An Improvement on Hering's Method of Measuring Mean Thermal Conductivities of Furnace Electrodes.

Thesis

Presented by

Course XIV.

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Electrochemical Laboratory,

Massachusetts Institute of Technology,

Cambridge, Mass.

AN IMPROVEMENT ON HERING'S METHOD OF MEASURING MEAN THERMAL CONDUCTIVITIES OF FURNACE ELECTRODES.

An Improvement on Hering's Method of Measuring Mean Thermal Conductivities of Furnace Electrodes.

INTRODUCTION.

In Volume XVI of the Transactions of the American Electrochemical Society (1909, p.292) Hering derives a formula for calculating the mean heat conductivity of furnace electrodes. If an electrode of length L and cross-section S is heated by an electric current until, when equilibrium is established, a temperature difference of T degrees exists between the middle and either end of the electrode, the power input being W, the expression for the mean thermal conductivity for a given temperature range is

$$k = .0299 \frac{WL}{TS}$$

where k is in gram-calorie-centimeter-centigrade-degree units, W in watts, L in centimeters, T in centigrade degrees, and S in square centimeters. Upon the precision of the value for the mean heat conductivity depends the correctness with which the dimensions of electrodes for minimum heat loss and, therefore, minimum energy loss, can be predetermined for particular conditions. Hering, therefore, pointed out the practical importance of determining for different temperature ranges the mean heat conductivities of the mateials used as electrodes. He also devised a method and made a number of measurements*. This method consisted in imbedding a rod in insulating material, surrounding it with a cage of six similar rods, sending the same current thru each of the rods and measuring the current thru the middle rod, the voltage drop across it, and the temperatures at the middle and at the ends. Such an arrangement was assumed by Hering to give nearly perfect heat insulation to the middle rod, so that no heat flowed from its sides, this being the condition under which the formula for mean heat conductivity, k , is applicable.

Wilkins* used Hering's method for the determination of the conductivities of graphite electrodes, and found that there was a flow of heat from the sides of the middle rod and that, therefore, values obtained by this method must be in error. This was shown by the facts that, first, the measured temperatures along the rod fell below those calculated by the formula*

$$t = T - \frac{Tl}{L} + \frac{Wl}{2jkS} - \frac{wl^2}{2jkS} ;$$

second, the temperature of the insulating material at points equidistant from the central electrode and two adjacent auxiliary electrodes and equidistant from the ends was found to be considerably lower than the temperature of the central rod.

*Trans. Am. Electroch. Soc. 17,166,(1910).
**H.S.Wilkins, M.I.T. Theses, (1914).
***Hering, Trans. Am. Electroch. Soc. 16,287,(1909).

The following investigation was undertaken with the view of obtaining more reliable data by actually establishing conditions of perfect heat insulation.

GENERAL DESCRIPTION.

METHOD. - The rod for which measurements are to be taken is held within a tube of the same material. Both the rod and the tube are electrically insulated from each other and have separate terminals at their ends, so that independent currents can be sent thru them. The currents are supplied from buss-bars fed from a motor-generator set capable of giving large currents at low voltages. The same ends of the rod and of the tube are connected to the buss-bar of the same polarity to eliminate a potential difference which would otherwise exist. At first a current is sent thru the tube untill the desired temperature is nearly reached. Then the circuit thru the rod is closed and the current is gradually increased until the temperature of the rod is the same as that of the tube, provided thermal equilibrium has been established. The readings of temperature, voltage, and current are then taken. This method was suggested and the apparatus was set up by Prof. M. deKay Thompson.

APPARATUS. - The arrangement of the apparatus is shown in Fig.1. The rod and the tube were of carbon and were obtained from the National Carbon Co. The length of the rod was about 76cm. and fitted to the length of about 2.5cm. from

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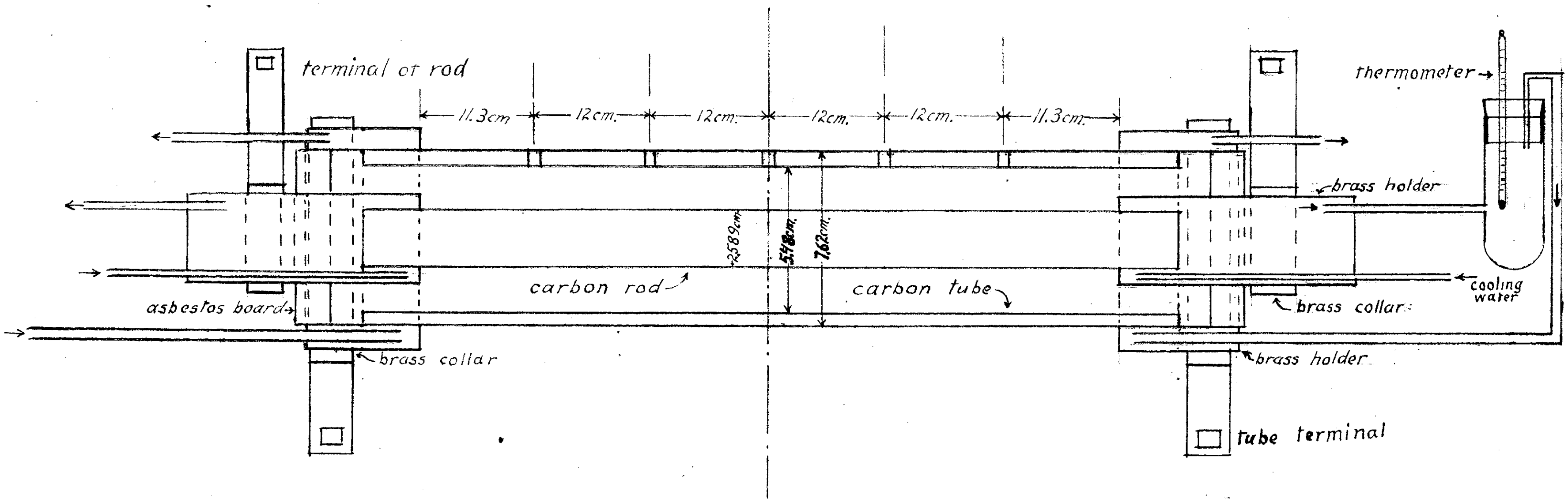


Fig. 1.- Sectional View of Complete Apparatus.

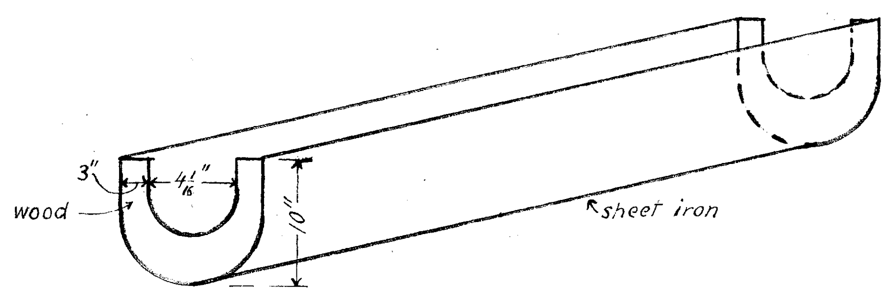


Fig. 2.- Trough.

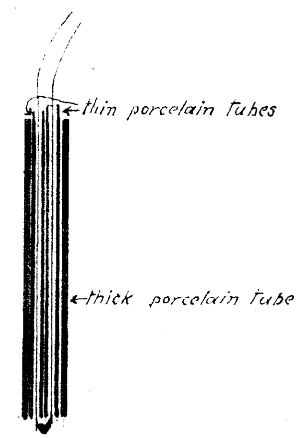


Fig. 3.-Thermo-couple of run 2.

each end into brass holders, so that the length of the rod between the holders was 70.57cm. The diameter of the rod was 2.589cm. and the cross-section 5.262sq.cm. The tube was of the same length as the rod and the distance between its brass holders was the same as for the rod. The inside and outside ~~diameters~~ of the tube were 2.74 and 3.81cm., respectively, making the cross-section 21.98sq.cm. The brass holders were water cooled. The ends of the electrode and tube were first copper-plated from an ordinary plating solution then soldered into the holders. Electrical connection was made by brass collars which could be tightened around the holders. The rod and the tube were electrically insulated from each other by means of asbestos boards, as shown in the diagram. A hole about one centimeter in diameter was drilled thru the top of the tube in the middle, and then four similar holes at equal distances, to permit the insertion of thermo-couples. The holes were kept covered with a little loose asbestos to prevent unnecessary air circulation. The entire apparatus rested on the brass holders of the tube in the trough shown diagramatically in Fig.2. The trough was employed primarilly as a convenient support for the apparatus; of course, it also prevented excessive circulation of aid and thus served to shorten the time necessary to get thermal equilibrium.

TEMPERATURE MEASUREMENTS. - The temperature of the rod and of the tube were measured by means of copper-ideal alloy (copper-nickel) thermo-couples used with a Leeds and Northrup potentiometer. The cold junctions of the couples were kept in test tubes filled with oil, thermometers passing thru the stoppers of the tubes to show the cold-junction temperatures. The wires exposed to hot temperatures were protected and insulated from each other up to the hot junction with asbestos string which was intertwined with the wires. This gave good insulation and flexibility which was found to be essential and which could not be obtained with the use of porcelain tubing insulation. With the potentiometer used a change of one degree could be easily detected. Instead of taking the temperatures of the ends of the rod directly, the temperatures of the exit cooling water were taken with thermometers. With the large amounts of cooling watter used for the comparatively low temperatures of experimentation, the cooling watter was hardly heated.

VOLTAGE AND CURRENT MEASUREMENTS. - The voltage drop along the rod was measured with a Weston voltmeter which could be read accuratly to less than five thousands of a volt. The voltmeter reading included the drop along about $2\frac{1}{4}$" of each brass holder of the rod; this drop was considered negligible. The currents thru the rod were measured with a Weston ammeter and shunt; one tenth of an ampere could be estimated. A more sensitive ammeter was not necessary, because fluctuations of the current generally amounted to about 0.2 ampere, due to the voltage of the generator not being constant. Both the voltmeter and the ammeter were calibrated with a potentiometer in the calibrating room of the Electrical Engineering Department. The currents thru the tube were measured with a large ammeter. The currents were adjusted by means of large carbon rheostats.

In order to point out the difficulties which were encountered and how they were overcome; in order to present the data which may be helpful for future investigations, but, chiefly, in order to show what was done to the electrode from run to run in case the properties of carbon change with the passage of current thru it, each run will be taken up separately. The important results will be summarized latter.

RUN 1.

The data obtained are shown in the table below.

This run showed that the inside of the tube was much hotter than the outside.

Current thru tube kept at 170 amps.

No current thru rod.

Minutes of Heating.	Temp. at Middle of Tube on outside.	Temp. at Middle of Rod.	Temp. of End.
15	178 °C	---	9 °C
30	219	---	"
35	219	---	"
40	212	---	"
45	212	---	"
50	---	270	"
55	215	275	"
60	215	---	"

RUN 2.

The object of this run was to find out the temperature gradient from the rod, thru the intervening space to the tube, at the middle section. This was done by allowing a couple to rest on the rod until it was shown that equilibrium was reached, then the couple was drawn out very gradually, about 1mm. at a time, and the temperatures taken. The couple is shown in Fig.3. The outside porcelain tube fitted tightly into the hole.

Current thru tube - 170 amps.

No current thru rod.

Minutes of Heating.	Temp. on Rod.	Approx. dist. from Rod in mm.	Temp.
20	213 °C		
25	235		
30	245		
35	251		
40	256		
45	262		
50	265		
55	267		
60	268		
65	269		
70	268		
75	268		
--	---	1	268
--	---	2	263
--	---	3	258
--	---	4	255
--	---	5	258
--	---	6	255
--	---	7	250
--	---	8	243
--	---	9	236
--	---	10	228
--	---	11	218
--	---	12	208
--	---	13	190
150	268		

This run has shown the necessity of measuring the temperatures on the inside of the tube and in different places.

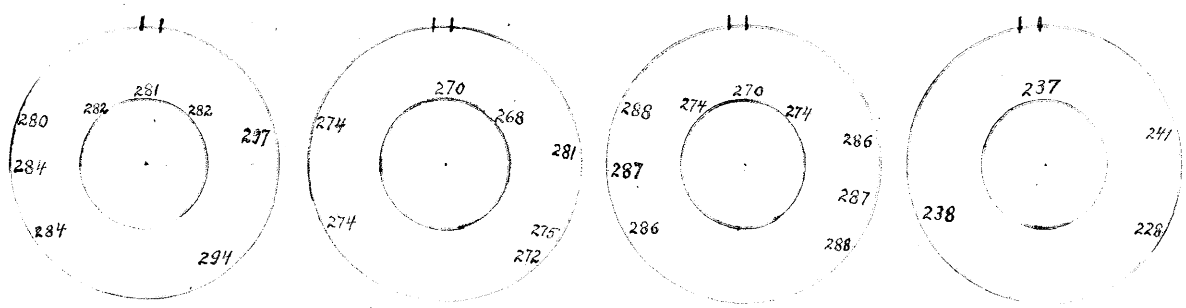
RUN 3.

In this and the following runs the asbestos-insulated couples were used.

The object of this run was to determine the character and magnitude of variation in temperatures around the different sections. The different points were reached by bending the couple up or down and inserting thru the holes. The results are best shown diagramatically.

Current thru tube - 170 amps.

No current thru rod.



Middle Section   12 cm. to left   12 cm. to right   24 cm. to right

It is easily seen that there is nothing regular in the way the temperatures vary around a section. Considering the middle section, the average of the temperatures around the tube is 289° C, while that on the rod is 282° C. The differencewas so small that it at ones became evident that much uncertainty would come in wherever it would have to be determined when the rod was to be considered as at the same temperature with the tube. This was especially true, since there were points around a section between whose temperatures there was a greater difference than there was between the average temperatures of the rod and that of the tube.

RUN 4.

It was thought that by heating the tube to a higher temperature than was done in the last run a greater temperature difference would be obtained between the tube and the rod and consequent measurements would be more certain. This run was made with this object in view.

In this and the following runs all holes except the one used at the time are covered with loose astestos.

(Tested and found that, 1/ different points on same section attain equilibrium at same time; 2/ couples behave identically.)

Current thru tube - 190 amps.

No current thru rod.

Temp. of cooling water - 6.5 ^{o}C.

Middle Section			Sect. 12cm. to right			Sect. 24cm. to right		
Tube		Rod	Tube		Rod	Tube		Rod
323	337	326	322	331	320	290	275	283
		324			318			280
327	333	329	325	327	320	280	260	280
330		326.3	326.3		319.3	276.3		281

Evidently the attempt to get a greater temperature difference between the rod and the tube was not successful. Moreover, at the section 24cm. from middle the average for the rod is higher that that for the tube. The fact that at at that section there is a difference of 30 ^{o}C. between two points on the tube makes matters more confusing.

RUN 5.

In this run 210amps. were sent thru the tube. After three hours equilibrium was established and the temperature of the rod at the middle reached 369° C. Then the circuit thru the rod was closed and 5 amps. sent thru it with the following results.

Time in Minutes.	Temperature of Rod.
0	369
5	370
10	373
15	374
20	376
25	376
30	373
35	371
40	369
45	374
50	375
55	377
60	375

Hours of passing 5 amps. thru rod.	Diff. between average temps. of tube and rod at middle section.
0	10°C
1	12
$2\frac{3}{4}$	8

This run showed that 5 amps. was of little effect at these temperatures and that a higher current would be required.

RUN 6.

In this run the tube and the rod were heated simultaneously with independent currents of values giving approximately equal current densities.

The current thru the tube was kept constant at 150 amps. thruout the run. The current thru the rod was kept at a constant value (as well as it could be done with the slightly fluctuating generator voltage) until equilibrium was established, and the readings taken. Then it was brought up or down by means of the carbon rheostat to some new value and, after reaching equilibrium, new readings were taken, and so on.

In taking the readings I guided myself by two representative points at the middle section, one on the tube and other on the rod. Previous runs have shown that these points were neither the hottest nor the coldest and came very close to the calculated average temperatures. It is for these points that the curves in Fig.5 are drawn. The use of a double-throw switch made it possible to read the two temperatures almost simultaneously.

Current through tube - 150 amps.

Amps. thru Rod.	Volts.	Temperature. of Rod.	Temperature. of Tube.
30.7	----	286.5	282.5
29.7	1.675	284	284
31.6 *	1.780 *	288 *	285 *
33.2	1.870	291	288
36.7	2.060	296.5	290
29.7	1.680	284	283
28.6	1.620	285	285
27.6	1.560	284	284
25.5	1.447	280	280

$k = .0299 \frac{WL}{TS} = .0721$

$r = .00422$

These data are plotted in Fig.5.

In the interval marked *, the temperatures around sections were taken the average values of which were as follows

	Middle	12cm.	24cm.	End.
Rod	281 °C	273	235	7.5
Tube	281	271	223	7.5

The temperature gradient calculated by Hering's formula is

Middle	12cm.	24cm.	End.
----	255	158	7.5

The calculated and observed temperature gradients are plotted in Fig.6.

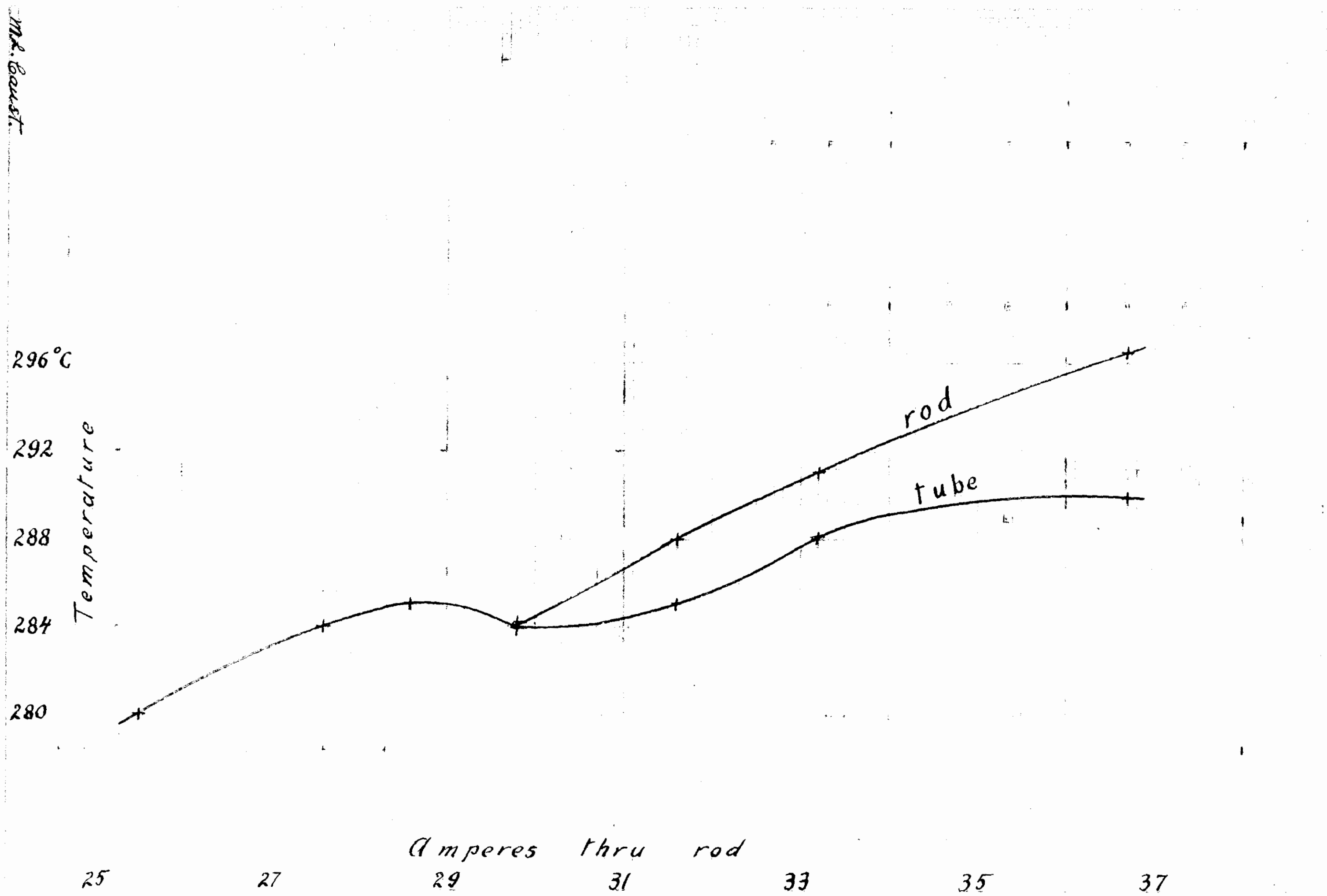


Fig. 5 — Change in temperature with changing current thru rod.

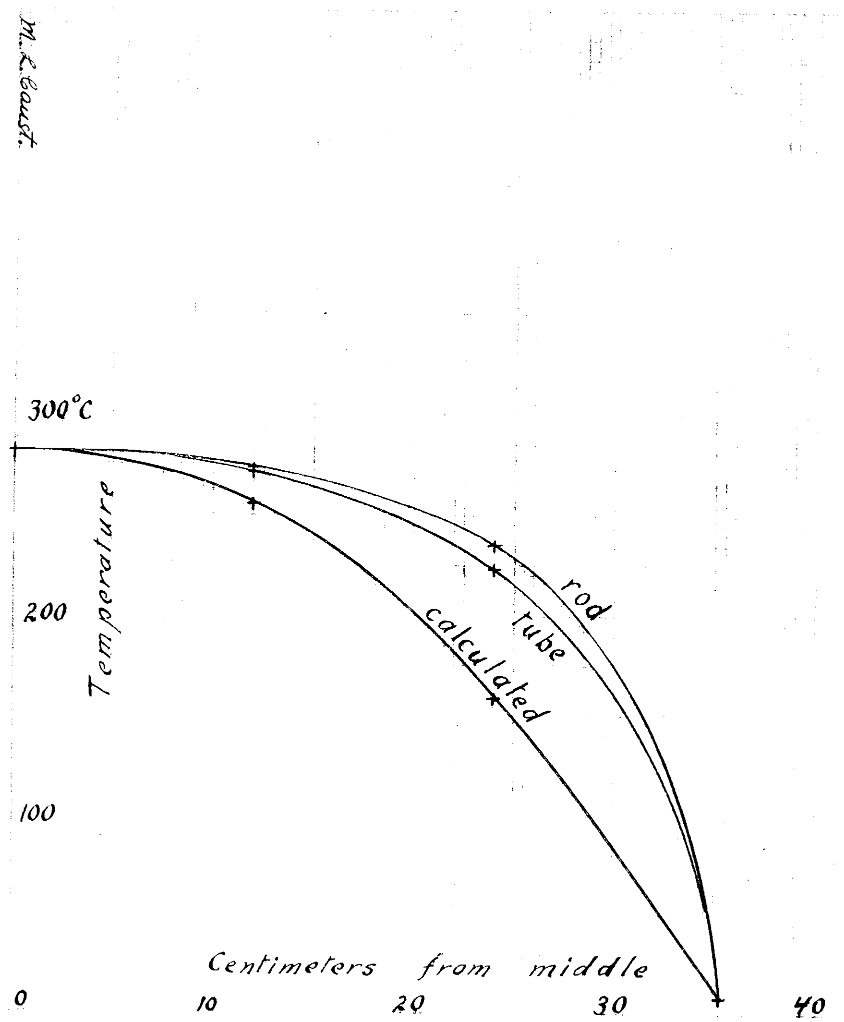


Fig. 6. — Temperature Gradients

An examination of Fig.5 must lead to the conclusion that the point where the two curves separate, namely, at 29.7 amps., is the point where the flow of heat is beyond doubt from rod to tube. At any point to the left one can not be sure that the existing temperature is not due to the current thru the tube. At any point to the right, the rod is considerably hotter than the tube and the desired condition of no flow of heat from the sides of the electrode is not realized. The temperature gradients plotted in Fig.6 show that even 29.7 amps. thru the rod make the latter hotter than the tube. However, since it is impossible to make the gradients of the tube and of the rod coincide thruout, one must have the rod hotter than the tube in order to be on the safe side.

RUN 7.

The object of this run was, first, to get results similar to those of run 6, but for somewhat higher temperatures; second, to get the temperature gradients on each side of the middle section.

It took so long to reach equilibrium and then to get the temperatures around the five sections, that such gradual variations in the current thru the rod as were made in the last run could not be gone into here.

The following were the data obtained.

Current thru tube - 180 amps.

Amps. thru Rod.	Volts.	Temperature. of Rod.	of Tube.
33.2	1.875	348.5	346
31.8	1.785	346	346

The temperature gradients were taken with 31.8 amps. flowing thru the rod, and are shown in Fig. 7. The temperatures plotted are the average temperatures around the sections and are given in the table below.

	End	24cm.	12cm.	Middle	12cm.	24cm.	End.
Rod	7.8	287	333	347	344	298	8.0
Tube	7.8	264	327	344	341	282	8.0
Calc.	---	192.5	313	347	313	192.5	---

It is seen from the curves in Fig.7 that the temperature gradient is not exactly the same on each side, but the difference is not very great.

The rod was unquestionably at a higher temperature than the tube, even more so than was true in run 6. Therefore, the value for k calculated with 31.8 amps. must be toogreat.

$$k = .0299 \frac{L}{S} \frac{31.8 \times 1.785}{(347 - 8)} = .0670$$

$$r = \frac{1.785}{31.8} \frac{S}{L} = .00419$$

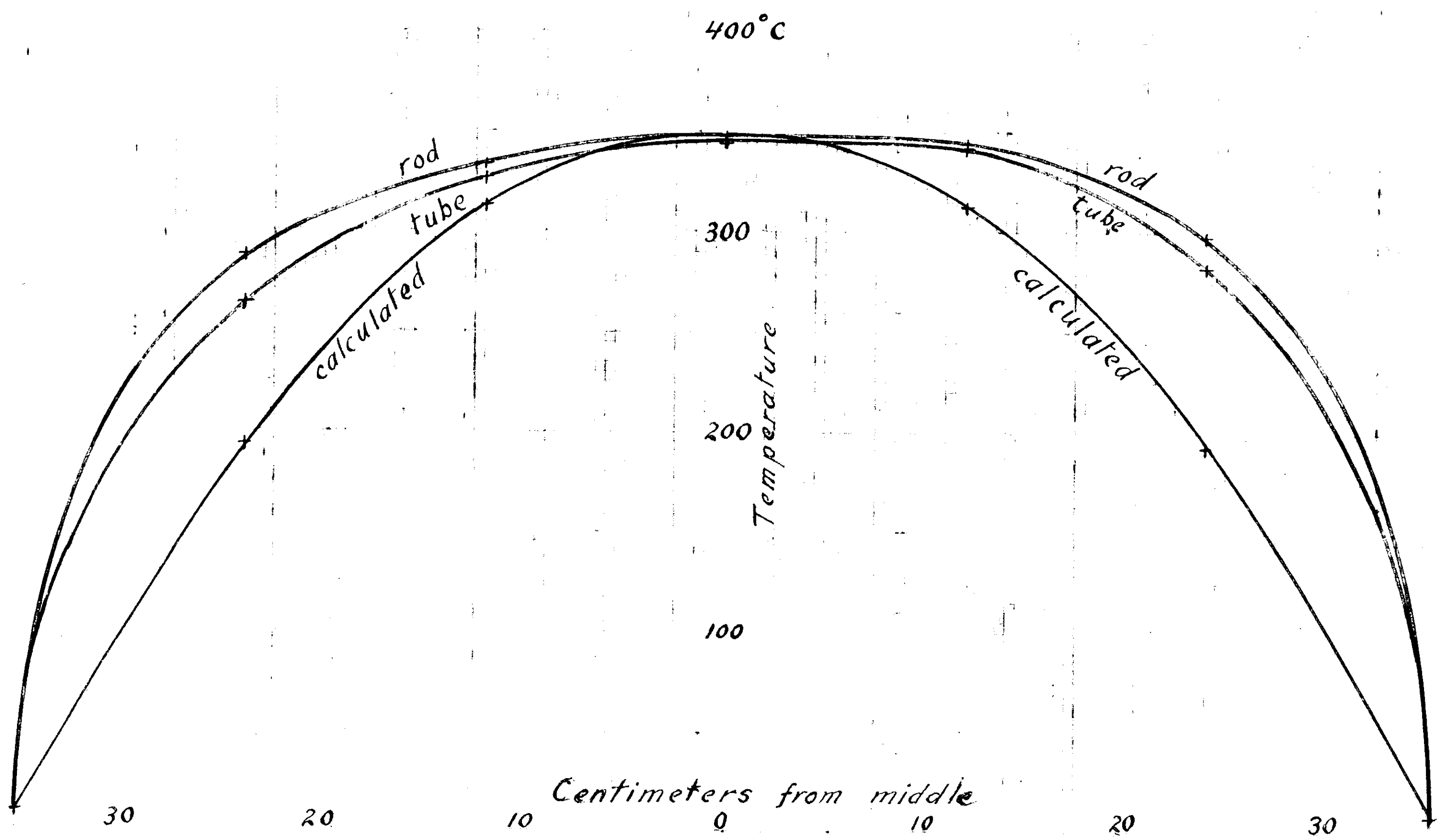


Fig. 7. —Temperature Gradients

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RUN 8.

This run was intended to be made the same way run 6 was made, but for higher temperatures. Two couples were inserted thru the middle hole, one resting on the rod, the other on the tube. The current thru the tube was 200 amps. The current thru the rod was 20.0 amps. at first and was gradually increased. When the latter current was already as great as 45.0 amps. and the rod was apparently still at lower temperature than the tube, the couples were reset to see whether the readings were correct. This at once showed that the rod was already to hot. (Evidently the couple which was supposed to touch the rod was, in fact, hanging in the air.) It was too late to try to get back to the desired point. In this run, therefore, only the data plotted in Fig.8 were obtained. It is seen that this curve looks very much like the corresponding curve in Fig.5. Taking the point indicated by the arrow as the correct point we get

$$k = .400 \frac{32.7 \times 1.815}{399 - 9} = .0609 \ (?)$$

$$r = .00414$$

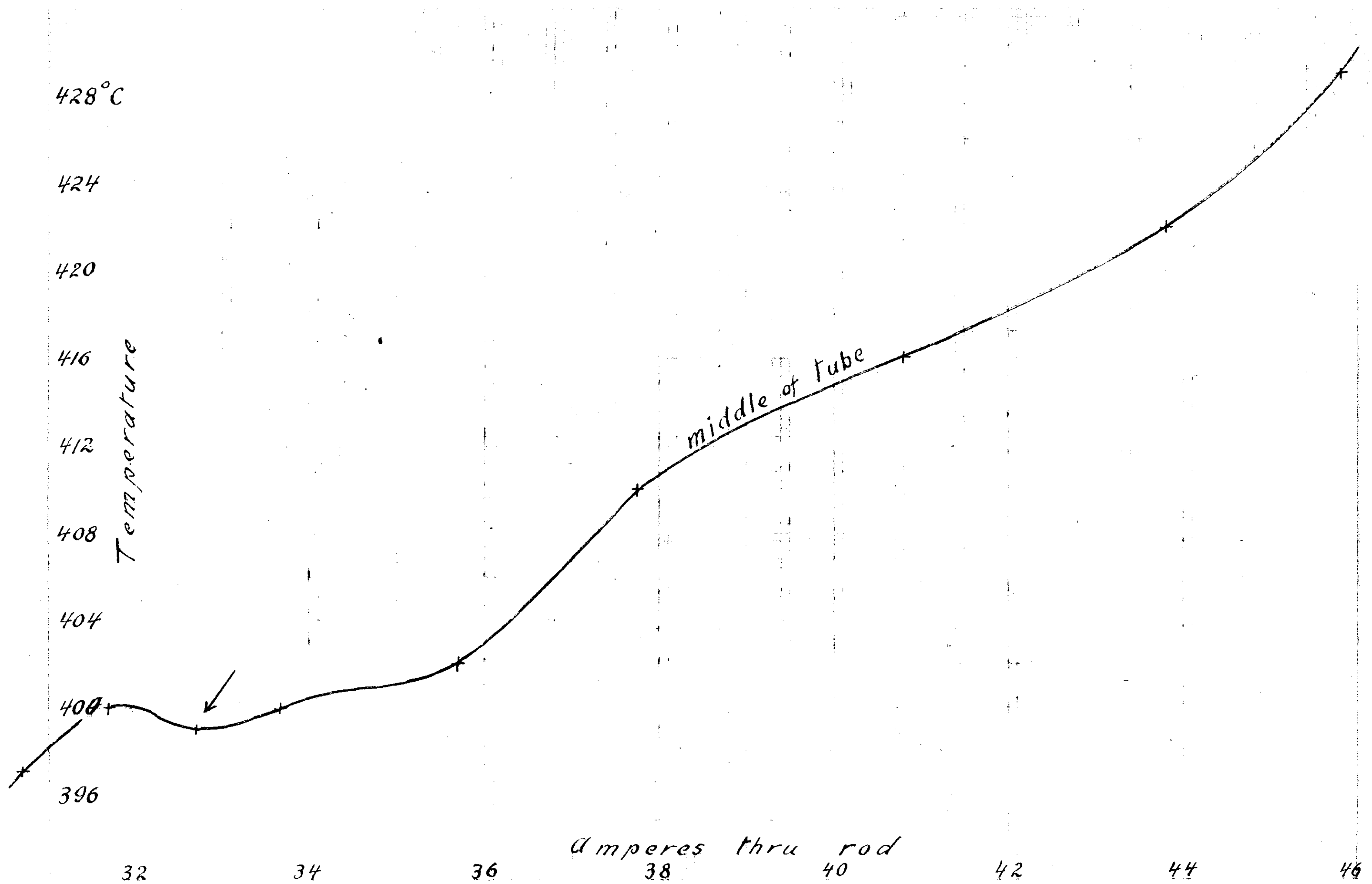

Fig. 8. —Change in temperature with changing current thru rod.

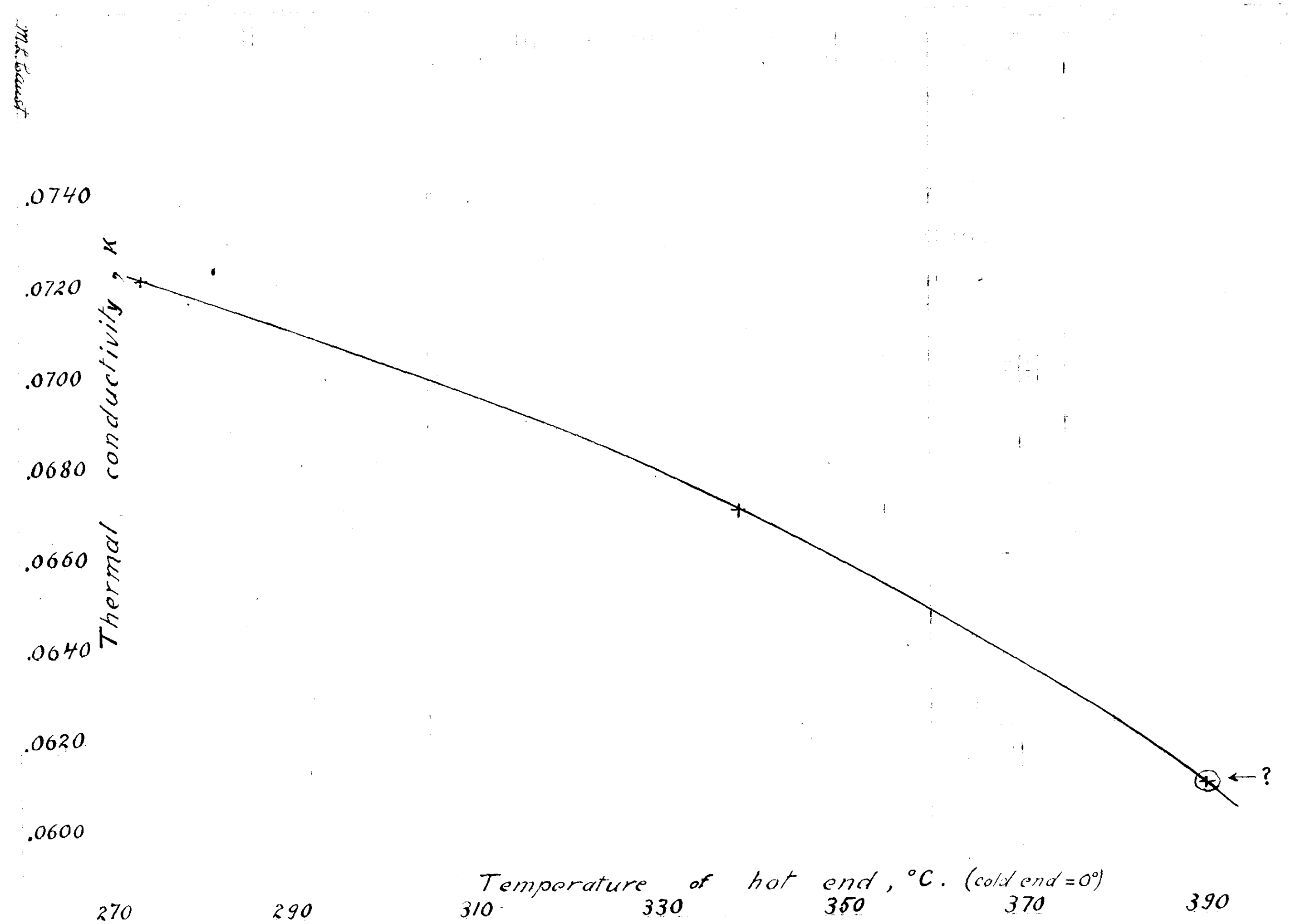

Fig. 9.—Change of Thermal Conductivity with Temperature.

RUN 9.

Began with 200 amps. thru tube and 30 amps. thru rod, so as to repeat run 8, but got unusually high temperatures.

In the following table the results of runs 8 and 9 are compared.

Current thru tube - 200 amps.

	Run 8		Run 9	
Hours of Heating	Amps. thru Rod at the Time.	Temp. at Middle.	Amps. thru Rod at the Time.	Temp. at Middle.
$\frac{1}{2}$	--	---	30	428
$1\frac{1}{2}$	29	395	30	438
$2\frac{1}{4}$	30	397	29	448
3	33	400	28	456
4	--	---	28	526
5	43	422	28	Red heat, disintegration of tube.
$5\frac{3}{4}$	45	429	28	

Why in this run, after a half hours heating, a temperature should be obtained equal to that obtained in run 8 only after $5\frac{3}{4}$ hours, and with a higher current thru rod, is not plain. The rapid rate of temperature increase indicates that oxidation set in almost from the very beginning, and accoring to Moissan* carbon does undergo oxidation between 375 and 490 ^{o}C. But why has this not occurred in run 8?

* Bull. 77, U. S. Bureau of Mines, p.42.

RUN 10.

Current thru tube - 150 amps.

	Run 10		Run 6	
Time in Hours.	Amperes thru Rod	Max. Temp.	Amperes thru Rod.	Max. Temp.
½	20	Red heat	--	----
5	--	---	28-35	300 ^{o}C.

After allowing to cool and sending smaller currents I again obtained unusually high temperatures. Evidently the tube could be used no longer to obtain reliable results.

I conclude from this run and run 9, that, once oxidation of an electrode is allowed to set in, and if after cooling it is again heated with an electric current, much less power will be required to bring it up to the oxidation temperature than was required before.

RUN 11.

The same rod was placed within a tube of galvanized sheet iron, (because another carbon tube could not be obtained.) To increase the resistance of the tube a spiral of about 4" pitch was cut throughout its length, going around six times. The tube was wrapped with a double layer of asbestos paper. to shut out the air.

Measurements at the middle section showed that the correct temperatures could not be obtained by just allowing the couple to rest on the smooth iron. On the upper half of the tube the couples could be held firmly against the iron. For this reason only the temperatures of the upper half of the tube were taken.

Current thru tube - 190 amps.

Middle Section.

Amperes thru Rod.	Temp.of Tube		Temperature of Rod.		
23	352	332	334	330	332
25	347	340	348	340	340
27	362	352	350	340	347
29	365	---	355	---	---

It required so much time to obtain equilibrium with each small change in current, that the desired stage of equal temperatures for tube and rod could not be reached the same day.

RUN 12.

The object of this run was to continue the previous run.

Current thru tube - 190 amps.

Middle Section.

Amperes Thru Rod.	Temp. of Tube	Temp. of Tube	Temperatures of Rod.	Temperatures of Rod.
29	364	359	361	363
30	371	359	364	359
32	371	357	367	361
33	387	370	382	373
35	404	395	398	391
37	414	402	410	401
40	425	414	422	412

These data did not seem to show anything conclusive. I had much difficulty in this run trying to keep the current thru the rod constant.

SUMMARY.

1.- An experimental investigation (by Wilkins) has shown that Hering's method of measuring mean thermal conductivities did not fulfil the condition of perfect insulation.

2.- A tube of the same material as the electrode was substituted for the six auxiliary electrodes and the insulating material of Hering's method.

3.- Temperature gradient curves were obtained falling above the calculated curves, where by Hering's method the opposite relation between the curves is found.

4.- The mean heat conductivity of a carbon electrode of the National Carbon Co., for the temperature range 280° C. (hot end) to 8° C. (cold end), is .0721 gram-calorie-centimeter-centigrade units; the resistivity is .00422 ohms per cm. cube.

For the temperature range 350° to 10° the thermal conductivity is .0670 and the resistivity is .00419.

For the temperature range 400° to 10° the thermal conductivity is .0609 (?), the resistivity is .00414.

5. -These values for the thermal conductivity are about 20% lower than Herring's value for approximately the same temperature range, which is what would be expected if

there is a flow of heat from the sides of the electrode in Hering's method. My values for electrical resistivity are in perfect agreement with Hering's, showing that the kind of electrode used is the same.

6. - The difficulties of the method are: First, temperatures at two points around the same section of the tube may differ by a greater amount than do the average temperatures of the tube and of the rod at the same section. Second, the temperature difference between the tube and the rod under any condition of heating is so small that excessive time is required before the desired thermal state is reached.

7. - This method, therefore, could hardly be used for higher temperatures with insulating material to prevent oxidation, because of the time which would be required to attain equilibrium. It may be possible to inclose the apparatus in a space filled with some inert gas and have an intricate system of couples permanently fixed in.

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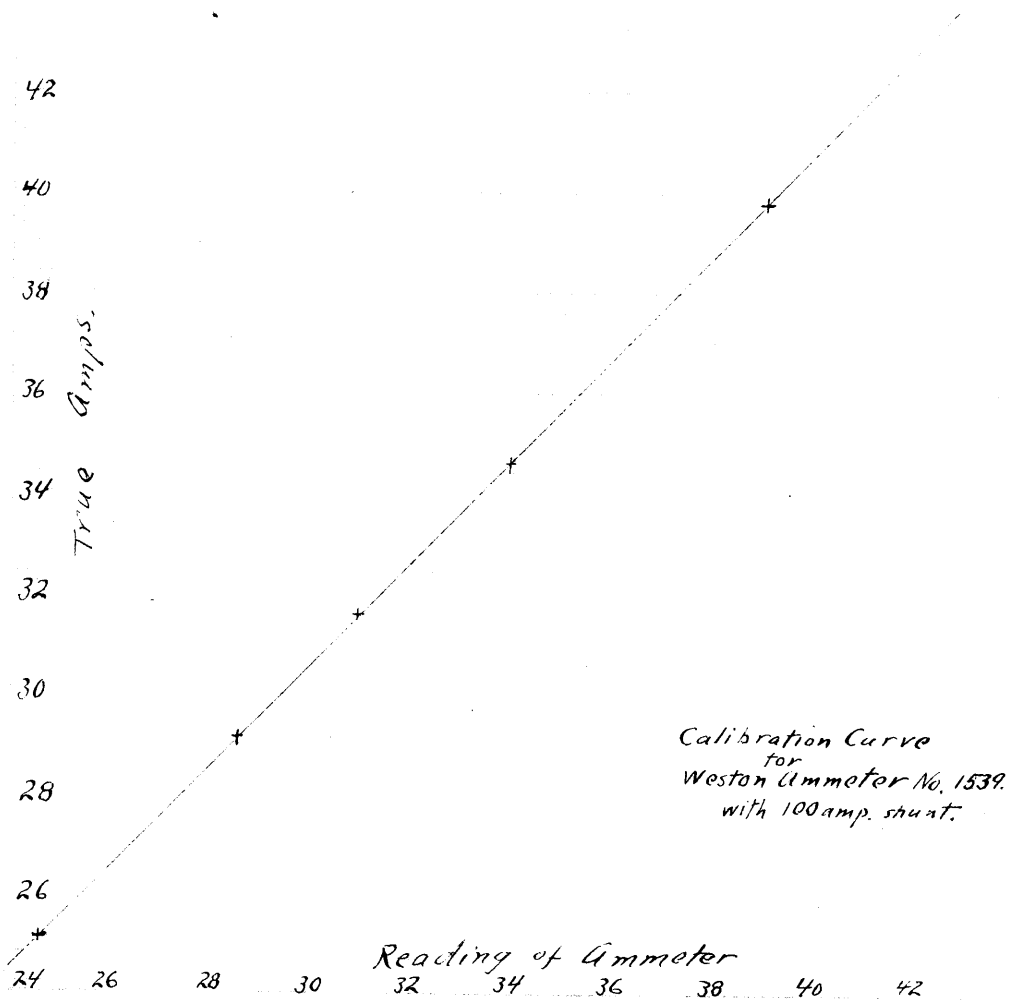

42
40
38
36
34
32
30
28
26
True Amps.
Calibration Curve
for
Weston Ammeter No. 1539.
with 100 amp. shunt.
Reading of Ammeter
24
26
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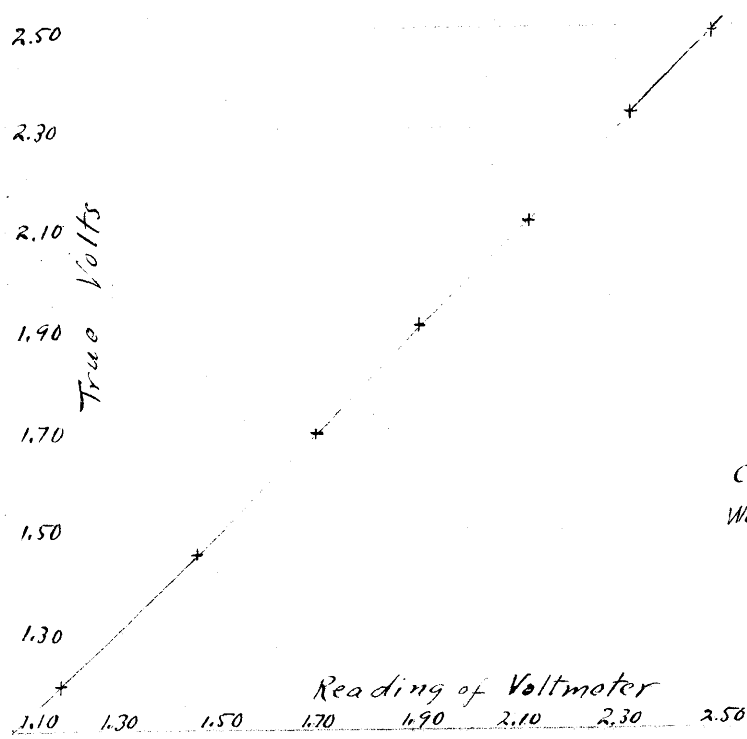
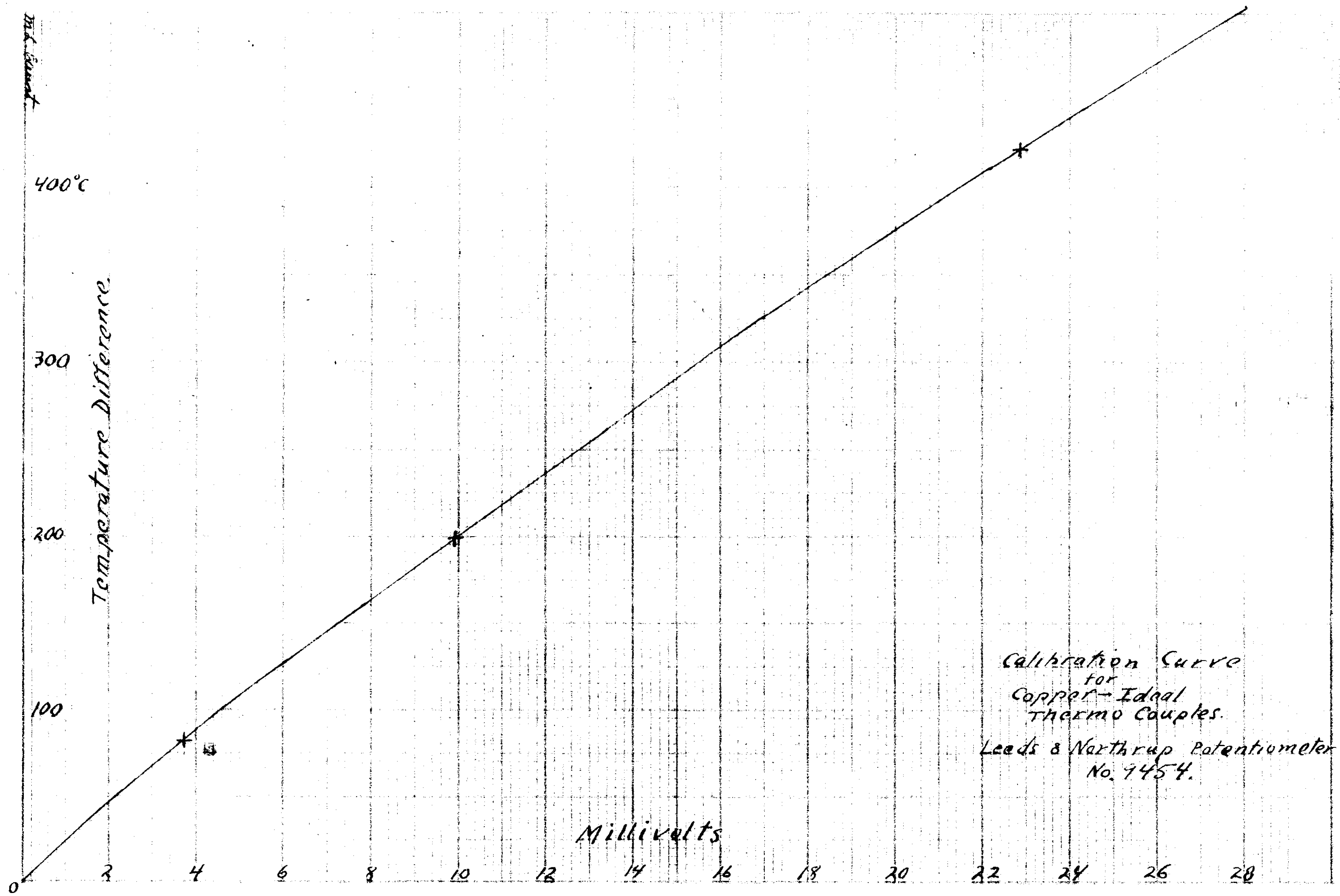
42



Calibration Curve
for
Weston Voltmeter No. 1409.
3 volt scale.


Temperature Difference
400°C
300
200
100
0
2
4
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12
14
16
18
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22
24
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Millivolts
Calibration Curve
for
Copper – Ideal
Thermo Couples.
Leeds & Northrup Potentiometer
No. 9454.