Laboratory Notes.

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1. Electric Resistance of Cobalt.

The manner in which the electric resistance of cobalt varies with high temperatures does not seem to have been studied with any great care. The peculiar behaviour of nickel and iron as regards their change of resistance with temperature is now well known[1]. With a view to see if cobalt presented any similar peculiarity, I set Mr. Ōmori, one of the graduating students in Physics, to investigate the question.

The piece of cobalt used was cut from a sheet of rolled cobalt which had been given me by Professor Tait. Dr. E. Divers, F. R. S., kindly determined its composition by an analysis of a very small quantity (about 20 grains) supplied him. The result of the analysis is as follows:

Carbon found 0·77 % may be as much as 1·00 %
Silicon... ... 0·15
Iron ... ... 0·73

with a minute quantity of manganese and perhaps $\frac{1}{10}$ % of a metal undetermined. Dr. Divers regarded it as of remarkable purity for a furnace product.

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1) See my paper *On the Electric Resistance of Nickel at High Temperatures*, *Trans. Royal Soc., Edin.*, Vol. XXXIII (1886)—also abstract in the *Journal of the College of Science*, *Tokyo*, Vol. I.

The method of experiment was essentially the same as that described in my earlier paper on nickel. Four stout copper rods, 60 cm. long and 0·7 sq. cm. cross section, were fixed in a vertical position some little distance apart. Their lower extremities were joined in pairs by two coiled wires, one of which was a specimen of nearly pure platinum and the other the cobalt strip that was the special object of investigation. The upper extremities of the rods were joined by stout copper strips to a commutator, which was in connection with a Wheatstone Bridge resistance box of ordinary construction.

In one series of experiments the lower ends of the rods with their connecting wires were dipped in a vessel of oil which could be heated up to a temperature of nearly 240° C. A thermometer, centrally placed so that its bulb lay at the mean level of the platinum and cobalt coils, was used for measuring the temperature. The oil was heated very gradually and was kept briskly stirred until a few seconds before a reading was to be taken. One of the wires was meanwhile thrown into the Wheatstone Bridge, and the resistance adjusted slightly in advance. The temperature was then allowed to rise very slowly until reversal of the commutator in the galvanometer branch gave no deflection. When the equilibrium was thus attained the thermometer reading was noted. In this experiment chief attention was given to the cobalt; a few measurements of resistance were made with the platinum, sufficient to give the most important temperature coefficient.

The resistance curves for the cobalt and the platinum are shown in the diagram (p. 293), Curves Nos. 1 and 2. All corrections have been carefully applied and the resistances are in legal ohms.

By interpolation amongst a number of contiguous measurements the resistance for each of the temperatures 100°, 140°, 180°, 220° C. was calculated as shown in Table I.

Table I.

Resistance of a Cobalt Strip in Legal Ohms at different Temperatures.			
Temperature.	Resistance.	First Difference.	Ratio.
100° C.	.12340		
		.01354	1.1097
140	.13694		
		.01516	1.1109
180	.15210		
		.01649	1.1084
220	.16859		

Since the second differences have appreciably different values, it is impossible to represent the law of change by means of a parabolic function. But the remarkable constancy of the ratios of successive pairs of resistances suggests an exponential function of the temperature as the expression for the resistance.

Thus we may put

$$R = R_0 \, e^{kt}$$

from which we find, if t is the temperature in degrees Centigrade,

$$k = \cdot 002605, \; R_0 = \cdot 09519$$

The measured resistance at 7°·5 C. was 0·09604, which does not differ from the value given by the formula by more than **1** per cent.

In my paper already referred to I found that the same form of expression held for the case of one of the nickel wires investigated, the only essential difference being in the value of the coefficient k, which for the nickel was .003.

The resistance of cobalt therefore does not change so quickly with temperature as does the resistance of nickel.

In the second series of experiments the lower ends of the rods with their connecting wires were inserted into a porcelain vessel. Asbestos was wrapped round the wires ; and the whole was heated in a charcoal furnace. The observations of resistance were made as the system was cooling, the cobalt and platinum being thrown alternately into the Wheatstone Bridge. The instants at which the balancing was effected were carefully noted, so that it was an easy matter to interpolate between two successive measurements for the one wire that resistance which corresponded to the intermediate measurement for the other.

By this means more than twenty distinct pairs of measurements were obtained, every cobalt resistance having its corresponding platinum resistance. After all corrections were made the platinum resistances were divided by the resistance of the platinum at 7°C.; and similarly all the cobalt resistances were divided by the resistance of the cobalt at this same temperature. The numbers were then classified into groups so as to afford the means of calculating by interpolation the cobalt resistances which corresponded to assumed convenient values of the platinum resistances. These are the numbers given in Table II. which epitomises the results of four distinct experiments. The measurements were all made during cooling, and the higher values are accordingly tabulated first. The first column contains the platinum resistances, taken as convenient multiples of the resistance at 7° C. measured *after* the experiment; and the other columns give in order the corresponding resistances of the cobalt.

Table II.

Platinum Resistances.	Cobalt Resistances			
	Exp. I.	Exp. II.	Exp. III.	Exp. IV.
2.0	5.8047	5.7996	5.9748	6.0361
1.8	4.5101	4.3423	4.4511	4.4580
1.6	3.1822	3.0536	3.0932	3.2216
1.4	2.2029	2.1795	2.1111	2.2602
1.2	1.5329	1.5337	1.5050	
1.0	1.0000	1.0000	1.0000	1.0000

If we assume that the changes in the platinum resistance follow the same law as in the earlier experiment with the oil, the rise of temperature which will just double the resistance is about 680° C.; and the interval from 1 to 1.2 may be taken as corresponding approximately to a rise of temperature of 136° C. According to the experiment in oil, the resistance of the cobalt would have been increased in the ratio 1.4248 to unity by this rise of temperature. It is apparent then that under the influence of the first excessive heating the cobalt has been considerably altered in its properties, so that the average temperature cœfficient for resistance up to 150° C. has been increased by a quarter.

That the successive heatings caused a marked change in the structure of the wire or strip is shown by the variations in the measured resistance at 7° C. These are given in Table III.

Table III.

When Measured.	Resistance of Platinum wire	Resistance of Cobalt Strip.
At the beginning	.8525	.09724
After 1st heating	.85028	.09135
,, 2nd ,,	.85028	.09354
,, 3rd ,,	.85013	.09674
,, 4th ,,	.85232	.09978

The fall in resistance after the first heating is no doubt due to some change in the contact resistances. It characterises both the platinum and cobalt. Subsequent heatings however do not change the platinum to any great extent until the very last experiment; but their effect on the cobalt is very marked. After the experiments were completed the cobalt was found to be much altered by oxidation. It was exceedingly brittle and broke into small pieces when it was being detached from the copper rods. While the observations were being made, it was noticed that the fourth experiment was much inferior in point of regularity and steadiness to the others, a fact sufficiently explained by the final condition of the metal.

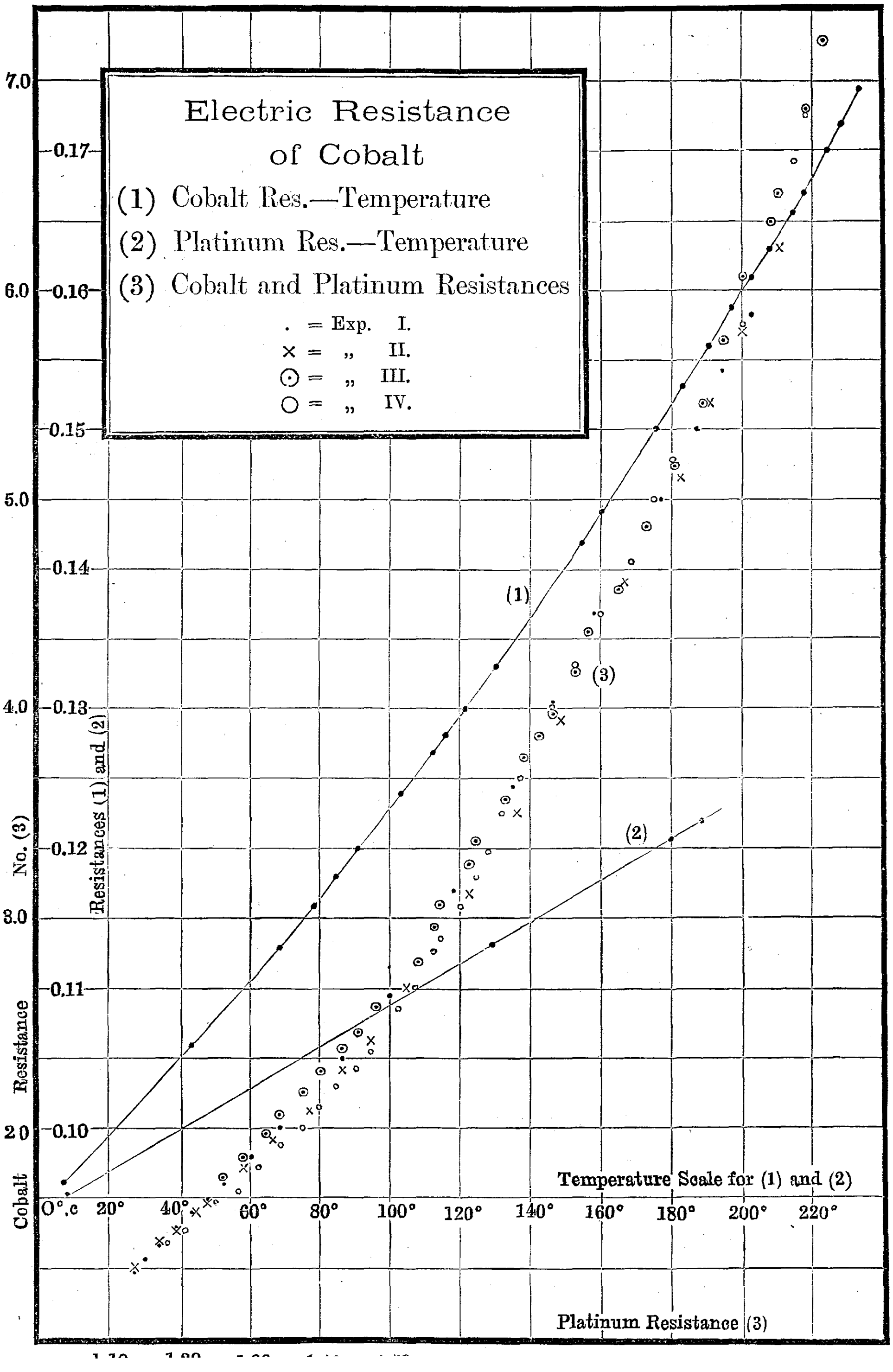
It is not surprising, then, that there is considerable divergence between the values of the temperature cœfficients as obtained from the earlier experiment in oil and the later series in the charcoal furnace.

What is surprising is, that in spite of the great alteration in structure going on in the strip, the general behaviour of the cobalt as shown in the first three experiments is essentially the same. This is well seen from the tabulation of the rates of change themselves. These quantities were calculated by the same general method of interpolation as was used in calculating the resistance. They correspond to the values of dy/dx if y and x are taken to represent respectively the corresponding resistances of cobalt and platinum. They are given in Table IV, the first column containing the values of the platinum resistances to which the tabulated rates of change correspond.

Table IV.

Platinum Resistance (Arbitrary Temp'r scale).	Rates of Change of Cobalt Resistance per unit Change of Platinum Resistance.			
	Exp. I.	Exp. II.	Exp. III.	Exp. IV.
2	7.02	7.30	10.33	9.15
1.8	6.19	7.24	6.74	5.09
1.6	5.45	5.57	6.63	6.10
1.4	3.76	3.58	3.65	3.66
1.2	3.58	3.23	2.78	

I have thought it sufficient to give the condensed numerical results as contained in Tables I, II and IV. The individual observations upon which these results are based are shown graphically in the diagram.



Electric Resistance of Cobalt
(1) Cobalt Res.—Temperature
(2) Platinum Res.—Temperature
(3) Cobalt and Platinum Resistances
. = Exp. I.
× = „ II.
⊙ = „ III.
○ = „ IV.
7.0
0.17
6.0
0.16
0.15
5.0
0.14
4.0
0.13
0.12
3.0
0.11
2.0
0.10
Cobalt Resistance No. (3)
Resistances (1) and (2)
(1)
(2)
(3)
Temperature Scale for (1) and (2)
0°.c
20°
40°
60°
80°
100°
120°
140°
160°
180°
200°
220°
Platinum Resistance (3)

Curves 1 and 2 have already been mentioned. They show the march of resistance with temperature as measured on a mercurial centigrade thermometer. In No. 3, the platinum resistances are virtually used as temperatures, and form the abscissæ. The ordinates are the corresponding cobalt resistances. The points belonging to the various experiments are distinguished by special mark.

It will be seen at a glance that in one particular cobalt behaves very like iron and nickel. There is a rapid increase in the steepness of the curve at the higher temperatures. In iron and nickel this rapid increase is followed at still higher temperatures by a distinct decrease, the curves bending so as to present a concavity toward the temperature (or platinum resistance) axis. Table IV. gives no hint of such a tendency in cobalt. The curves all become steeper with rise of temperature, if we except the distinctly irregular indications of Experiment IV.

It will be seen from Table IV. that Experiments I. and II. are in fair agreement throughout; and that all four experiments point to the existence of a critical temperature, at which the resistance begins to increase rapidly with rise of temperature. This critical temperature is about the stage 1.5, which corresponds approximately to 350° C. The same conclusion may be drawn from Table II. and expressed in these terms. Between the temperatures 400° and 700° C. the resistance of a cobalt strip increases on the average at a rate nearly twice as great as the average rate of increase between 0° and 300° C.

2. The Thermoelectric Positions of Cobalt and Bismuth.

So far as I know, the only satisfactory determination of the position of the Cobalt line on the thermoelectric diagram was made by

Professor Tait's students in the Physical Laboratory of Edinburgh University some fifteen years ago. The position of the Cobalt line, so found, was given along with the positions of certain alloys in a paper by Professor J. Gordon MacGregor and myself published in the Transactions of the Royal Society of Edinburgh, Vol. XXVIII (1878). The particular specimen of Cobalt used in these early experiments was a short rod obtained by electrolytic deposition. The noteworthy facts regarding its thermoelectric line were that it lay below nickel on the diagram, and that its inclination to the lead line was much greater than the inclinations of the iron and nickel lines.

As a Laboratory exercise I gave to Mr. Sawada, one of our students of physics, the task of studying the thermoelectric properties of the sheet cobalt described in the preceding note. The plan adopted was to form a multiple arc of Palladium and Bismuth and by proper adjustment of the resistances in these branches to obtain an intermediate line which should cut through the cobalt line at temperatures within easy reach.

Such an intermediate line passes through the neutral point of the component metals. It divides the region between their lines so that any transversal is cut into portions which are directly as the resistances in the branches of the multiple arc. Thus by varying the ratio of the resistances in these branches we may sweep through the region between the two corresponding diagram lines, interpolating so to speak any intermediate line suitable for our purpose. The extreme accuracy with which we can measure electric resistance enables us to fix the position of this intermediate line as accurately as the positions of the component lines are known.

The low position of cobalt on the diagram very much circumscribed the choice of metals for the multiple arc. Bismuth had to be one of them, as it alone was known to be below cobalt. The other metal fixed upon was Palladium, a substance convenient in every way. Its diagram line is straight up to high temperatures ; and its character does not perceptibly change even after severe heatings. Unfortunately, however, the necessity of using bismuth limited the investigation to moderate temperatures.

The bismuth was broken up into small pieces, which were packed tightly into the bore of a siphon shaped glass tube. Gentle heating in a Bunsen flame sufficed to melt the metal, which ran together and solidified on cooling into a fairly uniform rod. The junction wires were fused into the ends of the bismuth rod.

As finally set up, the apparatus consisted of a triple Cobalt-Bismuth-Palladium junction dipping in oil. This formed the "hot junction." Resistance boxes were included in the palladium and bismuth branches. Because of the magnitude of the thermoelectromotive forces between these three metals and copper, great precaution was necessary in keeping the various cold junctions at the same temperature.

The palladium branch always contained 100 ohms resistance. The resistance of the bismuth branch varied from infinity to 200, lower values carrying the intermediate line too far below the cobalt line. For each of the seven selected ratios of resistances, a careful series of thermoelectric observations was made. A delicate high resistance galvanometer was used ; and the temperatures were measured by a mercurial thermometer. The electromotive forces between the cobalt and each intermediate "equivalent metal" were in this way measured directly. From these the thermoelectric powers at chosen temperatures could be calculated. But one of these "equivalent metals" was palladium itself, when the resistance in the bismuth branch was made infinite. Subtracting all the other thermoelectric powers from this one, we obtained the thermoelectric powers between palladium and the other equivalent metals. The values of the thermoelectric powers were calculated for 0° C and 100° C and are given in the following Table. The symbol Bi stands for bismuth, Co for cobalt, and Pd for palladium. The various "equivalent metals" are represented by the symbol Pd Bi_n where the number n represents the ratio of the resistance in the bismuth branch to the resistance in the palladium branch. Thus Pd Bi_2 means that, since the palladium always contained 100 ohms resistance, the bismuth contained in this case 200 ohms. The electromotive forces are measured in microvolts.

Thermoelectric Powers referred to Palladium.

Metal.	Thermoelectric Power at 0°C.	at 100°C.	Neutral Point with Cobalt.
Co	7.00	17.31	
Pd Bi_{13}	5.98	6.46	−10°.4 C.
Pd Bi_8	9.38	9.96	+24°.5
Pd Bi_5	14.45	14.69	74 .1
Pd Bi_4	17.44	17.44	101 .4
Pd Bi_3	21.73	22.13	148 .9
Pd Bi_2	29.10	29.55	224 .0
Bi	86.0	88.8	

The numbers in the last row have been calculated from the numbers in all the six Pd Bi rows. For if p is the thermoelectric power between Pd and Bi and p_n the same between Pd and Pd Bi_n we know that

$$\frac{p - p_n}{p_n} = \frac{n}{1}$$

or

$$p = (n + 1)\, p_n$$

Thus from the six sets of values corresponding to p_n we obtain the following values for p at 0° C. and 100° C.

$n+1$	p_0	p_{100}
14	83.7	90.4
9	84.4	89.6
6	86.7	88.1
5	87.2	87.2
4	86.9	88.5
3	87.3	88.7
Means	86.0 ± .8	88.8 ± .7

This table is obviously an indication of the accuracy of the experiment.

And now, referring everything to the Lead line, and expressing the thermoelectric power in the form

$$p = \frac{de}{dt} = A + Bt$$

we obtain for the coefficients A and B the following values.

	A	$B \times 10^2$
Lead	0	0
Palladium	− 6.18	− 3.55
Cobalt..........................	−13.18	−13. 9
Bismuth	−92. 2	− 6. 4

According to the numbers deduced by Fleeming Jenkin from Matthiesen's experiments, bismuth lies four times further from lead than does cobalt. Here we have it seven times. Professor Tait's electrolytically deposited cobalt lies $4\frac{1}{2}$ times further from lead than does palladium. Here we have it a little over two times. According to Becquerel's numbers given at the end of the English translation of Mascart and Joubert's *Electricity and Magnetism*, the ratio at 50° C. of the thermoelectric powers of palladium and bismuth relatively to lead is as 7 : 40. Here we have 1 : 16.

These discrepancies are not surprising. We know how variable are the thermoelectric properties of stable alloys[1] intended to have the same composition, and how a very slight change in composition may be accompanied by a very large change in thermoelectric position. The present experiments must therefore be judged of altogether on their own merits. A simple comparison shows us that Professor Tait's cobalt will fit in to the region between lead and bismuth very much as Matthiessen's cobalt fits in to his own series. Thus the cobalt investigated here seems to differ from these other specimens in much the same way. The new cobalt indeed lies so high in the diagram that its line is higher than the line of Tait's nickel, for which A = − 21.8.

This unexpected result was at once tested. A rough experiment was made with the couple nickel-cobalt and a neutral point was obtained at a temperature below 100° C. This cobalt line therefore, at ordinary temperatures of the air, is above nickel ; but because of its greater downward inclination gets below it at temperatures above 100° C.

As regards the inclination of the cobalt line, the present result agrees as well with the earlier result as could reasonably be expected with two quite different specimens of the metal. Thus, expressed in the same units, the thermoelectric power of Professor Tait's cobalt is given by the formula.

$$p = -26.3 - 0.116\ t$$

whereas for the present specimen

$$p = -13.18 - 0.1386\ t$$

With the exception of the sharp upward bend in nickel, this gives the greatest inclination yet obtained for a thermoelectric line. It would

1) See the paper by MacGregor and myself already referred to, also my paper on *The Electrical Properties of Hydrogenised Palladium* (Trans. R. S. E., Vol. XXXIII., 1886)—abstract in this *Journal*, Vol. I.

be interesting to establish by direct experiment that the Thomson Effect is exceptionally large in cobalt.

The downward trend and comparatively large inclination of the bismuth line are also worthy of note. Because of the position of the line as a whole, lying far below the lines of all other metals, this large inclination does not greatly influence the electromotive forces, so that with bismuth couples the electromotive force is very approximately proportional to the temperature. This fact of course prevents us from making a very accurate determination of the coefficient B, which in the present experiments has a large probable error. Its mean value is a little greater than the value indicated in Battelli's direct measurement of the Thomson Effect in Bismuth[1].

Righi has shown[2] that the electric resistance of Bismuth is altered in a strong magnetic field. To find if any thermoelectric change accompanied magnetisation in nickel, a bismuth palladium couple was set up between the poles of a powerful electromagnet. No effect whatever was obtained, although the arrangement (slightly modified) was sensitive enough to show with great ease the thermomagnetic effect discovered by v. Ettingshausen and Nernst[3].

1) See Wied. Beiblätter, Vol. XI, 1887.
2) See Wied. Beiblätter, Vol. XIII, 1884.
3) See Wied. Annalen, Vol. XXIX, 1886.