TEMPERATURE COEFFICIENTS OF ELECTRICAL RESISTANCE. II.

By Albert Alexander Somerville.

THE work is a continuation of that described in the Physical Review, Vol. XXX., No. 4, in which data were given on nickel, nichrome, tungsten, and molybdenum. The materials that have been tested since are aluminum, silver, iron, copper, gold, manganin, constantan, "advance," porcelain, quartz, mica, glass, carbon, "excello," "ia ia," "superior," and magnesium. The temperature range is from 0° C. to 1000 or 1100° C. or to the melting point of the specimen. The work divides into four parts:

1. Attaining the desired temperatures.
2. Measuring the temperature at any time.
3. Measuring the resistance of the specimen.
4. Preventing the specimen from oxidizing.

The same electrical resistance furnace has been in use for more than half a year and has been heated to 1000° C. on an average of about five times a week. It consists of co-axial porcelain cylinders 50 cm. in length open at both ends. The inner diameter of the smaller is 3 cm. and the walls are 1 cm. thick; it is wrapped with one fourth inch nichrome ribbon wire and enclosed by the larger cylinder. After a few experiments the outer cylinder was also wrapped with nichrome and the two heating coils connected in parallel. The whole is jacketed with asbestos such as is used for encasing steam pipes. This reaches the first part of the problem, that of attaining a temperature of 1100° C. and in a very convenient manner where a 55- or 110-volt circuit is at command. The rate of temperature change is very easily controlled by placing variable resistance in series with the heating coils.

Callendar's[1] temperature resistance curve for platinum was taken as a standard for making temperature measurements. The plati-

[1] Phil. Trans., vol. 178.

num resistance thermometer has remained practically unchanged during several months' use. Its reading at zero or room temperature was taken each time it was heated, and was frequently read at the temperature of melting copper, that being taken as a fixed point.

The operation of the automatic temperature recorder as described in the first paper in the Physical Review remained unchanged. This apparatus, when once in order, does best when kept continually working. At present the sensibility is such that the reading across the scale is 400 platinum degrees. A variable resistance in series with the dummy leads of the thermometer enables one to readjust the zero point at any time; knowing the amount of this change one can start to measure temperatures at zero, and when a temperature of 400° is reached, by introducing the proper amount of resistance in series with the dummy leads, bring the pen drawing the curve, back to the other end of the scale and proceed towards 800°; this is repeated to reach beyond 800°. A significant mark or break in the curve is made at any time desired by short circuiting for an instant one arm of the bridge forming part of the recorder. The curve shown in Fig. 1 is a sample of the work done

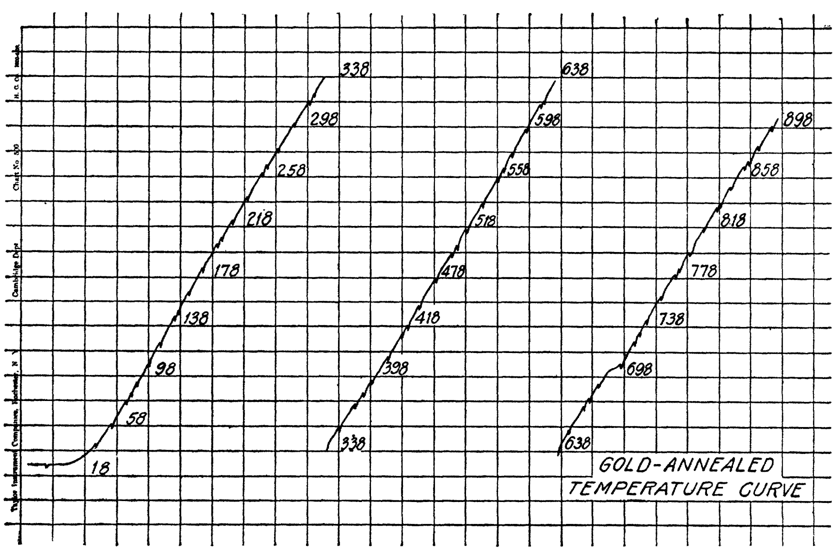

Fig. 1.

when the recorder is in good working condition. The units on the time or X-axis are five minutes each, and the time of a 1000° run is represented as about two hours. The temperature was made to increase at a fairly uniform rate by varying the current through the furnace. Readings indicated on the curve are on the platinum scale.

The transformation from platinum degrees to the Centigrade scale is made by applying the equation

$$T_c = pt + \delta\{(T_c/100)^2 - (T_c/100)\}$$

in which T_c is centigrade degrees, δ, a constant equal 1.5 for standard platinum wire and pt is best defined as being equal to

$$(R_c - R_0)/(R_{100} - R_0) \times 100.$$

Actual measurement of the resistance of a specimen was quite easy, being made on a box bridge, usually reading four decimals, and frequent readings being made on the dummy leads, for which copper has generally been used. Check marks were made on the temperature curve at the same time that a resistance reading was taken and later the temperature at that point was computed.

Probably the most serious inconvenience to working wires at high temperatures is due to oxidation. This trouble has been obviated by equipping a plant for the manufacture of nitrogen and its introduction into the heated region.

The outfit consisted of a nitrogen furnace made by filling a 2-inch iron pipe 2 feet in length with copper shavings, capping both ends, and running small iron pipes from each end so that air could be pumped through. A resistance furnace was built around it so that it could be brought to red heat. A motor-driven pump forced air through this pipe over the hot copper, which took up the oxygen while permitting the nitrogen to pass. In series with it was a wash bottle containing pyrogallol and potassium hydroxide, which served the double purpose of absorbing any oxygen remaining in the gas and indicating the rate at which the gas was flowing. Large bottles to add capacity closed the circuit, so that practically the same gas was pumped continuously through the nitrogen furnace. In parts of the circuit phosphorus pentoxide and calcium chloride were placed to absorb moisture.

When the resistance of a wire is to be measured, it is mounted in a quartz or porcelain tube, one end of which is closed—from the other end extend the lead wires and dummy leads—small quartz tubes are also introduced into the end of the larger tube in order to insulate the wires from each other—also to introduce nitrogen—the end of the larger tube is closed by means of plaster of paris. Then the nitrogen circuit is cut and the tube containing the wire to be measured is made part of the nitrogen circuit—the wire is soon surrounded by an atmosphere of nitrogen and is kept so by allowing a very small stream of the gas to flow continuously. By using ordinary precaution no trouble due to oxidation need be experienced.

The substances tested were those in general most commonly found in a laboratory. The resistance was measured first at the temperature of melting ice—subsequently the temperature was run up to about 1000° C. or 1100° C., or to the melting point of the material. The axes of the curves are *temperature* and *resistance*. For uniformity all resistances are reduced to unity at zero, except those of glass, porcelain, and quartz, in which cases the resistances of a cubic centimeter of the substances at the indicated temperatures are given.

The materials studied may be grouped in various ways. Copper, gold, and silver represent the comparatively pure metals. Not so much can be said of the aluminum and magnesium, but they are much alike. Manganin, constantan, advance, and ia ia form a group of alloys having a small coefficient. Porcelain, quartz, mica, and glass form another class, being non-conductors at ordinary temperatures. Carbon differs from all the others in that the coefficient is always negative. Iron is also in a class by itself. Excello, a good furnace wire put out by Herman Boker and Company, is very much like nichrome, for which data were given in a previous article.[1]

In some cases the wires were drawn through several stone draw plates and the change of resistance due to cold drawing and subsequent annealing was noted. In general, it may be said that cold drawing increases resistance—annealing to a certain extent decreases the resistance by relieving strain, and if carried farther

[1] PHYS. REV., April, 1910.

again causes an increase in resistance due to recrystallization. Successive heatings will cause further crystallization gradually approaching a limit, or if the material is a very hard one the strained condition due to drawing will not be entirely relieved except by continued heating. In rolled ribbon wire the crystals are broken down by the rolling and so lie closer together; there is no strain produced such as in drawing, so that heating at once causes crystallization and a corresponding increase in resistance. The same wire when drawn has a higher resistance, and when first heated this resistance decreases.

Copper.

The temperature coefficient of copper is usually given as about .0040 or .0041. One recent experimenter, who has worked on a

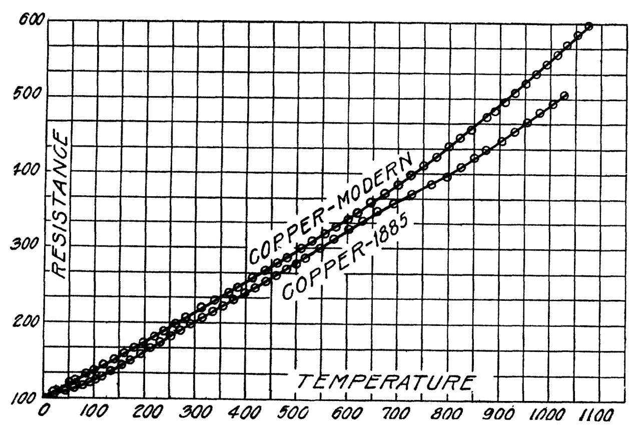

Fig. 2.

half dozen materials, at last report gives it as .0043 at 100° C. and less at 400°, which is contrary to the results obtained by any one else. The author gets various results, depending on whether the wire is hard-drawn or how well it is annealed. If the wire is hard-drawn the first heating will probably cause a decrease in resistance, so that the apparent coefficient is small, possibly only .0037. If the heating causes crystallization, the resistance increases unduly and the coefficient is larger, possibly .0042. Measuring again at zero, however, the coefficient is found to be smaller than that usually given. This refers to modern electrolytic copper, nearly pure.

Copper made twenty-five years ago, before the electrolytic process came to be used, is not nearly so pure, has a smaller coefficient, as is usual with alloys, and also an irregularity in the curve at such a temperature as might indicate the presence of iron.

Gold.

The effect of cold drawing and annealing is more noticeable in gold than any other substance studied. On this account two curves are shown, giving an idea how great a variation might be

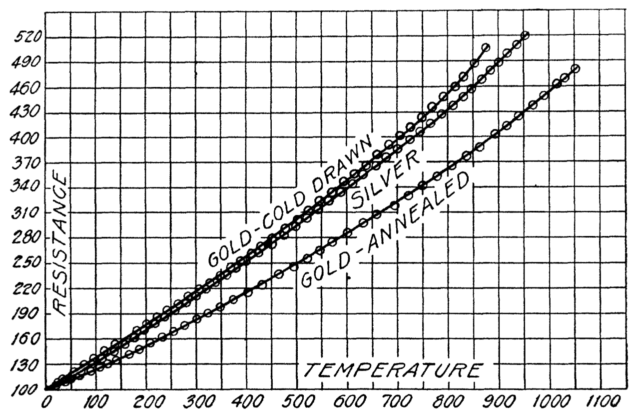

Fig. 3.

obtained in the coefficient. At first it was thought that a trace of silver was causing this small coefficient, but as chemical analysis did not indicate any impurities in subsequent specimens examined, the effects seem to be due entirely to mechanical working and annealing. Lead wires of platinum were used, as the melting point of copper and gold is lower than that of gold, and copper lead wires would melt at a point where they were fused to the gold at a lower temperature than the gold itself. The melting point of gold was used as a check on the temperature as indicated by the thermometer.

Silver.

Both the gold and silver were obtained from the Philadelphia Mint, the latter in the form of sheets. It was cut into strips, drawn into wires and then annealed. The change in resistance was not so great as in gold. Silver lead wires were used instead of copper for the same reason as above, that is, that copper lead wires melt off first at the point where fused to the silver. The similarity between the copper, gold and silver curves is to be noted, and also that the electrical resistance is nearly proportional to the absolute temperature.

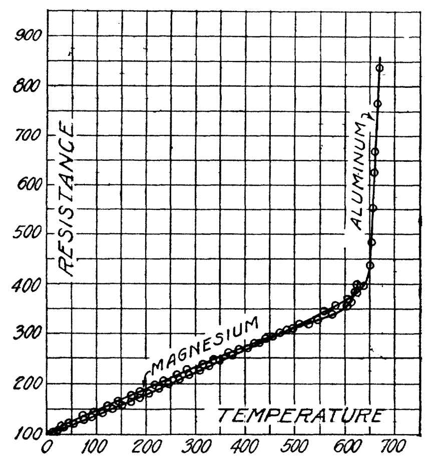

Fig. 4.

Aluminum.

Commercial aluminum of a good grade was tested. Lead wires of the same material were used on account of the difficulty of fusing a connection on to aluminum. The abrupt bend in the curve marks the point where the wire begins to soften, and the last point shows where the wire fell into pieces. The melting point is fairly definite, though not so much so as in the case of some of the other metals. The bend in the curve can be repeated several times with the same specimen provided the temperature is not carried so high that globules begin to form on the lower side of the wire and so permanently alter its shape and cross-section. Magnesium acts in almost exactly the same way as aluminum.

Iron.

A single specimen of iron wire was examined. It was annealed several hours at a temperature of about 1000° C. before any measurements were made on its resistance, and after that annealing scarcely any change was noted in the resistance due to successive heatings. It is to be observed that the coefficient is almost twice as large as that of most metals and increases rather rapidly to a certain point about 785° C., where there is an abrupt change. Over a range of a few degrees at the place where this sudden change occurs the electrical condition is very unstable, and during a change of four or five degrees it is impossible to measure the resistance, as it suffers such unusual variations in a short time. The recalescence

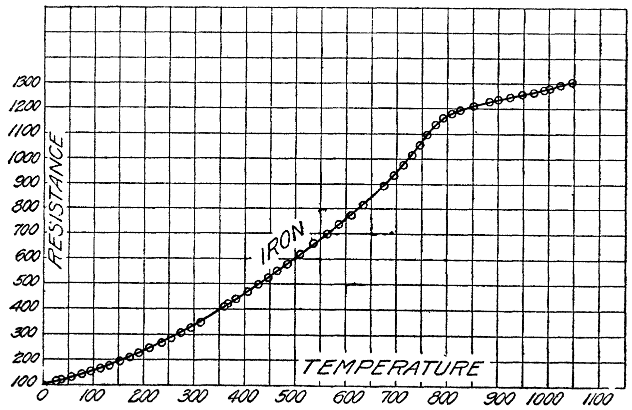

Fig. 5.

point of iron is given by most authorities as 775° C. to 790° C. At this point it ceases to be magnetic. The curve is readily reproducible and there is no hysteresis effect noticeable.

Manganin, Constantan, Advance and Ia Ia.

This group of alloys having a small temperature coefficient is interesting when compared. It appears that no mixture yet found will give a zero coefficient, but it may be stated that, as a general

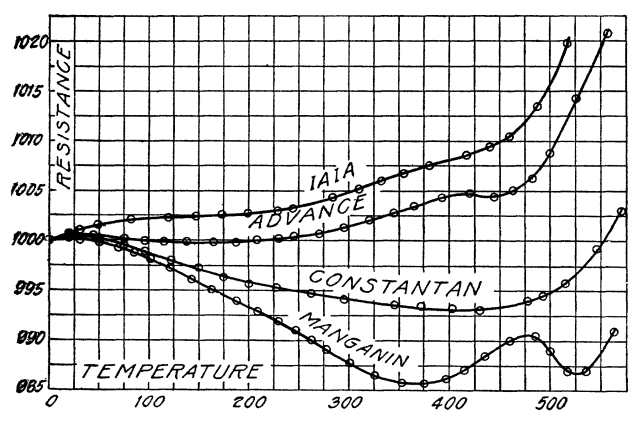

Fig. 6.

rule, the greater the purity of a metal the higher its coefficient, and that mixing metals will not only give a smaller coefficient, but may even cause it to change sign as the temperature varies. This latter fact is taken advantage of, and an alloy made in which the sign of the temperature coefficient of resistance will change at just about room temperature or slightly above this temperature. Thus the slope of the resistance temperature curve at this point is zero. In three of these alloys a maximum occurs at about room temperature, so for a short range of temperature their resistance is nearly constant. The actual increase in resistance from zero to 20° C. is: Manganin, .04 per cent.; constantan, .05 per cent.; advance, .02 per cent.; ia ia, .05 per cent. Constantan then pursues the smoothest course and the total variation up to 600° C. is less than 1 per cent. In the case of manganin the coefficient changes size and sign frequently. At about 850° C. the resistance of advance begins to increase rapidly.

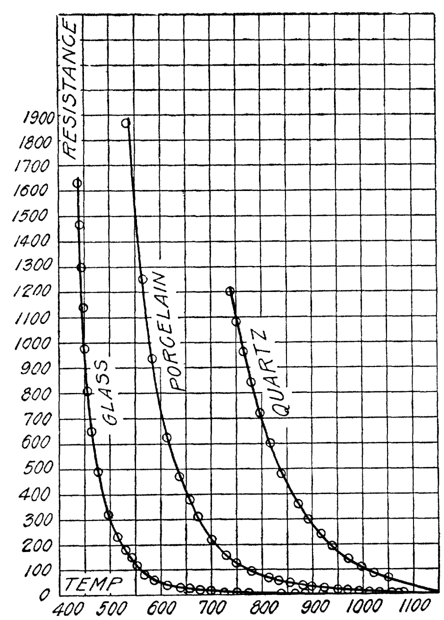

Fig. 7.

Porcelain, Quartz, Mica, and Glass.

These so-called insulators undergo enormous changes in resistance when heated. In each of these substances the resistance begins to decrease at a very definite temperature, and falls rapidly, so that within only a few degrees the resistance may change to one tenth of its former value. However, the resistance is still very high. In the liquid state glass becomes a sufficiently good conductor to carry current large enough to heat it farther and so cause it to fall apart. It is so difficult to secure two pieces of mica alike that only the general characteristics of the mineral can be represented by a curve. On first heating its resistance varies very much like that of porcelain, but after it has been held at a temperature of about 1100° C. for a few hours, its resistance increases until it is almost a perfect insulator. It has then become white and rather brittle. Presumably all impurities have been driven off; in this condition it makes the best frame known for a resistance thermometer.

In the case of fused quartz, which is made by squirting, if the logarithm of the resistance is plotted against temperature, a straight line results. The resistance of the transparent quartz, which is cast, does not begin to decrease until 1100° is reached and there the curve has a slope very nearly the same as that of the fused quartz at 740°. The Berlin porcelain begins to soften at about 1100° C. and as the resistance thermometer is enclosed in such a tube it cannot be run any higher. The resistance of these materials was measured while suspended in mid-air in the furnace.

CARBON.

Copper terminals were plated onto the ends of a piece of carbon 1 mm. in diameter and 10 or 15 cm. in length. This, like the speci-

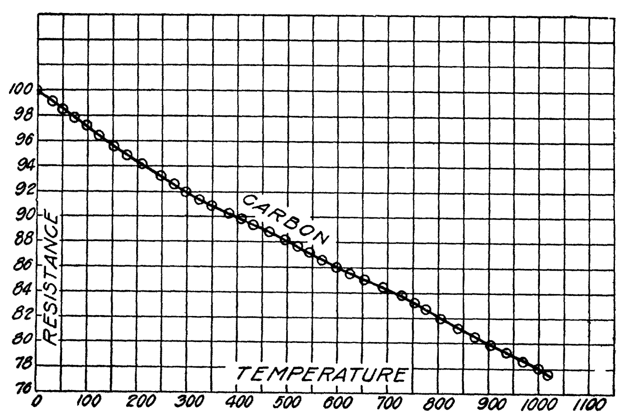

Fig. 8.

mens of wire, was mounted in a porcelain tube, and nitrogen forced in to take the place of air. Two slight peaks are seen in the curve, these occurring at temperatures of about 450° and 700°. The squirted carbons are supposed to be wholly amorphous or non-crystalline and so have a regular change of resistance. Graphite, another form of carbon, is crystalline, belonging to the hexagonal system. The temperature resistance curve of the graphite taken from a lead pencil shows two sharp peaks occurring at about the same temperatures as these slightly prominent ones in carbon, so it is not improbable that the carbon is, or has become slightly crystalline during the heating.

Excello and Superior.

These are two alloys furnished by Herman Boker and Company. The former, a nickel chromium alloy, does not oxidize in air and does not melt below 1200° C., and is therefore a good furnace

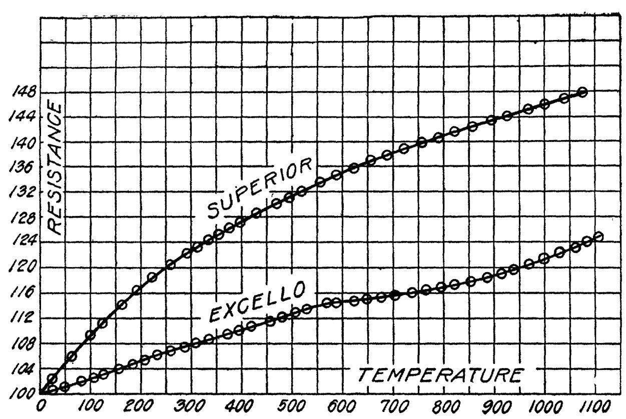

Fig. 9.

wire. It is also pliable, which is an advantage when winding a furnace.

Superior, a nickel-steel alloy, is also a wire that works well. It is evidently thoroughly annealed, as heating to a thousand degrees and cooling to zero again, brings it back almost exactly to its original resistance.

The temperature coefficient, *i. e.*, the slope of the temperature-resistance curves, is plotted against temperature in Figs. 10

to 15 and the values of the temperature at different temperatures are also given in the table at the close of this article.

Some of the apparatus used has been secured by a grant by the Smithsonian Institute. For this and other apparatus used, and for

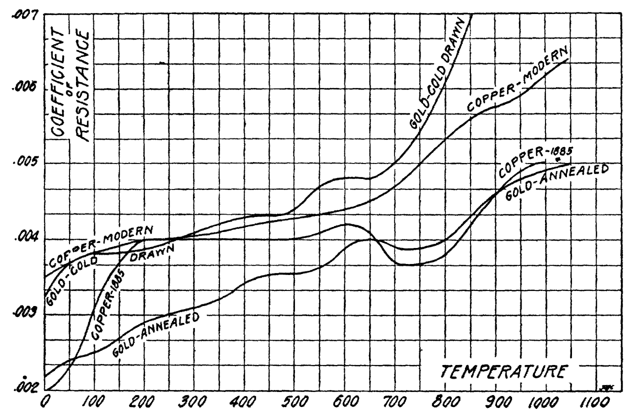

Fig. 10.

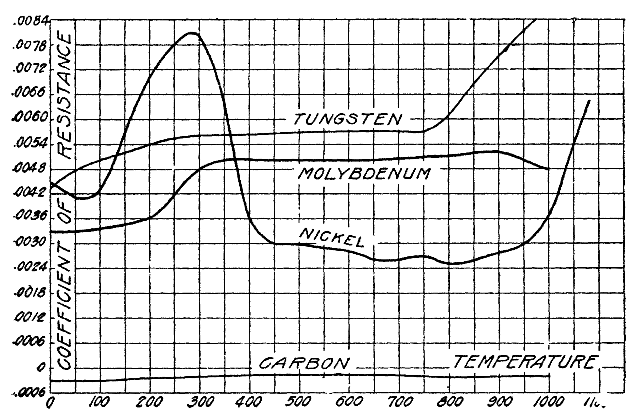

Fig. 11.

the suggestions made by Prof. J. S. Shearer and other members of the Physics Department the auther desires to express his thanks.

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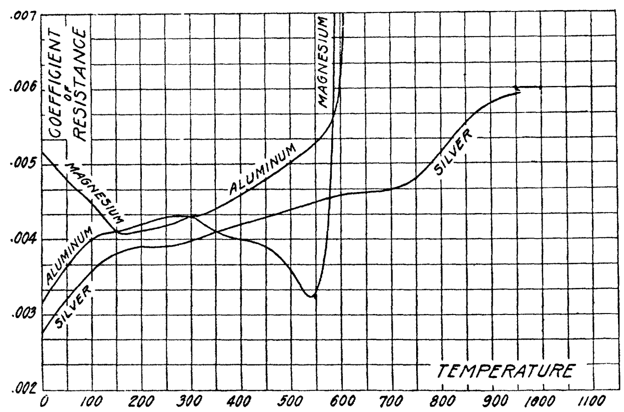
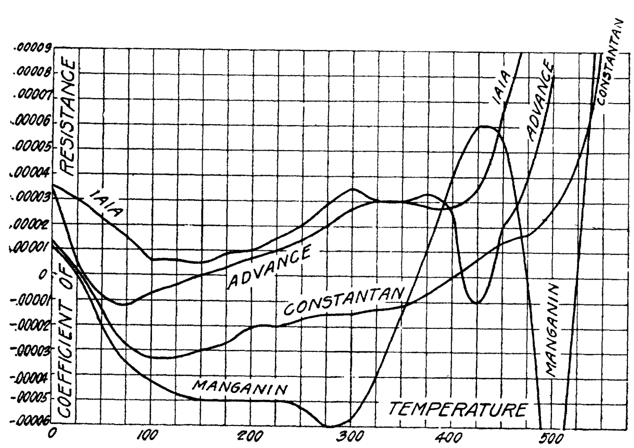


COEFFICIENT OF RESISTANCE
MAGNESIUM
ALUMINUM
SILVER
TEMPERATURE
.007
.006
.005
.004
.003
.002
0
100
200
300
400
500
600
700
800
900
1000
1100

Fig. 12.



COEFFICIENT OF RESISTANCE
IAIA
ADVANCE
CONSTANTAN
MANGANIN
TEMPERATURE
0
100
200
300
400
500

Fig. 13.

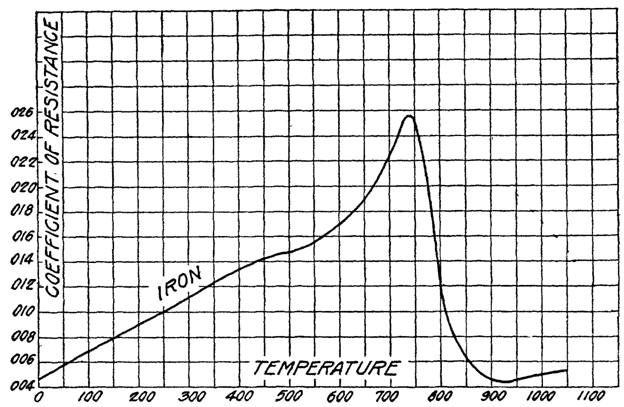

COEFFICIENT. OF RESISTANCE
.026
.024
.022
.020
.018
.016
.014
.012
.010
.008
.006
.004
IRON
TEMPERATURE
0
100
200
300
400
500
600
700
800
900
1000
1100

Fig. 14.

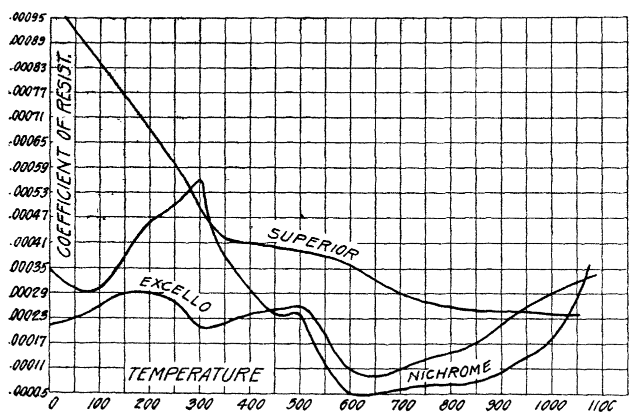

COEFFICIENT OF RESIST.
.00095
.00089
.00083
.00077
.00071
.00065
.00059
.00053
.00047
.00041
.00035
.00029
.00023
.00017
.00011
.00005
SUPERIOR
EXCELLO
NICHROME
TEMPERATURE
0
100
200
300
400
500
600
700
800
900
1000
1100

Fig. 15

Temperature Coefficients of Electrical Resistance.

Temperature, Centigrade.	Advance.	Ia/Ia.	Manganin.	Constantan.
12.5	.000020	.000033	.000006	.000008
25	.000005	.000030	.000000	.000002
50	−.000008	.000022	−.000020	−.000014
75	−.000012	.000015	−.000035	−.000028
100	−.000007	.000006	−.000042	−.000033
125	−.000004	.000006	−.000047	−.000033
150	.000000	.000005	−.000050	−.000030
175	.000003	.000009	−.000050	−.000027
200	.000007	.000010	−.000050	−.000020
225	.000010	.000015	−.000050	−.000020
250	.000014	.000020	−.000052	−.000017
275	.000020	.000029	−.000060	−.000015
300	.000027	.000035	−.000057	−.000015
325	.000030	.000030	−.000040	−.000013
350	.000030	.000030	−.000015	−.000012
375	.000033	.000028	.000010	−.000007
400	.000025	.000028	.000040	.000000
425	−.000010	.000035	.000060	.000007
450	.000020	.000067	.000055	.000014
475	.000040	.000110	.000000	.000017
500	.000080	.000200	−.000110	.000027
525	.000105		.000000	.000047
550	.000105		.000150	.000100

Temperature, Centigrade.	Gold, Cold Drawn.	Gold, Annealed.	Silver.	Iron.	Tungsten.	Molybdenum.	Nickel.	Nichrome.
25	.0035	.0023	.0030	.0052	.0046	.0033	.0043	.00032
50	.0037	.0024	.0032	.0057	.0048	.0033	.0041	.00030
100	.0038	.0025	.0036	.0068	.0050	.0034	.0043	.00030
150	.0038+	.0027	.0038	.0079	.0052	.0035	.0057	.00038
200	.0039	.0029	.0039−	.0090	.0054	.0036	.0070	.00046
250	.0040	.0030	.0039	.0100	.0056	.0042	.0078	.00050
300	.0041	.0031	.0040	.0111	.0056	.0048	.0080	.00056
325							.0080	.00043
350	.0042	.0032	.0041	.0123	.0056	.0050	.0064	.00038
375							.0048	
400	.0043	.0034	.0042	.0133	.0056	.0050	.0036	.00030
425							.0032	
450	.0043	.0035	.0043	.0142	.0056	.0050	.0030	.00024
500	.0044+	.0035	.0044	.0147	.0057	.0050	.0030	.00024
550	.0047	.0036	.0045	.0155	.0057	.0050	.0029	.00012
600	.0048	.0039	.0046	.0170	.0057	.0050	.0028	.00005
650	.0048	.0040	.0046	.0189	.0057	.0050	.0026	.00005
700	.0050	.0039	.0047	.0224	.0057	.0050	.0026	.00006
725				.0248				
750	.0054	.0039	.0048	.0250	.0057	.0050	.0027	.00007
775				.0200				
800	.0061	.0040	.0052	.0120	.0061	.0051	.0025	.00007
825				.0080				
850	.0066	.0043	.0055	.0065	.0068	.0052	.0026	.00008
875				.0052				
900		.0046	.0058−	.0046	.0075	.0052	.0028	.00010
950		.0048	.0059	.0046	.0081	.0050	.0030	.00014
975						.0049		
1000		.0049		.0050	.0089	.0048	.0037	.00018
1050		.0050		.0053	.0093		.0054	.00028
1075							.0062	.00036

Temperature, Centigrade.	Aluminum.	Magnesium.	Copper, Modern.	Copper, 1885.	Carbon.	Superior.	Excello.	Quartz.	Porcelain.	Glass.
25	.0034	.0050	.0036	.0021	−.00030	.00096	.00022			
50	.0037	.0048	.0037	.0023	−.00030	.00092	.00023			
100	.0040	.0045	.0038	.0031	−.00031	.00084	.00026			
150	.0041	.0041	.0039	.0037	−.00028	.00076	.00029			
200	.0042	.0041	.0040	.0040	−.00025	.00068	.00029			
250	.0043	.0042	.0040	.0040	−.00024	.00060	.00027			
300	.0043	.0043	.0041	.0040	−.00023	.00049	.00021			
350	.0044	.0041	.0041	.0040	−.00020	.00042	.00022			
400	.0046	.0040	.0042	.0040	−.00018	.00041	.00024			
450	.0048	.0039	.0042	.0040	−.00018	.00040	.00025			−32.00
475										−32.00
500	.0050	.0036	.0043	.0040	−.00020	.00039	.00026			− 6.00
525		.0032								− 3.60
550	.0053	.0033	.0043	.0041	−.00020	.00038	.00020			− 2.50
575	.0054	.0040					.00015		−16.00	− 1.50
600	.0060	.0100	.0044	.0042	−.00019	.00036	.00011		− 9.80	− .80
625	.0120	.0250							− 6.20	− .45
650			.0045	.0041	−.00018	.00032	.00009		− 4.60	− .30
675									− 3.70	− .20
700			.0047	.0037	−.00018	.00029	.00011		− 2.80	− .17
725									− 2.00	− .14
750			.0050	.0037	−.00020	.00027	.00013	−10.00	− 1.60	− .10
775								− 8.02	− 1.00	− .07
800			.0053	.0038	−.00022	.00026	.00015	− 6.40	− .70	− .06
825								− 5.20	− .50	
850			.0056	.0042	−.00022	.00025	.00017	− 4.20	− .40	
875								− 3.20	− .35	
900			.0057	.0046	−.00020	.00025	.00022	− 2.60	− .30	
925								− 2.20	− .25	
950			.0059	.0049	−.00020	.00025	.00026	− 1.80	− .20	
975								− 1.30	− .16	
1000			.0062	.0050	−.00020	.00024	.00029	− 1.00	− .12	
1025								− .80		
1050			.0064			.00024	.00032	− .65		

Department of Physics,
Cornell University, June, 1910.