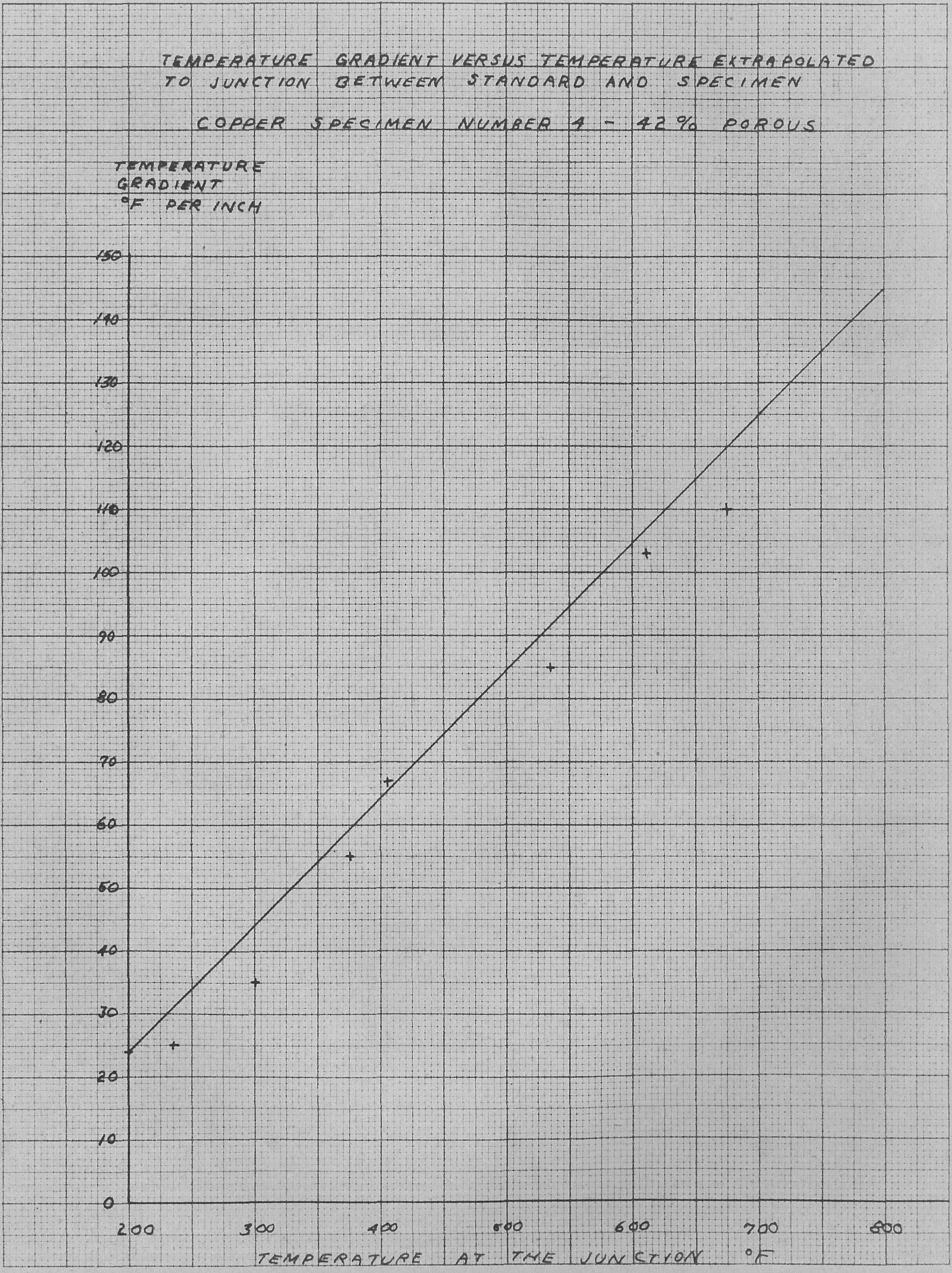
FIGURE 12



TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

COPPER SPECIMEN NO. 3 - 39 % POROUS

FIGURE 13



TEMPERATURE GRADIENT VERSUS TEMPERATURE EXTRAPOLATED TO JUNCTION BETWEEN STANDARD AND SPECIMEN

COPPER SPECIMEN NUMBER 4 - 42% POROUS

FIGURE 14

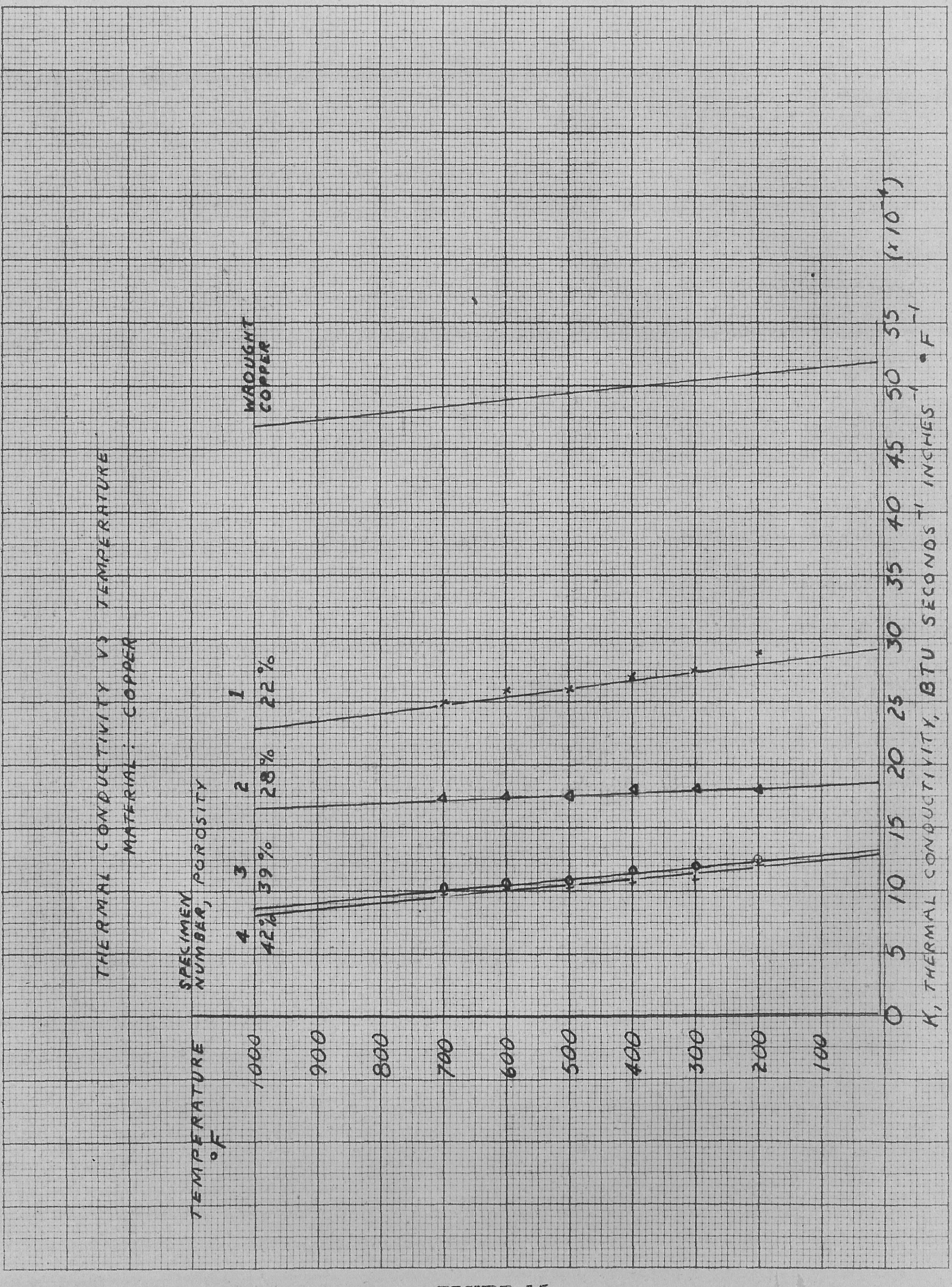

THERMAL CONDUCTIVITY VS TEMPERATURE
MATERIAL: COPPER
SPECIMEN NUMBER, POROSITY
4 42%
3 39%
2 28%
1 22%
WROUGHT COPPER
TEMPERATURE °F
1000
900
800
700
600
500
400
300
200
100
0
5
10
15
20
25
30
35
40
45
50
55
K, THERMAL CONDUCTIVITY, BTU SECONDS⁻¹ INCHES⁻¹ °F⁻¹ (x 10⁻⁴)

FIGURE 15

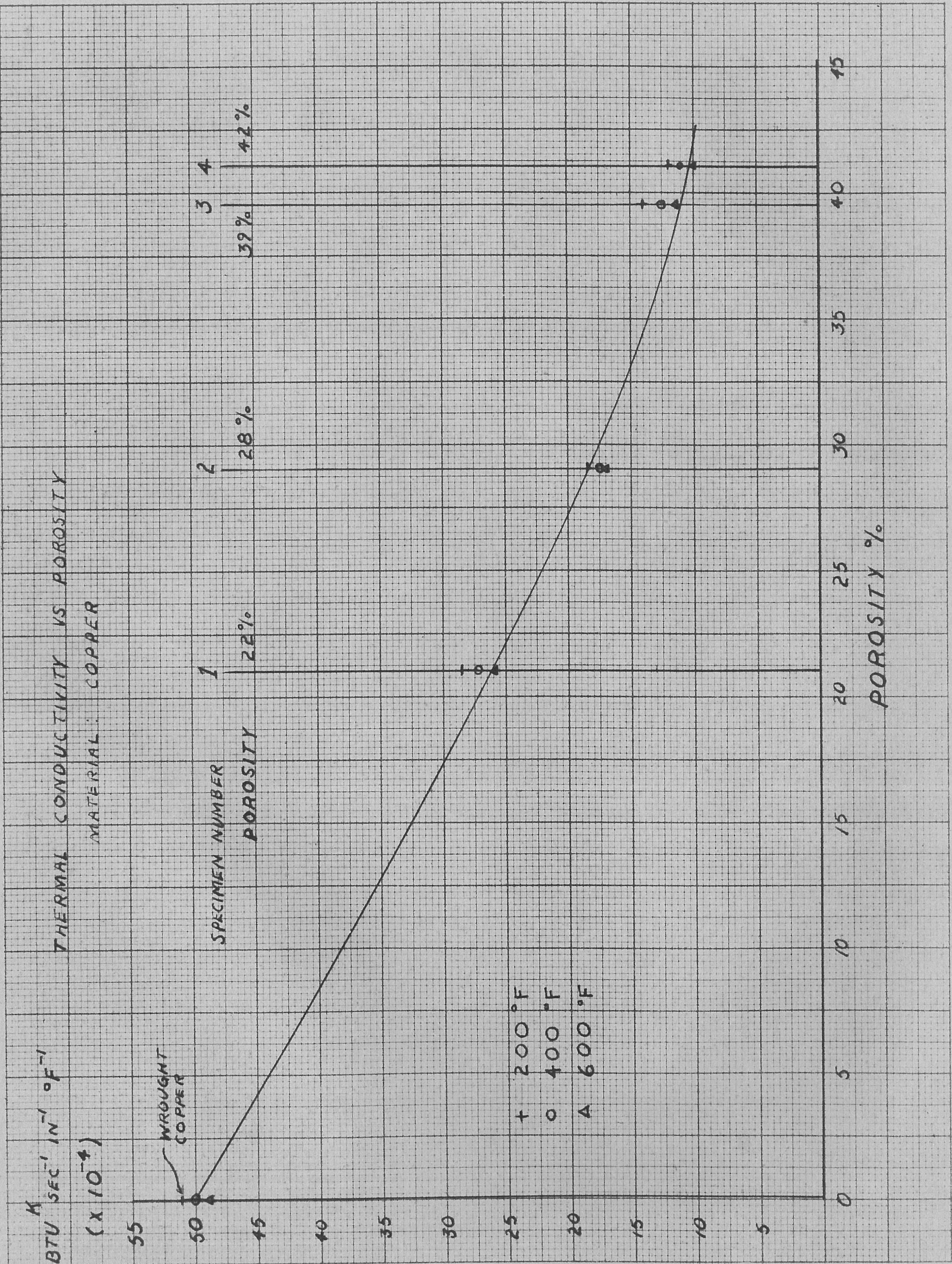

THERMAL CONDUCTIVITY VS POROSITY
MATERIAL: COPPER
K
BTU SEC⁻¹ IN⁻¹ °F⁻¹
(x 10⁻⁴)
WROUGHT COPPER
SPECIMEN NUMBER
1
2
3
4
POROSITY
22%
28%
39%
42%
+ 200 °F
o 400 °F
A 600 °F
55
50
45
40
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
POROSITY %

FIGURE 16

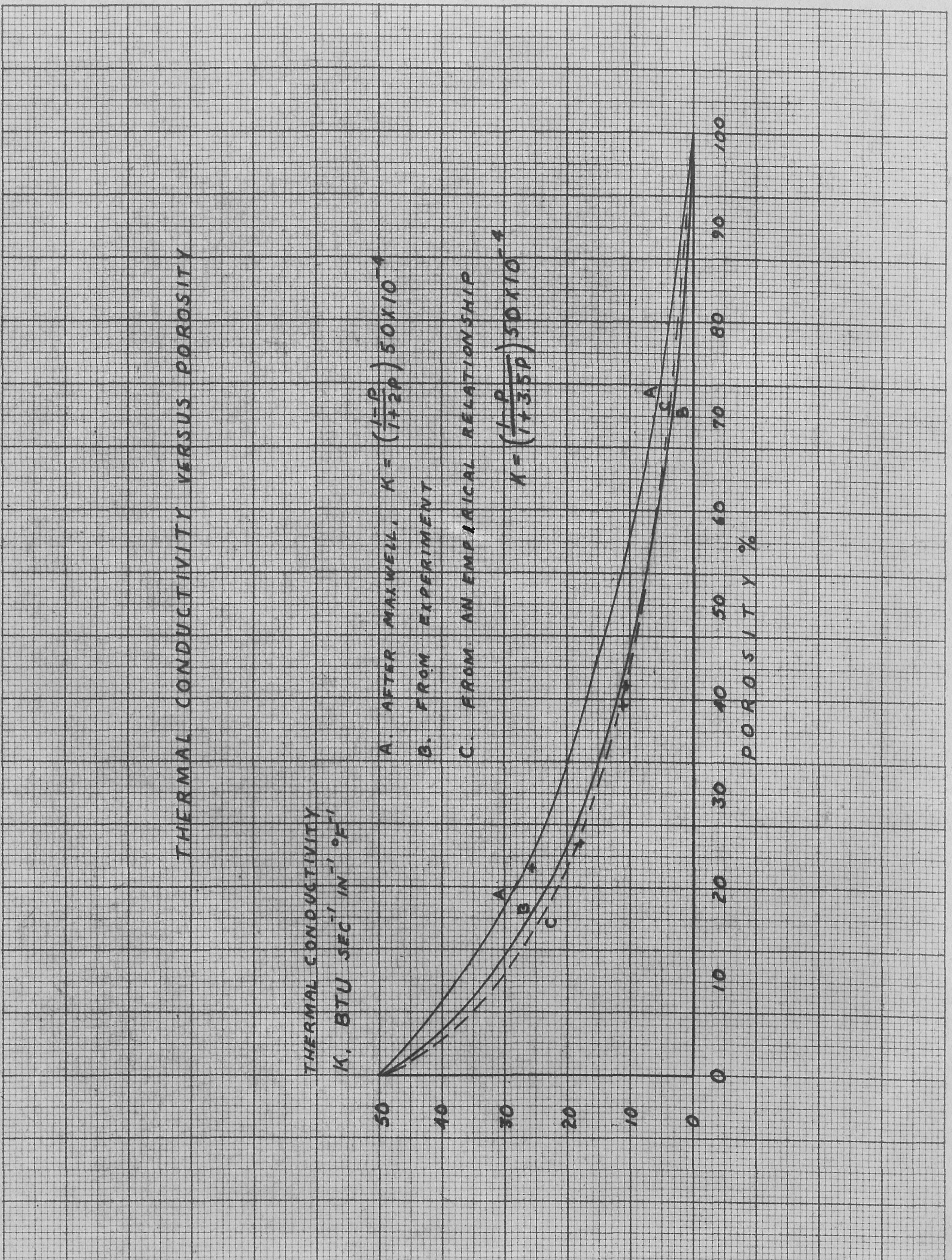
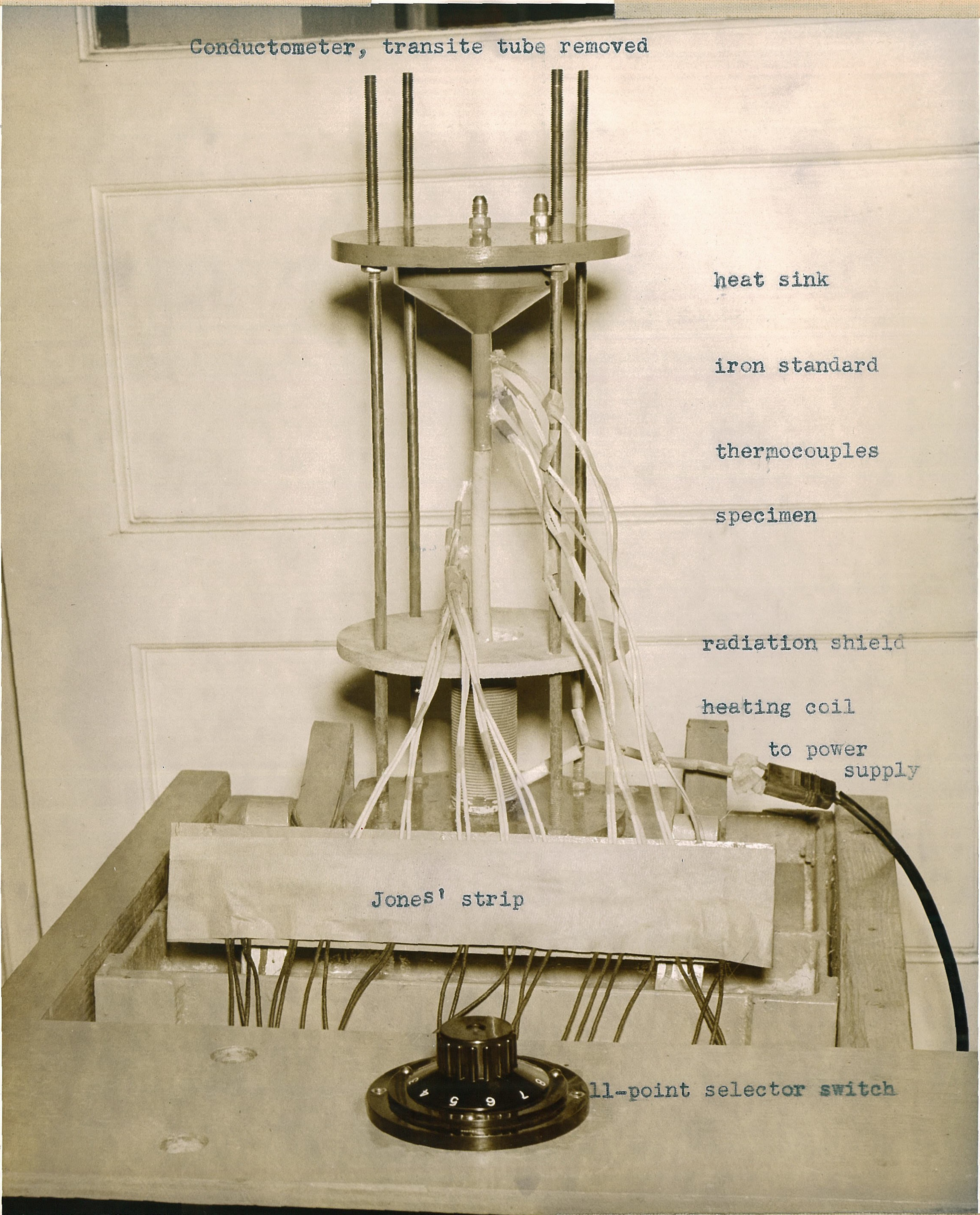
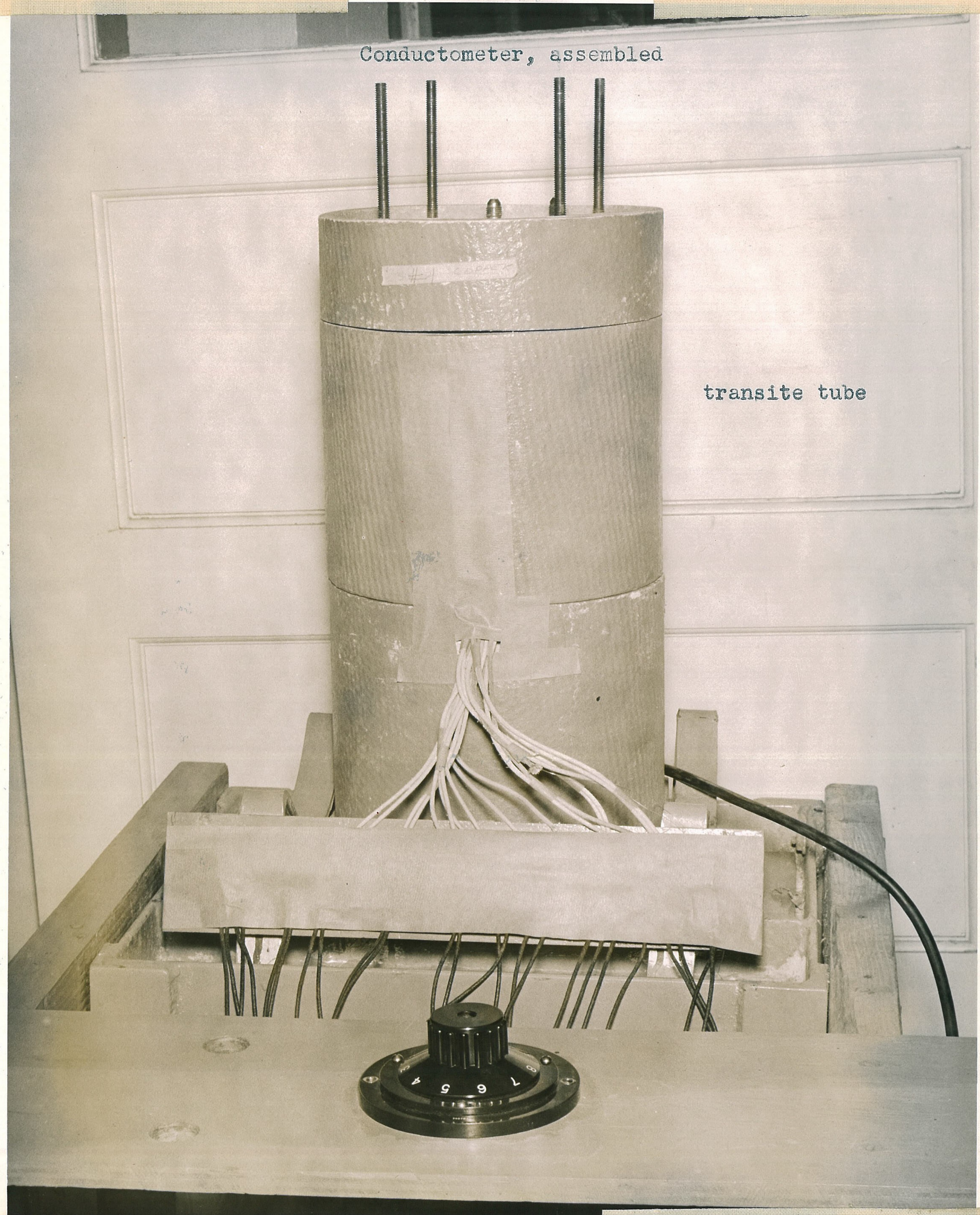

THERMAL CONDUCTIVITY VERSUS POROSITY
A. AFTER MAXWELL, $K = \left(\frac{1-P}{1+2P}\right) 50 \times 10^{-4}$
B. FROM EXPERIMENT
C. FROM AN EMPIRICAL RELATIONSHIP $K = \left(\frac{1-P}{1+3.5P}\right) 50 \times 10^{-4}$
THERMAL CONDUCTIVITY
K, BTU SEC^{-1} IN^{-1} $°F^{-1}$
50
40
30
20
10
0
POROSITY %
0
10
20
30
40
50
60
70
80
90
100
A
B
C
A
C
B

FIGURE 17



Conductometer, transite tube removed

FIGURE 18

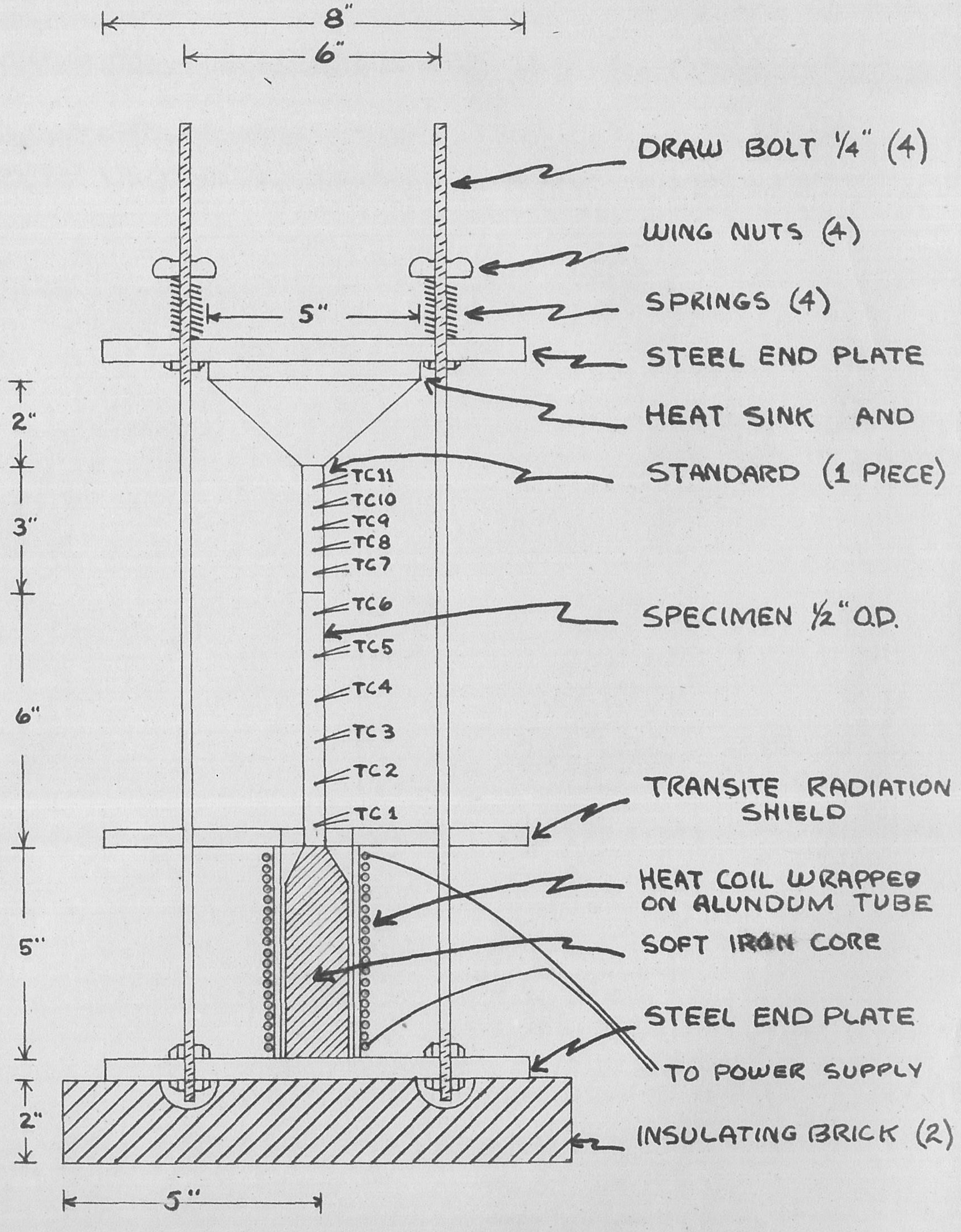


Conductometer, assembled

transite tube

FIGURE 19

CONDUCTOMETER CROSS-SECTIONAL VIEW



1/4" = 1"

FIGURE 20