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Ratio of the thermal and electrical conductivities for gas carbon

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RATIO OF THE THERMAL AND ELECTRICAL CONDUCTIVITIES FOR GAS CARBON.

by

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A

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Approved by D. H. Gottschalk

Professor of Chemistry.

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RATIO OF THE THERMAL AND ELECTRICAL CONDUCTIVITIES FOR GAS CARBON.

INTRODUCTION.

The method of F. Kohlrausch[*] for the determination of the ratio of the heat conductivity λ to the electrical conductivity $\varkappa$ of a substance is of practical value as well as of theoretical interest. Of practical value because there may be obtained from it- with much greater ease than by direct methods- the heat conductivity which has immediate applications, not only to the design and construction of furnaces, but to various other matters of similar import: Of theoretical interest to the physicist, because of the Wiedemann-Franz law[#] and its consequent relation to the electron theory; to the mathematician[$], because of the applicability of the Fourier analyses.

(*) Kohlrausch, Ann.der Phy. (4) I, 145, (1900).
Kohlrausch, Sitz.Ber.der Berlin Ak.d.W. 38 711, (1899).
Jaeger und Diesselhorst, Sitz.Ber.der Berlin Ak.d.W. 38 719, (1899).
Jaeger und Diesselhorst, Wiss. Abh.der Phy.-Tech. Reichs. 3 269, (1899).

(#) e.g. See Winkelmann's Handbuch.

($) e.g. See Carslaw, "Introduction to Fourier's Series and Integrals, and the Mathematical Conduction of Heat", or Fourier, "Theory of Heat."

Kohlrausch's method consists in sending a steady electric current through a rod of the material under consideration, the ends of which are kept at the same constant temperature. This rod will be heated according to Jaule's law. The rod is insulated as well as possible and when equilibrium is reached, we have a flow of heat from the middle of the rod towards the ends. The stationary condition means that just as much heat is being generated as is flowing towards the ends.

It can be shown that if the temperature difference between the middle and one of the ends is U, and the voltage drop between the two ends is V, then $\frac{\lambda}{\varkappa} = \frac{1}{8}\frac{V^2}{U}$ (*). If V is expressed in volts, U is expressed in degrees Centigrade and $\varkappa$ has been determined in $\frac{1}{\text{ohm cm}}$, then λ will be given in $\frac{\text{watts}}{\text{cm degree}}$. In order to reduce λ to the dimensions $\frac{\text{gram cal.}}{\text{cm watt sec.}}$, we must use the relation $\frac{\lambda}{\varkappa} = 0.02983\frac{V^2}{U}$. (The calculation follows from the relation 1 erg/sec.= 10^{-7} watts = 2.394 X 10^{-8} gram.cal/sec.)

This, however, assumes the case of perfect heat insulation; that is, that none of the heat generated is lost by radiation, conduction or convection through the curved surface of the rod. In an actual experiment such

(*) Müller-Pouillet's Lehrbuch der Physik, Vol. III, Page 779.

losses do occur and must be determined; this may be done by a similar experiment without the use of the electric current. From the data thus obtained, a correction factor may be calculated which is then applied to an experiment with current, providing that other conditions are the same.

In the case of good conductors this correction factor is relatively small when the proper precautions are observed. If, for example, cotton is the insulating material, convection will be almost entirely excluded and conduction and radiation will be reduced to a minimum. On this account the rod will offer so much less resistance to the carrying of the heat current, than the insulating material, that almost entirely all of the heat will follow the rod of the material being experimented upon.

In this respect metals are ideal for this method. One drawback, however, presents itself. The electrical resistances of these materials are small. This means that it will take large currents to make the difference in temperature and the voltage drop between the middle of the rod and the ends great enough to be measured with sufficient accuracy. In the case of a copper rod a current of 340 amperes was necessary to make a temperature difference of 2.5° C. and 0.006 volts* in 5.5 cm.length, and this

(*) Jaeger und Diesselhorst, Wiss.Abh.der Phy.-Tech Reich. 3 269, (1899).

current had to be maintained steady for about one hour.

On the other hand the case of poor conductors presents an advantage in that only small currents are necessary to get the desired temperature drop and an easily measured difference of potential. In the case of the gas carbon rod used in these experiments 3.5 amperes are sufficient, and in the case of poorer conductors, as galena, blende, etc., only a fraction of an ampere would be needed.

Poor conductors of electricity are also poor conductors of heat and one would be led to think that the correction loss would be correspondingly greater. The object of these preliminary experiments was to find out, whether or not, this loss would be so large as to render this method unfit for use.

If this proved true when the ordinary precautions were taken, then another method might be tried. The rod of the material under investigation was to be placed in the axis of a glass cylinder the ends of which were to be soldered to the water baths and the interior of which was to be platinum plated. The platinum plated layer was to decrease in thickness as the center of the rod was approached. The apparatus was then to be connected with an air pump and a high vacuum (a few thousandths of a mm. of mercury) obtained. The connecting tube could then be sealed off and the apparatus would be ready for use. An electric current would be sent along the platinum plated layer and this would generate heat- most at the center- which would greatly reduce the radiation; furthermore, the bright shining platinum plated surface would serve to reflect back almost all of the radiant heat. The high vacuum would also prevent conduction and convection. Lack of time prevented trying this arrangement, but it is hoped that at some future time it will be given a trial.

DESCRIPTION OF APPARATUS.

The following apparatus was used in the experiments:

WATER BATHS. Two water baths were placed at the ends of the carbon rod. These served to keep the end of the rod at a constant temperature. They were supplied with water by means of a small centrifugal pump situated in a thermostat about 30 cm. away. The water was pumped through large rubber tubing to a "Y", where the stream was divided, one-half of it flowing through each water bath, then back to the thermostat.

The water baths consisted of circular sheet iron cylinders about 9 cm. in diameter and 14 cm. long. Each bath held approximately 750 cc. Their surface was surrounded by a c●m. layer of cotton held in place by a covering of canton flannel. Their construction is best shown by Fig. 1.

Fig. I.

Crossection of end baths and Carbon Rod.

The direction of the flow of the water is denoted by the arrows. The metal tubes A, A' were purposely extended to within an inch of the surfaces of attachment of the rod. This insured an even temperature by causing a good circulation of the water. The openings marked B,B' are for the outflow and are connected to the thermostat by means of rubber tubing. C,C' served as receptacles for one solder joint of the thermocouples and for a thermometer. All connections between the thermostat and the water baths were made as short as possible to prevent undue cooling of the water and to increase the capacity of the pump. The water was supplied at a rate of about three liters per minute. This meant a velocity of about 24 cm. per minute in the baths.

THE ROD. The rod experimented upon was a cylinder of gas carbon 9.5 cm. long and about 1 cm. in diameter. It contained three small holes- about 1 mm. in diameter and 5 mm. deep- bored at right angles to the axis of the rod. The middle hole was placed as near the middle of the rod as was possible and the other holes were placed at a distance of 2.2 cm. on either side. This fastening of the rod was accomplished in the following manner: each end was given an extremely thin plate of copper. This made it possible ~~to solder~~ to solder the rod to a square sheet of copper which was in turn soldered to the proper end of the water bath. During the experiments heat losses from the curved surface of the rod were minimized by its being surrounded with a thick layer of cotton.

THERMOCOUPLES AND VOLTAGE WIRES.* Five thermocouples and three voltage wires were used. Three of the thermocouples were were used to obtain the differences in temperature between the three bore holes and the end bath; the other two were used to determine whether or not, the two end baths were at the same temperature. The three voltage wires gave the drop between the bore holes. The thermocouples were made of nickel and manganin wire and had a thermo electric force of about 20 microvolts per degree. Iron and manganin were chosen as the thermo elements, as they give a rather large deflection and at the same time are only fair conductors of heat. The manganin wires had a diameter of 0.1 mm. and the nickel wire 0.27 mm. The ends of the thermo couples were twisted together and soldered. They were then given a heavy coating of zapon lacquer. One solder joint of a thermocouple and one voltage wire (0.1 mm. manganin) were securely fixed in each bore hole by means of small wooden wedges. The other solder joints were further protected by being surrounded by thin glass tubing to prevent any possibility of chemi-electromotive force, and placed in the water bath. The other two thermocouples had one manganin wire in common. One solder joint dipped in each water bath and the common joint was placed in the thermostat. To the ends of each of the

(*) For wiring diagram and connections, see Fig. II, page 10.

voltage and thermocouple wires were soldered short, heavy, copper wires to insure better connections with the binding posts on the switchboards.

SWITCHBOARDS. * The switchboards were small blocks of wood containing mercury wells. Contacts with the voltage, thermocouple, and galvanometer wires were made by means of binding posts which were permanently connected to the mercury wells. The circuits were completed by means of amalgamated copper wires which bridged the way between the wells.

GALVANOMETER. A high sensibility galvanometer of the moving coil type, constructed by Leeds, Northrup & Co., was used for the measurement of the current in the thermocouple and voltage circuits. It had an internal resistance of 38.5 Ohms and a sensitiveness of about 80 megohms. It was found necessary to protect the galvanometer from chance air currents and against sudden temperature changes by surrounding it completely with cotton. Thermocurrents, however, could not be eliminated completely, due to the fact that a constant temperature room was not available, and that several contacts had to be made between different metals, as copper and mercury. On this account, a reversing key was placed in the circuit close to the galvanometer.

(*) See Fig. II, page 10.

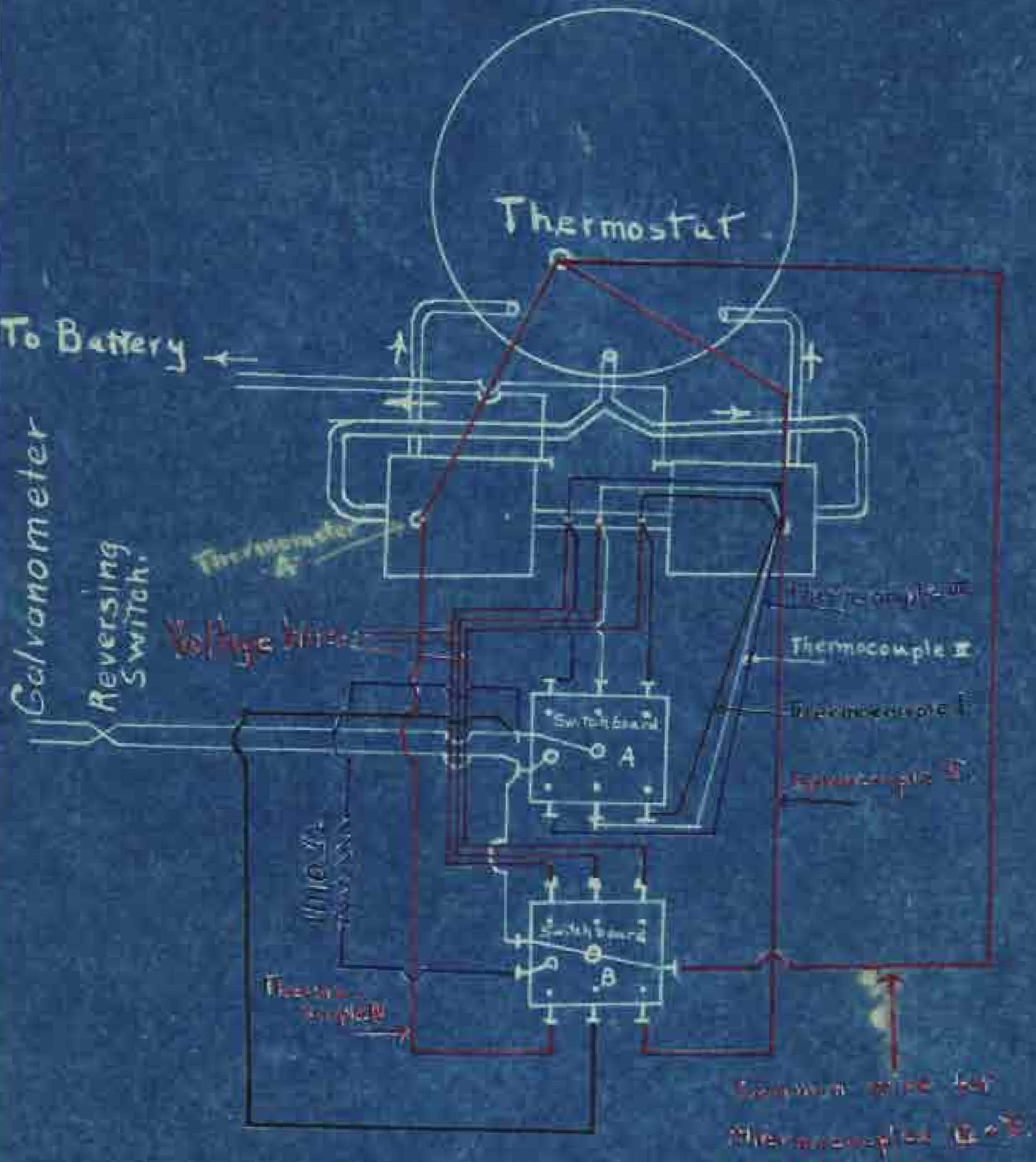
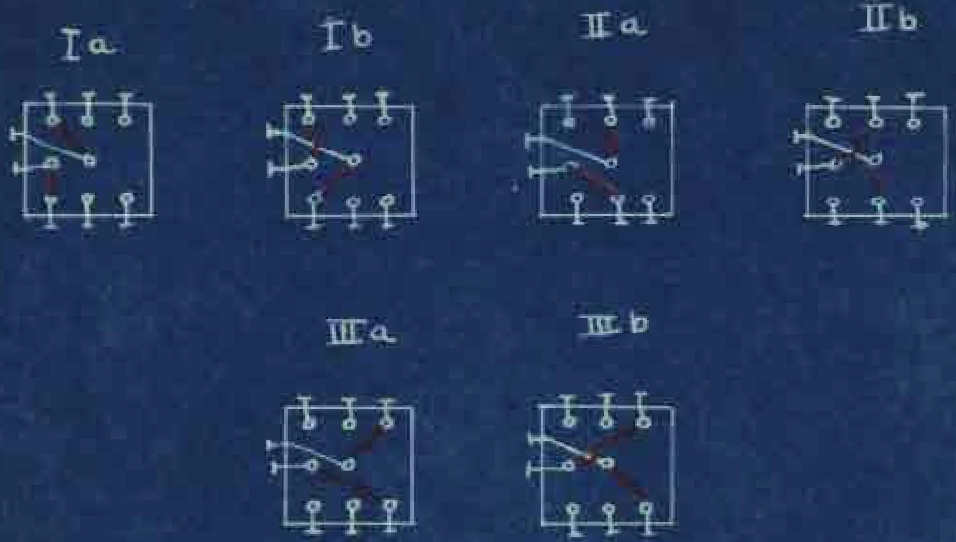


Fig. II.

Diagram showing connections and general arrangement of apparatus.

Switchboard "A".



Switchboard "B".

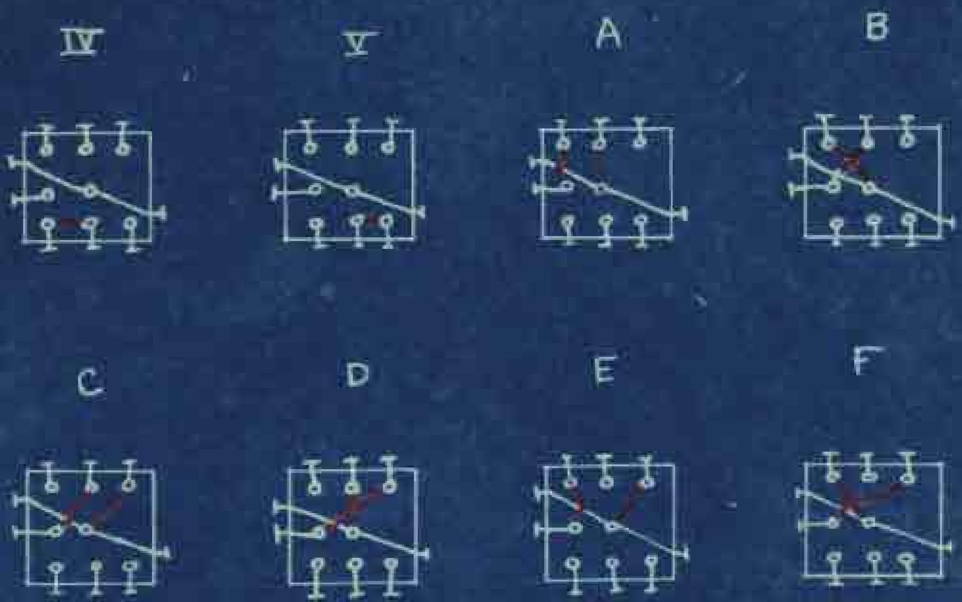


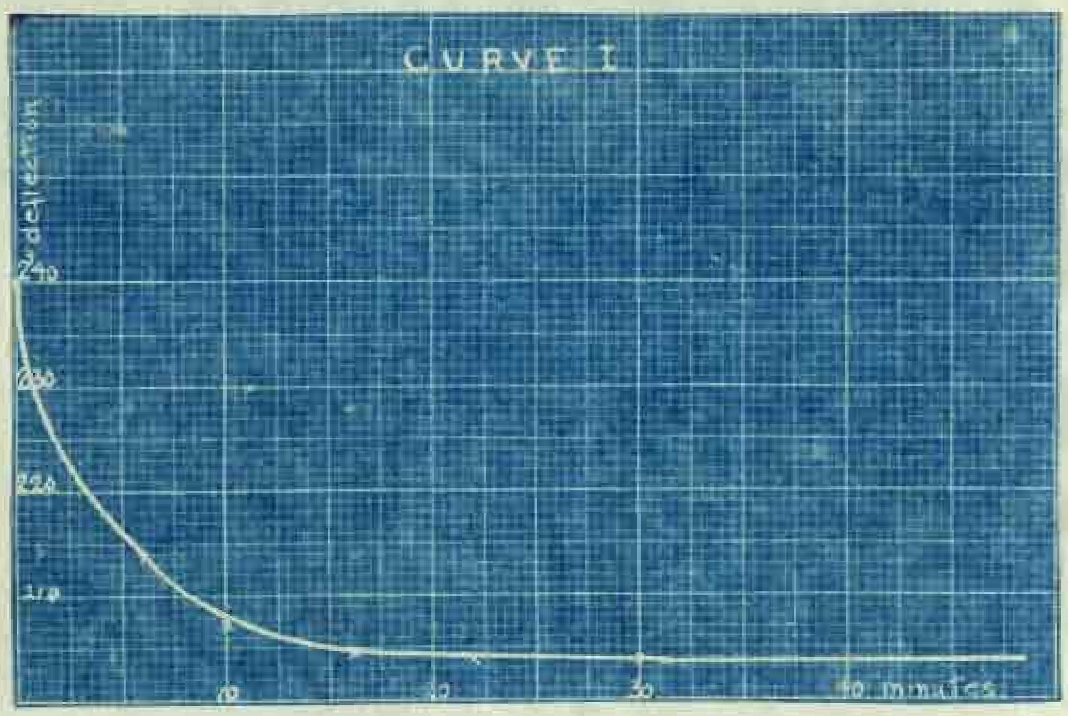
Fig. III.

By taking the sum of the readings of the current, direct and reversed, their effect was eliminated.

STORAGE BATTERIES. The necessary current for heating the carbon rod was supplied by means of a 12 cell, 40 ampere hour, Gould storage battery, Type M 305. This was kept charged during the time of its use and proved to be the source of a remarkably steady current.

DATA.

Figure II gives the numbering of the thermocouples, while figure III gives the lettering of the connections on the switchboards. Thermometer "A" gave the temperature of of one of the end baths. Thermometer "B" gave the temperature of the outer surface of the cotton packing. The letters "d" and "r" represent the position of the reversing key, "d" meaning that the current goes directly to the galvanometer, and "r" that the current is reversed. The + or – following the galvanometer reading indicated whether the reading is to the right or to the left of the zero point. The time required for the rod to come to a stationary condition was much smaller than had been expected. It was thought that due to the fact that gas carbon is such a poor conductor of heat, several hours would be necessary. This, however, did not prove true. The following curve shows the deflections of the galvanometer, plat- ted against time.



Although a half hour preliminary heating is sufficient, according to this curve, still several sets of readings were taken in each experiment to make sure that the rod was in thermal equilibrium.

Experiment No. 1.

Part 1. No electric current used.

Thermocouple and connections.		Reading of Galvanometer.	sum.	average.	Reading of Thermometer A.
I	ad	3.9–	11.0		29.93° C.
I	ar	7.1+		10.6	
I	bd	7.1+	10.2		29.93
I	br	3.1–			
II	ad	7.0–	18.0		29.93
II	ar	11.0+		17.5	
II	bd	10.9+	17.1		29.92
II	br	6.2–			
III	ad	4.2–	12.2		29.93
III	ar	8.0+		12.1	
III	bd	8.0+	11.9		29.93
III	br	3.9–			
IV	d	1.9+	.1		
IV	r	1.8+			
V	d	2.0+	.3		
V	r	1.7+			

Thermometer B read 23.5° C.

Part 2. A current of 4.49 amperes used.

Thermocouple and connections.	Reading of Galvanometer.	sum.	Average.	Reading of Thermometer A.
I ad	143.5+	284.5		29.99° C.
I ar	141.0−		284.2	
I bd	140.8−	284.0		29.92
I br	143.2+			
II ad	203.0+	403.0		29.92
II ar	200.0−		402.2	
II bd	200.0−	401.5		29.96
II br	201.5+			
III ad	151.9+	298.1		29.98
III ar	146.2−		296.8	
III bd	146.8−	295.6		29.95
III br	148.8+			
IV d	.8+	.2		
IV.r	1.0+			
V d	.8+	.2		
V r	1.0+			

Thermometer B read 25.0° C.

Voltage wire connections.	Reading of Galvanometer.	Sum.	Average.
Ad	105.8+	213.6	
Ar	107.8—		214.0
Bd	108.2—	214.4	
Br	106.2+		
Cd	126.8+	255.2	
Cr	128.4—		259.6
Dd	127.8—	254.0	
Dr	126.2+		
Ed	230.2+	465.7	
Er	235.5—		464.1
Fd	232.2—	462.4	
Fr	230.2+		

Experiment II.

Part 1. No electric current used.

Thermocouple and connections.	Reading of Galvanometer.	Sum.	Average.	Reading of Thermometer A.
I ad	48.1+	90.2	90.2	.75° C.
I ar	42.1−			
I bd	42.1−	90.2		
I br	48.1+			
II ad	59.1+	112.2	112.4	.73
II ar	53.1−			
II bd	53.3−	112.5		
II br	59.2+			
III ad	44.0+	81.7	81.7	.75
III ar	37.7−			
III bd	37.7−	81.7		
III br	44.0+			
IV d	3.8+	1.8		
IV r	2.0+			
V d	4.0+	2.6		.75
V r	1.4+			

Thermometer B read 22.48° C.

Part 2. A current of 4.095 amperes used.

Thermocouple and connections.	Reading of Galvanometer.	Sum.	Average.	Reading of Thermometer A.
I ad	166.7 +	329.4	329.6	.75° C
I ar	162.7−			
I bd	163.4−	329.9		
I br	166.5+			
II ad	232.1+	461.9	461.8	.75
II ar	229.8−			
II bd	229.8−	461.8		
II br	232.0+			
III ad	169.7+	335.8	336.0	.75
III ar	166.1−			
III bd	166.4−	336.2		
III br	169.8+			
IV d	4.0−	11.6	10.3	.75
IV r	7.6 +			
V d	3.0−	9.0		
V r	6.0 +			

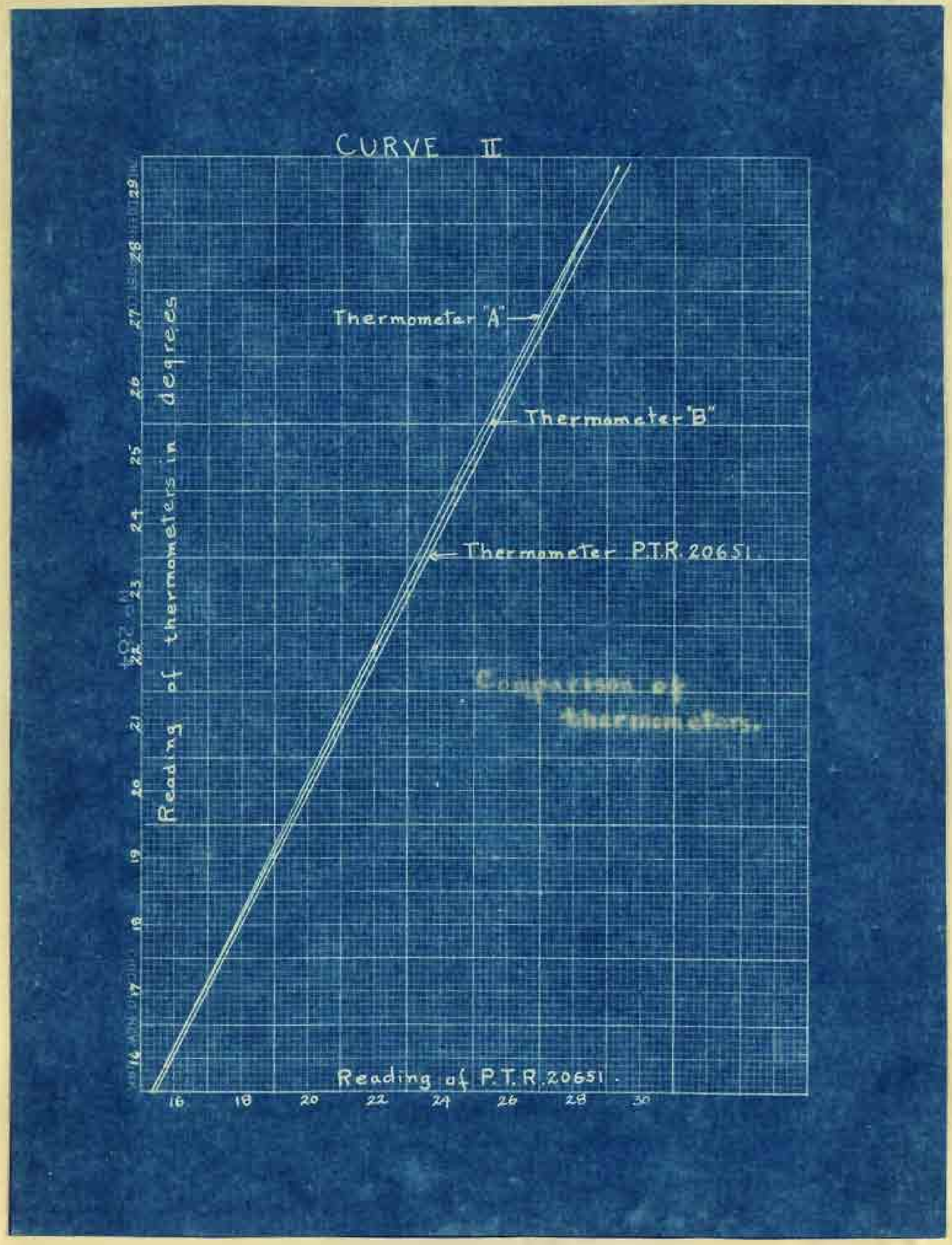
Voltage wire connections.	Reading of Galvanometer.	Sum.	Average.
Ad	99.6–	197.7	197.7
Ar	98.1+		
Bd	98.2+	197.6	
Br	99.4–		
Cd	118.6–	235.6	235.3
Cr	117.0+		
Dd	116.9+	235.1	
Dr	118.2–		
Ed	215.0+	427.8	428.0
Er	212.8–		
Fd	212.9–	428.3	
Fr	215.4+		

Thermometer B read 21.70

CALIBRATION OF APPARATUS.

Comparison of the Thermometers used. The thermometers were bound together and placed in the thermostat. By a comparison of the thermometers at various temperatures the following data was obtained. P. T. R. # 20651 was taken as the standard.

Thermometer A.	Thermometer B	Thermometer P.T.R. # 20651.
29.47	29.36	29.07
29.15	29.13	28.85
28.85	28.90	28.68
28.30	28.24	27.98
27.55	27.50	27.24
25.92	25.80	25.66
24.55	24.40	24.30
23.45	23.28	23.22
22.15	22.00	21.97
21.00	20.80	20.78


CURVE II
Thermometer "A"
Thermometer "B"
Thermometer P.T.R. 20651.
Comparison of thermometers.
Reading of thermometers in degrees
Reading of P.T.R. 20651.
16
18
20
22
24
26
28
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16
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29

Calibration of Thermocouples. The thermocouples were left connected exactly as in the previous experiments, with the exception of the solder joints, which were in the carbon rod. These were bound together and placed in a large bath of water. By varying the temperature of the water in the thermostat that supplied the end baths, any desired difference in temperature would be produced. During the experiment the following data was obtained. Thermometer C gives the temperature of the end bath and P. T. R. # 20651 gives the temperature of the large bath of water.

Thermocouple and connections.	Galvanometer reading.	Sum.	Average.
I ad	9.1+	17.3	17.3
I ar	8.2-		
I bd	8.2-	17.3	
I br	9.1+		
II ad	7.9+	16.9	16.4
II ar	9.0-		
II bd	8.4-	15.9	
II br	7.5+		
III ad	7.6+	16.3	15.7
III ar	8.7+		
III bd	8.0-	15.0	
III br	7.0+		
IV d	7.1+	13.1	
IV r	6.0-		
V d	7.2+	13.2	
V r	6.0-		

Thermometer P. T. R. # 20651 15.80°
Thermometer C 14.95°
Corrected reading of Thermometer C 15.11° *

(*) The values for the corrected readings of thermometer C were found by special comparison.

Difference in temperature = $15.80^{\circ} - 15.11^{\circ} = .69^{\circ}$

Thermocouple and connections	Galvanometer reading.	Sum.	Average.
I ad	63.4+	125.2	125.4
I ar	61.8−		
I bd	61.9−	125.7	
I br	63.8+		
II ad	63.5+	125.4	125.4
II ar	61.9−		
II bd	62.0−	125.4	
II br	63.4+		
III ad	61.2+	123.5	123.2
III ar	62.5+		
III bd	62.0+	122.9	
III br	60.9+		
IV d	49.7+	97.8	
IV r	48.1−		
V d	49.9+	97.9	
V r	48.0−		

Thermometer P. T. R.# 20651 19.90°

Thermometer C 15.01

Corrected reading of thermometer C 15.19

Difference in temperature = $19.90 - 15.19 = 4.71^{\circ}$

Thermocouple and connections.		Galvanometer reading.	Sum.	Average.
I	ad	127.2+	253.6	253.4
I	ar	126.4−		
I	bd	126.2−	253.2	
I	br	127.0+		
II	ad	126.2+	253.7	253.1
II	ar	127.5−		
II	bd	127.2−	252.5	
II	br	125.3+		
III	ad	125.1+	251.3	251.3
III	ar	126.2−		
III	bd	126.2−	251.2	
III	br	125.0+		
IV	d	101.2+	201.2	
IV	r	100.0−		
V	d	101.2+	201.1	
V	r	99.9−		

Thermometer P. T. R. 20651 25.01

Thermometer C 15.09

Corrected reading of thermometer C 15.24

Difference in temperature $= 25.01 - 15.24 = 9.77^{\circ}$

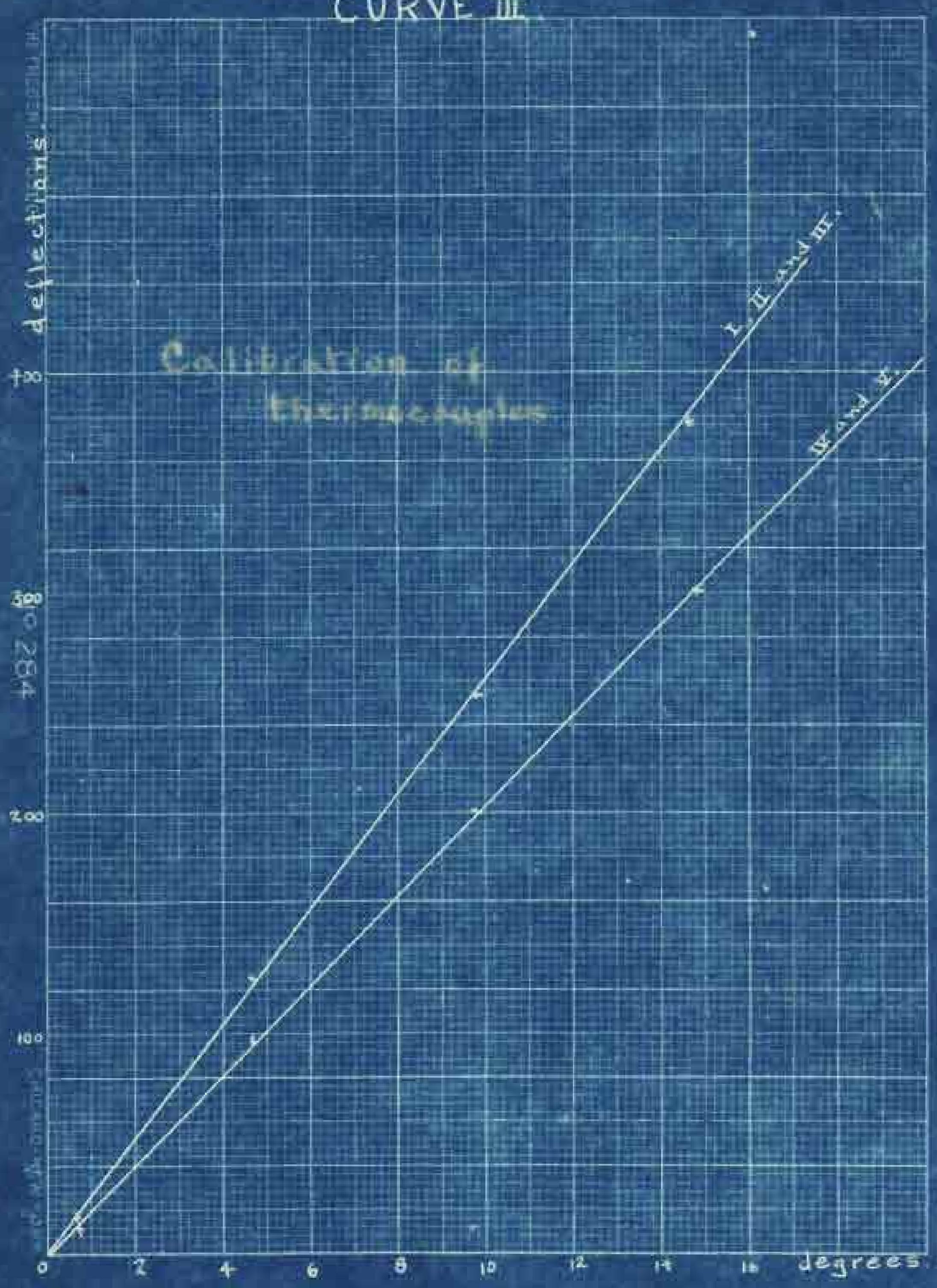
Thermocouple and connections		Galvanometer reading.	Sum.	Average.
I	ad	188.9+	374.9	378.6
I	ar	186.0−		
I	bd	190.2−	382.2	
I	br	192.0+		
II	ad	191.2+	378.8	379.4
II	ar	189.2−		
II	bd	189.6−	379.9	
II	br	191.3+		
III	ad	188.6+	379.1	378.7
III	ar	190.5+		
III	bd	190.2−	378.2	
III	br	188.0+		
IV	d	152.7+	303.3	
IV	r	150.6−		
V	d	152.3+	302.7	
V	r	150.4−		

Thermometer P. T. R. #20651 29.90°

Thermometer C 15.13

Corrected reading of Thermometer C 15.24

Difference in temperature = 29.90 − 15.24 = 14.66°


CURVE III
deflections
Calibration of thermocouples
I, II and III.
IV and V.
degrees
400
300
200
100
0
2
4
6
8
10
12
14
16

CALIBRATION OF VOLTAGE WIRES.

A storage battery whose electromotive force had been accurately measured, was connected to an Ostwald Potentiometer, and various voltages were shunted off and connected to the circuit containing the voltage wires. The general arrangement of the apparatus and the switchboard connections are shown in Fig. IV.

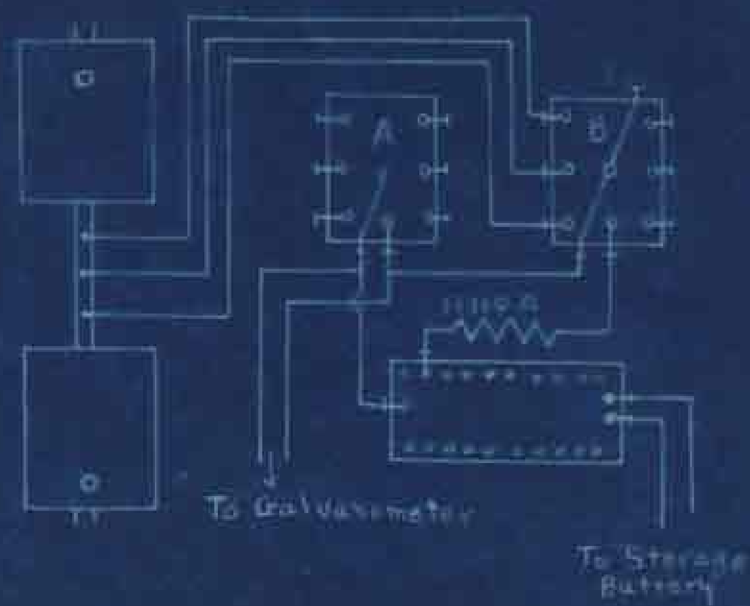
Voltage of Storage Battery 2.09

Fraction of voltage tapped off	Voltage tapped off	Sum of Galvanometer readings direct and reversed				Average.
		M	N	O	P	
10/1000	0.0209	103.1	103.1	103.1	103.2	103.1
20/1000	0.0418	205.7	205.8	206.2	205.5	205.8
30/1000	0.0627	307.0	307.1	306.5	306.9	306.9
40/1000	0.0836	406.6	407.0	406.2	406.3	406.5

It may be noted that this method of calibration assumes the drop of voltage at the contacts of the manganin wire and the carbon rod to be zero. That this is not the case is obvious from the voltage drops given in experiments No. 1 and 2.

If we let a, b and c represent the voltage drop due to the contacts in the boreholes I, II and III, respectively, then the true drop between I and II is 214.0 – a – b and between II and III is 259.6 – b – c. Their sum is equal to 473.6 – a – 2b – c. The voltage drop between I and III is equal to 464.1 – a – c. Equating these two, we get 2b = 9.5, or b = 4.8. By similar procedure with experiment II, we get b = 2.5

This fact has no signification in the present experiments, but should be taken into consideration in more refined work. The drops a and c can, of course, be determined in a like manner by the use of two auxiliary boreholes.



Switchboard Connections

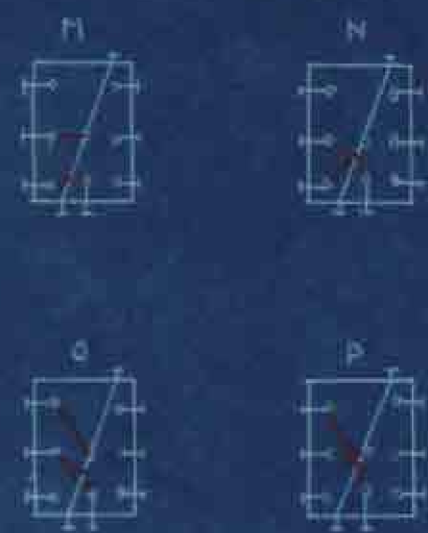
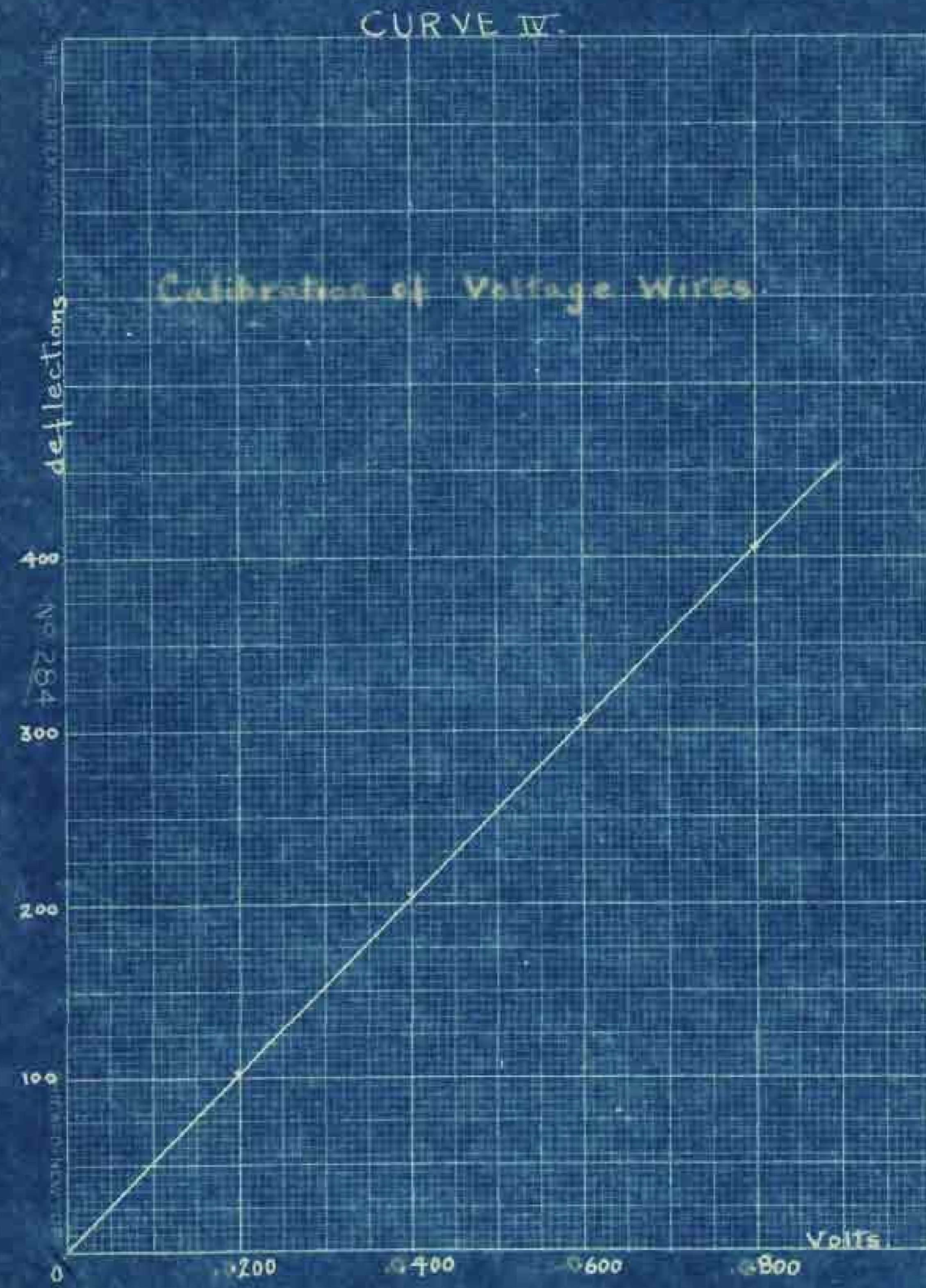


Fig. IV.


CURVE IV.
Calibration of Voltage Wires.
deflections.
400
300
200
100
0
.0200
.0400
.0600
.0800
Volts.

CALCULATIONS AND RESULTS.

If we let Δ represent the temperature of the middle borehole minus the arithmetical mean of the temperatures of the other two boreholes, and let N equal the outer temperature of the packing material plus $1/6\ \Delta$ minus the temperature of the middle borehole, then- in the case of the experiments without current- $e = \frac{\Delta}{N}$*, and in the case of the experiments with current, $U = \Delta - eN$.* Adding to this information the fact that $\frac{\lambda}{\varkappa} = 1/8\ \frac{V^2}{U}$, we can calculate the value of $\frac{\lambda}{\varkappa}$ in experiments I and II.

* Jaeger und Diesselhorst, Wiss. Abh. der Phy.-Tech. Reichs. 3, 269, (1899).

From experiment I, part 1, and calibration curves we obtain:

Temperature of borehole I = 29.93 − .20 − .45 = 29.28

Temperature of borehole II = 29.93 − .20 − .70 = 29.03

Temperature of borehole III = 29.93 − .20 − .48 = 29.25

$\Delta = 29.03 - \frac{1}{2}(29.25 + 29.28) = -.235$

Temperature of outer layer of cotton packing =

23.50 − .10 = 23.40

$N = 23.40 - 29.03 + 1/6\ (-.235) = -6.02$

$e = \frac{\Delta}{N} = \frac{-.235}{-6.02} = .039$

From Part II, in a similar manner:

Temperature of borehole I = 29.96 − .20 + 10.95 = 40.71

Temperature of borehole II = 29.96 − .20 + 15.50 = 45.26

Temperature of borehole III = 29.96 − .20 + 11.45 = 41.21

$\Delta = 45.26 - \frac{1}{2}(40.71 + 41.21) = 4.30$

Temperature of outer layer of cotton packing

25.00 − .15 = 24.85

$N = 24.85 - 45.26 + 1/6\ (4.30) = 19.70$

$U = \Delta - eN = 4.30 - .039 \times 19.70 = 3.53$

Voltage drop = .090

$\frac{\lambda}{x} = 1/8\ \frac{V^2}{U} = 1/8\ \frac{(.090)^2}{3.53} = .000287$

From Experiment II, Part 1,

Temperature of borehole I = .75 + 3.50 = 4.25

Temperature of borehole II = .75 + 4.30 = 5.05

Temperature of borehole III = .75 + 3.10 = 3.85

$\Delta = 5.05 - \frac{1}{2}(4.25 + 3.85) = 1.00$

Temperature of outer layer of cotton packing =

22.48 - .20 = 22.28

$N = 22.28 - 5.05 + 1/6\ (1.00) = 17.39$

$e = \frac{\Delta}{N} = \frac{1.00}{17.39} = .058$

From Part 2:

Temperature of borehole I = .75 + 12.70 = 13.45

Temperature of borehole II = .75 + 17.80 = 18.55

Temperature of borehole III = .75 + 12.95 = 13.70

$\Delta = 18.55 - \frac{1}{2}(13.45 + 13.70) = 4.98$

Temperature of outer layer of cotton packing =

21.70 - .20 = 21.50

$N = 21.50 - 18.55 + 1/6(4.98) = 3.78$

$U = \Delta - eN = 4.98 - .058 \times 3.78 = 4.76$

Voltage drop = .085

$\frac{\lambda}{\varkappa} = 1/8\ \frac{V^2}{U} = 1/8\ \frac{(.085)^2}{4.76} = .000189$

BIBLIOGRAPHY.

Winkelmann's Handbuch.

Carslaw, Introduction to Fourier Series and Integrals and the Mathematical Conduction of Heat.

Müller Pouillet's Lehrbuch der Physik, Vol. III.

Kohlrausch, Ann. der Phy. (4) I, 145, (1900).

Kohlrausch, Sitz. Ber. der Berlin Ak. d. W. 38, 711, (1899).

Jaeger und Diesselhorst, Sitz. Ber. der Berlin Ak. d. W. 38, 719, (1899).

Jaeger und Diesselhorst, Wiss. Abh. der Phy.-Tech. Reichs., 3, 269, (1899).

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