VIII.—*The Electrical Resistance of Nickel at High Temperatures.* By CARGILL G. KNOTT, D.Sc. (Edin.), F.R.S.E., Professor of Physics, Imperial University, Tokayo, Japan. (Plate XII.)

(Read 5th July 1886.)

In the *Proceedings of the Royal Society of Edinburgh* for 1874–75 there is a short paper on the "Electrical Resistance of Iron at a High Temperature." It is the record of certain experiments made by three of us, then students in the Physical Laboratory of the University of Edinburgh; and its conclusion is that there is a peculiarity in the behaviour of iron as an electric conductor at the temperature of a dull red heat. At this temperature other physical peculiarities are known to exist, particularly as regards its thermal expansion, its thermal capacity, and its specific heat for electricity. The discovery of these striking properties we owe respectively to Dr GORE,* Professor BARRETT,† and Professor TAIT.‡

Professor TAIT'S discovery, that the THOMSON effect in iron changes sign at certain high temperatures, is in itself very striking; and, when taken in connection with other coexistent peculiarities, suggests various lines of inquiry. The most obvious is, perhaps, the question as to its occurrence in other metals. There is one other metal which rivals iron in thermoelectric eccentricity, namely, nickel. At a temperature of 200° centigrade, its THOMSON effect gradually changes sign from a considerable negative value to a large positive value, changing back again to nearly its original value at 300° C. If nickel thus agrees with iron in one exceptional feature, it may well be expected to agree in others. In short, Does nickel between the temperatures of 200° and 300° C. undergo exceptional changes in length? is there a phenomenon corresponding to BARRETT'S reglow? and has the electric resistance any unusual change at these temperatures? The first and third questions may be readily answered by experiment; the second, however, seems to offer almost insuperable difficulties as a subject of investigation. The following paper deals with the third of these inquiries.

I have thought it well to embody, along with the results for nickel, corresponding results for iron. The chief reason for this is, that in the experiments conducted in 1874 by Messrs SMITH and MACFARLANE and myself, only a

* *Proc. Roy. Soc. Edin.*, 1869, and *Phil. Mag.*, 1869.

† *Phil. Mag.*, 1873.

‡ *Trans. Roy. Soc. Edin.*, 1872–73.

general qualitative result was obtained. The method adopted was not one which lent itself to accurate quantitative determinations, and to obtain such is in itself an important quest. Moreover, the ultimate nature of the peculiarity can only be seen in its true light by a direct comparison of the individual characteristics as shown by iron and nickel. The great difficulty in making such a comparison arises from the high temperature at which the phenomenon shows itself in iron; and a further complication springs from the change in the metal, due to oxidation and tempering. In the case of nickel, however, the critical temperature is within reach of a mercurial thermometer, and the oxidation is insignificant. It is highly probable, then, that the results for nickel will be more definite and unmistakable than those for iron.*

In the experiments to be described, the resistances were measured by the simple form of Wheatstone bridge. The wires were generally tested in pairs, necessarily so in the measurements at very high temperatures. Four stout copper rods, 60 cm. long, ·7 square cm. cross-section, furnished with strong shoulder binding screws at the extremities, were fixed in a vertical position some little distance apart. Their lower extremities were joined in pairs by two wires, one of which was a specimen of nearly pure platinum, and the other the nickel, iron, or palladium wire which was being tested. The upper extremities of the rods were joined by stout copper wires to a commutator, which was in connection with a Wheatstone bridge resistance box of ordinary construction. The current was obtained from a gravity Daniell of high resistance; and the measurements were made by means of a dead-beat mirror astatic galvanometer constructed by ELLIOTT BROTHERS.

The earlier experiments and some of the later ones were carried out by Messrs HIRAYAMA and SANEYOSHI, two science students in the Imperial University, Tokayo, and were originally intended simply as an exercise in laboratory work. Two wires, one of nickel and the other of platinum, were coiled in long spirals, and fixed to the lower extremities in the manner already described. A vessel containing olive oil was then brought into position, so that the wires were wholly immersed. The temperature was gradually raised by means of a spirit-lamp, and the resistances measured at convenient intervals. The temperatures were given by a centigrade thermometer, whose bulb hung in the centre between the terminals of the wires. The oil was briskly stirred the whole time, so as to secure a practically uniform temperature throughout the mass. The thermometer itself was tested directly at freezing and boiling points, and the necessary corrections applied. The error being the same at both points, it was assumed to apply throughout the whole range of readings. Two specimens of nickel wire were studied, which we shall distinguish as the thick nickel and the thin nickel. Tables A and B give the observations for

* See also *Proc. Roy. Soc. Edin.*, ix. 120, 1875–76. [P. G. T.]

these wires; tables C and D give the corresponding results for platinum and palladium. They are added simply for the sake of comparison.

The first column contains the corrected temperatures; the second the resistances corrected for the connections; and the third these resistances reduced so as to make the resistance at 0° C. equal to 100. The value of the resistance of the wire at 0° C. was in all cases calculated—in the case of platinum and palladium from the empirical parabolic formula which was found to agree well with the observations, and in the case of nickel by the method of successive differences from the first five or six numbers. This latter method was used because, for the nickel measurements, it was found quite impossible to obtain a suitable formula of ascending powers of temperature up even to the fourth. The reduced resistances of the third column for each wire are represented graphically in their relation to temperatures on Plate XII. (I.). The diameters and specific resistances of each wire are given at the head of each list of numbers.

The resistances throughout are measured with greater accuracy than the temperatures. In some cases, the temperature being steady, the resistance was adjusted by means of a large shunt set in an arc along with the units of the resistance box. In other cases—and this was latterly found the more convenient method—the resistance was fixed as near as the coils would allow, and the temperature of the wire slowly raised till the current through the galvanometer just vanished. Hence, although the resistances in table A appear only to the third significant figure, they are really certain to the fourth.

TABLE A.—*Thick Nickel.*

Diameter = ·05 cm. Specific resistance = 9697 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
0° C.	·724 ohms	100
10°	·757	104·6
20°	·79	109·1
29°	·82	113·3
66°·4	·95	131·2
88°	1·03	142·3
98°·6	1·07	147·8
114°·6	1·14	157·5
122°·6	1·17	161·6
131°·6	1·21	167·1
142°·3	1·26	174·0
167°	1·37	189·2
187°	1·47	203·0
198°·5	1·53	211·3
215°	1·62	223·8
220°·3	1·65	227·9
233°	1·72	237·6
251°	1·83	252·8
255°	1·85	255·5
264°·8	1·91	263·8
267°·5	1·93	266·6

TABLE A.—*continued.*

Diameter = ·05 cm. Specific resistance = 9697 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
278° C.	2·00 ohms	276·2
281°	2·02	279·0
293°	2·10	290·1
295°	2·11	291·4
300°	2·15	296·7
301°·4	2·16	298·4

TABLE B.—*Thin Nickel.*

Diameter = ·0154 cm. Specific resistance = 14500 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
0° C.	1·914 ohms	100
9°	1·96	102·4
33°·4	2·09	109·2
56°·5	2·233	116·6
76°	2·38	124·3
99°	2·55	133·2
120°·4	2·716	141·9
143°·7	2·915	152·3
165°	3·091	161·5
182°·5	3·259	170·3
203°	3·457	180·6
226°	3·697	193·2
248°·8	3·96	206·9
266°	4·17	217·9
290°·4	4·48	234·1
305°	4·73	247·1

TABLE C.—*Platinum.*

Diameter = ·049 cm. Specific resistance = 16800 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
0° C.	1·02 ohms	100
35°·5	1·11	108·8
58°	1·164	114·1
80°·5	1·208	118·4
99°·5	1·256	123·1
119°	1·30	127·5
141°·3	1·35	132·4
163°·8	1·40	137·3
186°·3	1·45	142·2
204°	1·484	145·5
221°·3	1·523	149·4
243°·1	1·58	154·9
261°	1·612	158·0
278°	1·642	161·0
295°·8	1·69	165·7

TABLE D.—*Palladium.*

Diameter = ·0396 cm. Specific resistance = 10680 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
0° C.	1·595 ohms.	100
9°	1·64	102·8
31°	1·77	111·0
56°	1·914	120·0

TABLE D.—*continued.*

Diameter = ·0396 cm. Specific resistance = 10680 (C.G.S.).

Temperature.	Resistance of Wire used.	Resistance reduced for comparison.
76°·5 C.	2·02 ohms	126·7
99°	2·146	134·6
120°·4	2·265	142·0
144°	2·39	149·9
165°	2·508	157·3
184°·5	2·607	163·5
204°	2·72	170·5
226°	2·832	177·6
247°	2·94	184·4
268°·5	3·05	191·2
291°·5	3·163	198·3
305°	3·216	201·3

A glance at the columns of reduced resistances, or at the representative curves, shows at once one peculiarity of nickel as compared with the other metals, namely, the comparatively great increase of resistance throughout the measured range of temperature. The curves further show, by the manner of their curvature, that the rate of increase of resistance of a given nickel wire per degree centigrade *increases* as the temperature rises; whereas this rate of increase diminishes in the case of platinum and palladium. The same fact is readily shown from the numbers themselves by dividing the successive first differences of either column of resistances by the corresponding temperature differences.

The impossibility of representing the march of the nickel resistance by an empirical formula of ascending powers of the temperature has been already noticed. Some mode of formulating the results is, however, advisable, so as to make them numerically comparable with the results for platinum and palladium, which can be represented very approximately in the usual way. The following mode seems to be in many respects suitable:—

First, calculate by strict interpolation methods from five contiguous observations, the resistances corresponding to successive conveniently chosen temperatures, say, 0°, 50°, 100°, 150°, 200°, and 250°. Then tabulate, as in the subjoined table, the successive differences of these resistances. In the series of 2nd differences we recognise at once the impossibility of applying a parabolic equation to the results for nickel.

Table of Successive Differences of Thick Nickel Resistances.

Temperature.	Resistance.	1st Differences.	2nd Differences.
0°	·724		
		·168	
50°	·892		·016
		·184	
100°	1·076		·035
		·219	
150°	1·295		·024
		·243	
200°	1·538		·044
		·287	
250°	1·825		

Table of Successive Differences of Thin Nickel Resistances.

Temperature.	Resistance.	1st Differences.	2nd Differences.
0°	1·914		
		·275	
50°	2·189		·091
		·366	
100°	2·555		·045
		·411	
150°	2·966		·050
		·461	
200°	3·427		·084
		·545	
250°	3·972		

Although it is impossible to get a single parabolic equation to apply all through, we may calculate parabolic equations to apply to successive overlapping segments of a hundred degrees' range, taking as initial points the successive temperatures 0°, 50°, 100°, 150°. We thus obtain four equations, which will be found to agree closely with the observations. To compare these equations with those for other metals, such as platinum and palladium, would then be an easy matter.

It is to be remembered, however, that the usual method of representing observations by an empirical formula of ascending powers of the one variable has rarely any deep significance. What is of real importance in all such investigations is to know, first, what the value of a certain quantity is, and, second, how it varies under given conditions; and in many instances the latter is the main object of research. It is so in the present inquiry. It should be our object, then, to tabulate our results in such a manner that the rate of change of resistance per degree of temperature may be evident at a glance for all temperatures. The usual equation is of the form

$$R = R_0(1+\alpha t+\beta t^2),$$

from which we may almost at once calculate dR/dt for any temperature. What we wish, however, is not so much this quantity as the quantity $R^{-1}dR/dt$, which is the real rate of change of resistance.

In the following table this quantity is calculated for the four series of observations already given, so that the peculiarities of nickel may be readily indicated. The quantities are estimated for the temperatures 50°, 100°, 150°, 200°, since for these alone can be safely estimated the rates of change in the case of the nickel. The necessary calculation is most readily effected by means of the formula—

$$\frac{1}{R_t}\frac{dR_t}{dt} = \frac{1}{R_t}\left(\frac{\Delta_1}{\tau}+\frac{\Delta_2}{2\tau}\right),$$

where Δ_1 Δ_2 are the first and second differences in the series of resistances, corresponding to the temperatures $t-\tau$, t, $t+\tau$. The values for platinum and palladium are similarly estimated.

Temperature.	Values of $\frac{1}{R_t}\frac{dR_t}{dt}$ for			
	Thick Nickel.	Thin Nickel.	Platinum.	Palladium.
50° C.	·00395	·00293	·00218	·00302
100°	·00375	·00306	·00198	·00249
150°	·00357	·00294	·00170	·00225
200°	·00342	·00294	·00142	·00197

This table shows very distinctly the real nature of the difference between nickel and the other two metals; it is a difference only of degree. The quantity $R^{-1}dR/dt$ or $d \log R/dt$, we shall, for brevity's sake, call the logarithm rate, per unit rise of temperature being understood. It appears, then, that nickel differs from platinum or palladium, or most other metals, in the fact that its logarithm rate does not change so much with rise of temperature. In the case of the thin nickel, indeed, it is practically constant, so that the march of resistance with temperature could be very approximately represented by a simple logarithmic equation.

It may be noted that the logarithm rates for platinum and palladium are approximately inversely as the corresponding absolute temperatures. Hence we have

$$\frac{1}{R}\frac{dR}{dt}=\frac{k}{t}$$

For platinum, $k=\cdot 7$ roughly;
" palladium, $k=\cdot 95$ "

Integrating and evaluating the constant by the condition

$$R=100 \text{ when } t=274,$$

we find, for platinum, the formula

$$R=1\cdot 97\times t^{0\cdot 7};$$

and, for palladium,

$$R=\cdot 483\times t^{0\cdot 95}.$$

These formulas will be found on trial to be in fair agreement with the numbers given in tables C and D.

We may also by integration of

$$\frac{1}{R}\frac{dR}{dt}=\cdot 003$$

obtain a formula for the thin nickel. Its form is

$$\text{Nap. log. } (R\times\cdot 0228)=\cdot 003\times t,$$

where t is, as before, the absolute temperature. This expression will likewise be found to suit the numbers given in the last column of table B.

There is no very obvious mode for obtaining a similar formula for the thick nickel.

It may be remarked that this mode of representing the temperature relations of resistance by a power of the absolute temperature—a power which may be fractional—includes as a special case the well-known statement that, for pure metals, the resistance is directly as the absolute temperature. For small ranges of temperature the equation

$$R = CT^k$$

may be easily thrown into the approximate form

$$R = R_0(1 + at + bt^2),$$

where T is absolute temperature, t centigrade, and the other quantities are constants. In this case a is to a first approximation equal to k times the reciprocal of 274.

We now pass to the discussion of the second series of experiments. In these the temperature was raised to a fairly bright red heat by means of a charcoal furnace. The four stout copper rods, with the attached wires which were to be tested, dipped into a porcelain vessel through suitable holes in the lid. The vessel itself stood inside a small charcoal furnace, and was heated by red charcoal dropped in around it. After reaching its highest temperature the charcoal and wires gradually cooled; and during this cooling the resistances of the two wires were measured in rapid alternation.

To obtain what might be regarded as simultaneous values of the resistances, means of successive pairs of readings for the one metal were interpolated. In every case the one wire was the same piece of platinum, whose indications served the purpose of a thermometer. In terms of its resistances, the resistances of the other wires could be expressed, graphically or otherwise. Many experiments were made with each kind of wire, and a vast number of observations accumulated. These I have not thought necessary to reproduce in the form in which they were obtained. The five curves of Plate XII. (II.), however, which tell their own tale clearly enough, are drawn from the observations, conveniently reduced, of the five best experiments. The reductions were the same as those made in the earlier series of experiments; that is, the resistance at 0° C. for each metal was reduced to 100, and the other resistances changed proportionally.

Although the numbers themselves are not reproduced, their essence is given in table E, which is really a comparative table of the resistances of certain wires at various temperatures from 0° C. to a fairly bright red heat. The series of platinum resistances, as shown in the first column, rises from 100 to 230 by successive additions of 10. From the reduced observations in the several experiments, the resistance of any metal corresponding to each one of the chosen platinum resistances can be readily calculated. Thus the number 401 in the fourth column means that a piece of thick nickel, whose resistance at 0° C. is 100, has a resistance of 401 at that temperature at which 190 is the resistance of a piece of platinum whose resistance at 0° C. is also 100. In short, the platinum column serves the purpose of a provisional temperature scale, in terms of which the resistances of the other metals are expressed. Under each column a row of differences is added. These bring out strongly the peculiarities which are disclosed by a glance at the curves of Plate XII. (II.). On the left of the platinum column a few numbers are given to indicate the temperature in degrees centigrade. Above the value 320° C., the estimation is only approximate, and is based on the assumption that platinum wire changes in resistance according to a parabolic function of the temperature. 700° C. may be regarded as a fair approximation to the highest temperature. Besides the nickels and palladium used in the former series of experiments, two specimens of iron were investigated, and are given for purposes of comparison.

TABLE E.—*Comparison of the Resistances of various Metals at different Temperatures.*

Temp. in ° C.	Platinum.		Palladium.		Thin Nickel.		Thick Nickel.		Iron (1).		Iron (2).	
	Resist.	Diff.	Resist.	Diff.	Resist.	Diff.	Resist.	Diff.	Resist.	Diff.	Resist.	Diff.
	230		303		350		476		713		718	
		10		14		12		19		80		75
580°	220		289		338		457		633		643	
		10		14		13		17		83		75
	210		275		(325)		440		550		568	
		10		12		13		22		65		54
	200		263		311		418		485		514	
		10		14		14		17		60		51
420°	190		(249)		297		401		425		463	
		10		15		15		23		54		58
	180		234		282		378		371		405	
		10		16		16		43		45		50
320°	170		218		266		335		326		355	
		10		17		31		52		42		50
270°	160		201		235		283		284		305	
		10		17		29		43		42		44
220°	150		184		206		240		242		261	
		10		17		30		34		28		42
180°	140		(167)		176		206		214		219	
		10		17		24		36		34		32
130°	130		150		152		170		180		187	
		10		17		19		29		32		32
84°	120		133		133		141		148		155	
		10		17		15		21		27		28
40°	110		(116)		(118)		(120)		121		127	
		10		16		18		20		21		27
0°	100		100		100		100		100		100	

First, we notice that palladium is very similar to platinum in the manner of its changings, tending, however, to diminish in rate of change as compared with the platinum at higher temperatures. Secondly, we see at a glance that the behaviour of the nickels is very peculiar. About a temperature of 180° or 200° C. the rate of growth of resistance of a given wire with temperature undergoes a marked increase, and experiences a more evident decrease at a temperature somewhat above 300° C. Throughout this range of temperature the comparatively great slope in the resistance curve is very striking.

Thirdly, there seems to be a similar increase in the rate of growth of resistance of iron wire, occurring at a temperature a little below 600° C. It was unfortunately impossible to attain a much higher temperature with the means at our disposal; but in the very highest readings obtained there was sometimes an indication of a decrease setting in, as in the case of nickel. In the curves as drawn the peculiarities of the iron are not very distinctly shown. It was thought better, however, to draw the curve to the same scale as the curves for the other metals than to proportion the co-ordinates to make it well-conditioned. The curves indicate at once the extremely great increase of resistance in iron as compared with other metals. This is in accordance with former experiments; and the results here obtained agree fairly well with Von WALTENHOFEN'S results for steel (see WIEDEMANN'S *Electricität*, vol. i. p. 525). The measurements made by other experimenters do not agree nearly so well—as a rule, a much smaller increase has been found.

In this paper, however, no special emphasis is laid on the results for iron, except that they cannot be represented by any ordinary empirical formula, such as C. W. SIEMENS has given. So far as they go, they bear out our result of twelve years ago, that the rate of growth in resistance of iron experiences a marked increase at a temperature of a dull red heat. This peculiarity has now been proved to exist in the case of nickel, occurring however at a much lower temperature. The further peculiarity, so distinct in the case of nickel—namely, the subsequent decrease in the rate of growth—probably exists also in the case of iron. Indeed, on Von WALTENHOFEN'S authority, the continued increase of resistance of steel as the temperature rises from a red heat to a white heat tends to evanescence. This bears out the statement made above. Thus, it appears that iron and nickel agree in a certain peculiarity in the rise of their resistance with temperature. This peculiarity may be thus described. Within a certain range of temperature, the resistance of a given wire increases at a more rapid rate per temperature degree than at temperatures above or below this particular range. For nickel this range lies between 200° and 320° centigrade; for iron between a dull red and a bright red heat. Now, it is exactly within these ranges respectively that the thermoelectric peculiarities of nickel and iron occur. In no other metals have any similar peculiarities been observed. Hence we may regard it as an experimental truth that the interesting changes in the sign of the THOMSON effect in metals in which such changes do occur are accompanied by peculiar changes in the manner of growth of resistance with temperature.

In the case of the nickel, the simultaneousness of the two peculiarities was demonstrated by direct experiment. In effecting this direct comparison, we tried many modifications; but the essential characteristic of the experiment was to obtain, alternating with the resistance measurements, accurate determinations of the electromotive force of a nickel-palladium pair. In some cases the measurements of the platinum resistance were used as the temperature scale in which to express this electromotive force; in other cases the platinum wire was dispensed with, so far as resistance measurement was concerned, but was introduced as a third element in the thermoelectric junction, after the convenient manner invented by Professor TAIT. That is, the three wires—nickel, palladium, and platinum—were bound together as a triple junction, and the free extremities led off in such a way that the nickel-palladium circuit and palladium-platinum circuit could be thrown on to the galvanometer in rapid alternation. In this form of experiment the palladium-platinum circuit played the rôle of a thermometer. The platinum was very similar in its thermoelectric properties to the kind named "Soft Pt" in Professor TAIT's first approximation to a thermoelectric diagram. Its thermoelectric line was but slightly inclined to the palladium line, and the electromotive force of the palladium-platinum circuit increased at a somewhat quicker rate than the temperature as estimated in centigrade degrees.

In whatever way the temperature was virtually measured, whether by the resistance of platinum or the electromotive force of the palladium-platinum circuit, the experiment gave us the means of comparing directly the two peculiar effects of nickel. Two curves could be drawn, the one showing the march of the electromotive force of nickel-palladium with temperature, the other giving the same thing for nickel resistance. The resistance curve was similar in all respects to those already shown in Plate XII. (II.); the electromotive force curve reproduced with wonderful fidelity the old result of Professor TAIT. Beginning nearly straight at low temperatures, or if anything slightly concave upwards, it became, as the temperature approached 250° C., distinctly convex upwards. About 300° C. the neutral point was reached, and shortly after passing the vertex the curve became accurately straight, and continued so to the highest temperatures. In fact, it consisted practically of two straight portions, oppositely inclined to the line of temperatures, and connected by a parabolic arc with vertex at 300° C. This, of course, shows that the nickel line on the thermoelectric diagram, lying at low temperatures *below* the palladium line,* continues parallel thereto till the temperature reaches 200° C., after which it gradually bends up towards the palladium line. This it cuts through at the neutral point (300° C.), and almost immediately thereafter bends round again into parallelism with the palladium line. Now these two rapid bendings were found to occur just at the temperatures at which the peculiar bendings occurred in the resistance curve.

Similar experiments were tried on iron, with, however, doubtful results. This was certainly in the main due to the non-efficiency of the method of preparing and keeping a high temperature.

The main results of these experiments may be thus described :—

1. The rate of growth of the resistance of a given nickel wire with temperature is greater, on the average, than the corresponding quantity for platinum or palladium, and less than that for iron.
2. The "logarithm rate"—that is, the rate of change per unit rise of temperature of *unit* resistance at any temperature—falls off more slowly for nickel as the temperature rises to 200° C. than it does for platinum or palladium.
3. At about 200° C. the rate of resistance-growth for nickel increases markedly, and continues practically steady till about 320° C., when a sudden decrease occurs, and thereafter the resistance steadily increases at this diminished rate. In other words, between the limits of temperature specified, the slope of the resistance curve is much steeper than for any other temperature. The same peculiarity is probably possessed by iron between the temperatures of a dull red and a bright red heat.
4. The peculiarity occurs (in each case) between the limits of temperature within which the striking thermoelectric peculiarity discovered by TAIT also occurs—a peculiarity which is quite unknown in the case of any other metal.
5. There is thus a strong presumption that the THOMSON effect in metals has a close connection with the mutual relations of resistance and temperature; at any rate in metals in which the THOMSON effect is proportional to the absolute temperature (according to TAIT's theory), the "logarithm rate" of change of resistance seems to be very approximately inversely as the absolute temperature. In nickel and iron, in which the law of the THOMSON effect is peculiar, such a simple relation between resistance and temperature does not hold.

* It is to be regretted that certain writers still persist in turning the diagram, as it were, upside down, thus losing the advantage of TAIT's improvement on THOMSON's original form—an improvement which fits in so admirably with the *sign* of the THOMSON effect.