

ART. XLIII.—*Certain Generic Electrical Relations of the Alloys of Platinum*;* by C. BARUS.

IF the specific electrical resistance (s) of a metal be expressed by $s=f(\chi, t)$, where t is the symbol of temperature and χ a variable parameter, then the data of the present paper may be said to furnish evidence of an inherent physical relation between $f(\chi, 0)$ and $f'(\chi, 0)$ —i. e. the zero values of s and its first derived function with respect to t ,—provided the largest admissible value of χ be small in comparison with its maximum value. Usually variations of χ are produced by changing the qualities of the originally pure metal by small quantities of some foreign ingredient, metallic or not. With the understanding thus laid down, $f'(\chi, 0)/f(\chi, 0)$ is the succinct interpretation of what is ordinarily called temperature-coefficient, and which in the present paper will often be denoted by α . Conformably with the notation indicated $f(0, 0)$ and $f'(0, 0)$ are the constants of the unalloyed metal. When this is not thus explicitly stated, I will for the sake of brevity use $f(0)$ and $f'(0)$ in place of $f(\chi, 0)$ and $f'(\chi, 0)$, respectively.

* This paper indicates the chief result of the third chapter of the Bulletin on the measurement of high temperatures, to which reference has already been made. (See this Journal, xxxv, p. 407, 1888.)

The expression for electrical conductivity is here $1/f(\chi, t)$, to be abbreviated λ . If $s=s_0(1+at+\beta t^2+\dots)$, it follows that $\lambda=\lambda_0(1-at+(\alpha^2-\beta)t^2-\dots)$; and hence the temperature coefficients, taken in the sense just defined, are numerically identical, no matter whether reference is made to s or to λ .

The alloys of which the present paper treats are all characterized by high melting points, and by *non-crystalline* structure. Alloys fusing below red heat have not been systematically investigated, or lead to involved results. The case of amalgams* is complicated by changes of the physical state of aggregation. Strictly speaking investigations like the present hold only for those alloys for which data are in hand. Cf. § 3.

2. The advantages of selecting platinum-alloys for the investigation in question are manifold. Melted platinum appears to be a universal solvent of metals, and hence the variety of bimetallic platinum alloys, easily producible, is very great. Again one of the remarkable electrical properties of platinum is the tendency to form alloys of phenomenally high specific resistance; and quite within the limits stated in §1, an electrical effect of alloying amounting to as much as 500 per cent of the specific resistance of platinum, is no unusual occurrence. Finally platinum alloys have not yet been systematically studied. The present contribution is therefore new.

In the case of steel to which I shall allude in passing, variations of resistance allied in character to those here discussed may be produced by changes of temper. The range of electrical variation here is also very large, amounting to more than 300 per cent of the resistance of soft steel.

Phenomena extending over such an enormous range, and which admit of exact measurement throughout the whole interval of variation, deserve most careful scrutiny and comparison even in their approximate relations. But there is further evidence in hand of the importance of which, when my work was in progress, I was quite unaware. I shall endeavor to digest it in the next paragraph.

3. A research into the relations of electrical conductivity and temperature makes up a part of the labors of Matthiessen. In addition to his well-known results for pure metals, Matthiessen† and his friends investigate the electrics of alloys of PbAg, SnAu, SnCu, SnAg, ZnCu, AuCu, AuAg, PtAg, PdAg, CuAg, FeAu, FeCu, PCu, AsCu, and some other metals. Unfortunately not all of these alloys are available for the present discussion, as Matthiessen's purpose seems rather to have been the exploitation of a great number of series of groups of alloys. On the other hand it is my purpose to examine the

* Cf. C. L. Weber: Wied. Ann., xxiii, p. 447, 1884; *ibid.*, xxxi, p. 243, 1887. Battelli: Beiblätter, xii, p. 587, 1888.

† Matthiessen and Vogt: Pogg. Ann., cxxii, p. 19, 1864.

electrical behavior of as many alloys as possible of one given group. On perusing Matthiessen and Vogt's results, it appears that lead alloys,* tin alloys and iron alloys will have to be excluded from the present consideration, inasmuch as the data are either insufficient in number, or lie too far apart from each other and from the extremes of this series, or because of mechanical difficulties encountered in making the alloys and shaping the wires. There remain a very full series of copper alloys, viz: CuSn, CuZn, CuFe, CuP, CuAs; a series of silver alloys, viz: AgAu, AgPt, AgPd, AgCu; and a few gold alloys, viz: AuCu, AuAg. In view of the importance of these data I have computed the following tabular statement of Matthiessen's results, re-arranging the data in a way which for my special purposes is expedient. I have also added Matthiessen's† results for pure, soft metals. In table I, λ'_0 denotes the conductivity in Matthiessen's standards (Ag=100), α the temperature coefficient of the alloy, of which the composition is given on the same horizontal row. I have rounded off Matthiessen's long numbers, because the arbitrary errors introduced during the mechanical preparation of the alloys, together with the errors of structure and hardness and the more serious errors of imperfect homogeneity, make the extreme accuracy of the electrical datum illusory. The table furthermore contains λ_0 , the electrical conductivity in microhms referred to the cubic centimeter. This reduction is made by means of mercury.‡ In the last two columns of table I, the value of α computed by the formula $\alpha + m = n\lambda_0$ and the corresponding errors are inserted. Of these results further mention will be made below, and I need here only state that the constants m and n given at the end of the table are those which I derived from all the relevant observations, by the method of least squares.

The compositions given are volume per cents, except in the cases of phosphides and arsenides of copper where mass per cents are meant.

In interpreting these results by graphic methods, it is necessary to proceed with caution, for inasmuch as specific resistance enters into them reciprocally, large values of resistance will only be inadequately represented. Nevertheless, although the tables contain many such values, enough data remain to exhibit the striking linear character of the curves on which the gold, silver and copper points respectively lie. The initial tangent

* The metallic ingredient present in larger amount may be fitly used in designating the alloy.

† Matthiessen and v. Bose: *Pogg. Ann.*, cxv, p. 353, 1862.

‡ Jenkin who made similar reductions in the case of pure metals by means of lead, arrives at somewhat different numbers. A perfectly satisfactory absolute table can not be deduced.

TABLE I.—*Showing Matthiessen and Vogt's results for the electrics of gold, silver, and copper alloys.*

| | Alloy. | Composi- tion. | λ'_0 . | Observed $a \times 10^3$. | $\lambda_0 \times 10^3$ microhms. | Calculated $\delta a \times 10^3$. | $\delta a \times 10^6$. |
|----------------|--------|-------------------|----------------|-------------------------------|--------------------------------------|--|--------------------------|
| Gold alloys. | Au | ---- | 79 | 3.67 | 506 | 3.69 | — 2 |
| | AuCu | 1.6 % Cu | 56.1 | 2.65 | 359 | 2.63 | + 2 |
| | AuCu | 18.3 % Cu | 16.1 | 0.75 | 103 | 0.79 | — 4 |
| | AuAg | 20.1 % Ag | 21.5 | 1.11 | 137 | 1.03 | + 8 |
| | AuAg | 47.9 % Ag | 15.2 | 0.70 | 96 | 0.74 | — 4 |
| Silver alloys. | Ag | ---- | 109 | 3.82 | 691 | 3.83 | \pm 0 |
| | *AgCu | 1.5 % Cu | 79.7 | 4.12 (?) | 510 | ----- | ----- |
| | AgCu | 8.2 % Cu | 80.3 | 2.75 | 514 | 2.88 | —13 |
| | AgCu | 46.7 % Cu | 74.9 | 2.80 | 480 | 2.69 | +11 |
| | AgPt | 2.5 % Pt | 31.6 | 1.24 | 202 | 1.20 | + 4 |
| | AgPt | 5.0 % Pt | 18.0 | 0.77 | 115 | 0.73 | + 4 |
| | AgPt | 19.7 % Pt | 6.7 | 0.33 | 43 | 0.34 | — 1 |
| | AgPd | 23.3 % Pd | 8.5 | 0.32 | 55 | 0.41 | — 9 |
| | AgAu | 19.9 % Au | 21.7 | 0.90 | 139 | 0.86 | + 4 |
| | | | | | | | |
| Copper alloys. | Cu | ---- | 102 | 3.87 | 653 | 3.98 | —11 |
| | CuAg | 1.6 % Ag | 89.5 | 3.45 | 573 | 3.54 | — 9 |
| | CuAg | 4.8 % Ag | 82.3 | 3.25 | 527 | 3.29 | — 4 |
| | CuAg | 22.4 % Ag | 69.8 | 3.03 | 447 | 2.85 | +18 |
| | CuAu | 0.7 % Au | 84.0 | 3.32 | 538 | 3.35 | — 3 |
| | CuAu | 19.2 % Au | 20.5 | 0.86 | 131 | 1.11 | —25 |
| | CuFe | 0.5 % Fe | 38.9 | 1.55 | 249 | 1.76 | —21 |
| | CuZn | 5.0 % Zn | 60.4 | 2.47 | 387 | 2.52 | — 5 |
| | CuZn | 10.9 % Zn | 46.9 | 2.05 | 300 | 2.04 | + 1 |
| | CuZn | 23.6 % Zn | 21.3 | 1.88 | 136 | 1.14 | +74 |
| | CuZn | 29.4 % Zn | 21.7 | 1.27 | 139 | 1.15 | +12 |
| | CuZn | 42.1 % Zn | 21.8 | 1.37 | 140 | 1.16 | +21 |
| | CuSn | 1.4 % Sn | 62.5 | 2.68 | 400 | 2.59 | + 9 |
| | CuSn | 6.0 % Sn | 19.7 | 1.00 | 126 | 1.08 | — 8 |
| | CuSn | 11.6 % Sn | 12.1 | 0.69 | 77 | 0.81 | —12 |
| | CuSn | 12.3 % Sn | 10.2 | 0.67 | 65 | 0.74 | — 7 |
| | CuSn | 14.9 % Sn | 8.8 | 0.55 | 56 | 0.69 | —14 |
| | CuP | 1.0 % P | 23.6 | 1.32 | 151 | 1.22 | +10 |
| | CuP | 2.5 % P | 7.3 | 0.48 | 47 | 0.64 | —16 |
| | CuAs | trace | 61.1 | 2.64 | 391 | 2.54 | +10 |
| | CuAs | 2.8 % As | 12.9 | 0.74 | 82 | 0.84 | —10 |
| | CuAs | 5.4 % As | 6.3 | 0.52 | 40 | 0.61 | — 9 |

* Rejected.

$$(\alpha + m = n\lambda_0)$$

Gold alloys $m = -0.000045 \pm 0.000030$

$$n = +0.00721 \pm 0.00010$$

Silver alloys $m = -0.000112 \pm 0.000031$

$$n = 0.00538 \pm 0.00085$$

Copper alloys $m = -0.000386 \pm 0.000040$

$$n = 0.000551 \pm 0.00012$$

concides with the initial curves throughout an enormous extent of their course. Matthiessen* who expressed a similar

* Matthiessen and Vogt: Phil. Mag. (IV), xxvii, p. 467, 1863; Pogg. Ann., cxxii, p. 19, 1864.

result under a somewhat involved form, was well justified in computing by means of it the conductivity of a pure metal from data found for metals slightly impure. This computation premises the truth of Matthiessen's other principle that with certain distinct exceptions, the electrical temperature coefficients of all pure metals are the same (cf. § 6).

4. After Matthiessen and Vogt the curious relation in question seems to have failed to enlist further attention, and I believe that the next systematic investigation is that made by Dr. V. Strouhal and myself in studying the electricities of the iron-carburets.* We did not, however, in the former paper reduce our results from the curvilinear form in which they appear when temperature coefficient is expressed in terms of resistance, to the curves of the present linear character; and hence I may expediently make this reduction here. If temperature coefficient (y) be expressed as a function of specific resistance (x), and if a curve be passed through all the points investigated for iron, steel, cast-iron, then the following principal coördinates obtain:

| | | | |
|-------|---------|---------|---------|
| $x =$ | 15 | 45 | 70 |
| $y =$ | 0.00420 | 0.00166 | 0.00130 |

Interpreted by an hyperbolic equation of the form $(x+l)(y+m)=n$, these data lead to constants

$$l = -3.73, \quad m = -0.000706, \quad n = 0.0394,$$

which do not reproduce the graphic curve satisfactorily. Neither is l by any means negligible, so that the reduction to linear forms is out of the question. At first sight this seems to prove that iron, steel and cast iron do not here form a unique series; that the resistance variation due to the change of carburation from iron to cast-iron is in its nature different from the resistance variation observed on passing from soft to hard steel. It appears below, however, that the favorable position of iron here unduly influences the result. I will temporarily withdraw both iron and cast-iron from the series. For steel alone we found (using the graphic method already referred to)

| | | | |
|-------|---------|---------|----------|
| $x =$ | 15.9 | 28.9 | 45.7 |
| $y =$ | 0.00423 | 0.00244 | 0.00161, |

which data interpreted by the equation $(x+l)(y+m)=n$ now lead to the constants

$$l = 0.78, \quad m = -0.0001435, \quad n = 0.0682.$$

Here the constant l is small, being only about five per cent of the smallest steel value of x admitted. Inasmuch as a result

* Cf. Wied. Ann., xx, p. 525, 1883; Bulletin U. S. G. S., No. 14, p. 15 to 25, 1885.

similarly favorable to the reduction to linear forms is obtained by adding cast-iron to the steel series, I have assumed the equation

$$x(y+m)=n.$$

Using this equation as a basis for the application of the method of least squares, the observations of Dr. Strouhal and myself lead to the results contained in the following table. These results are easily understood, and I need hardly add that according to §1, the conductivity and temperature-coefficient of steel are respectively

$$\frac{1}{f(0)} \text{ and } \frac{f'(0)}{f(0)}.$$

TABLE II.—*Showing Strouhal and Barus' results for the electrics of iron-carburets, $f(0) (f'(0)/f(0)+m)=n$.*

| Metal. | Temper. | $f(0)$. | $f'(0)/f(0)$. | $f'(0)/f(0)$. | Diff. |
|-----------|---------------------|----------|----------------|----------------|-------|
| | | | Observed. | Computed. | |
| Steel | Soft | 15.9 | 0.00423 | 0.00417 | + 6 |
| " | Annealed light blue | 18.4 | 360 | 366 | — 6 |
| " | " full blue | 20.5 | 330 | 333 | — 3 |
| " | " yellow | 26.3 | 280 | 269 | + 11 |
| " | " light yellow | 28.9 | 244 | 249 | — 5 |
| " | Glasshard | 45.7 | 161 | 173 | — 12 |
| Cast iron | ----- | 78.5 | 129 | 119 | + 10 |

$$m = -0.000438 \pm 0.000097$$

$$n = +0.05930 \pm 0.00151$$

Applied to steel alone, the constants computed by the method of least squares show even better agreement, viz :

$$m = -0.000303 \pm 0.000079$$

$$n = +0.0620 \pm 0.0017$$

I omit the details, with the mere remark that the difficulties of measurement with a molecularly unstable brittle body like hard steel are great.*

5. I desire now to add to these remarkable results the new data which I found for platinum alloys. I shall endeavor to make my series more nearly complete; to investigate points more nearly contiguous and nearer in position to the pure metal than was the case in the foregoing series, as well as to introduce a great variety of platinum alloys. For both in Matthiessen and Vogt's results, and in Dr. Strouhal's and my results, the position of the individual points is not always near

* Prof. J. H. Langley kindly called my attention to recent data for manganese steel. Looking up Fleming's work (Lum. electr., xxvii, p. 589, 1888), I found his results to be $s=68$ and $a=0.0012$. In the above diagram $s=68$ corresponds to $a=0.0013$, showing satisfactory accordance with experiment even in this region of abnormally high specific resistance.

enough together to fully exhibit the character of the locus between them. Unfortunately the body of platinum from which I made my alloys was not rigorously pure, an annoyance which in the course of other parts of my work I had occasion to regret. So far as the present investigation goes, however, the hurtful effect of the impure platinum body is *nil*. It will appear even more clearly below, that the law to be investigated is independent of the ingredients of the platinum alloy, except in so far as they modify its electrical conductivity. Alloying here is merely a means of modifying resistance, and the results are studied with regard to the resistance produced, not with regard to the way in which resistance is modified.

6. In making the alloys a weighed amount of platinum was fused down on a lime hearth before the oxyhydrogen flame. The foreign ingredient was then added, and the product after cooling rolled down and drawn to wire form. The initiated will know that accidents are not infrequent and that the tedious operations must often be repeated. The details of fusion and other manipulation are given in the Bulletin. To make the electrical measurement, selected parts (length 30^{cm}, diameter 0.045^{cm}) of the wires were annealed at a red heat and then wrapped in a single layer around a little cylinder of porcelain (length 2^{cm}, diameter 0.45^{cm}) in such a way that the spires of the helix did not touch. The ends were appropriately fused to copper terminals. The little helix was then introduced into the space of constant temperature of my *boiling tube*, and consecutively heated to 25°, 100° (steam), 357° (mercury vapor).

The results of the measurements are given in the following table. The series contains 57 alloys, of which Δ_0 denotes the density and s_0 the zero specific resistance. The table contains two values for the temperature coefficient α , the first of which, α_0^{100} , holds for the mean increase between 0° and 100°, the second between 0° and 357°, linear equations presupposed.

The wires A, B, C, are of the same platinum body (B), purified by long-continued intense fusions on lime, before the oxyhydrogen blow-pipe.

The relation of these data to each other may be exhibited graphically, and since α_0^{100} is very nearly $f''(0):f'(0)$, the following chart, figure 1, preferably represents α_0^{100} as a function of s_0 . A few unmistakably exceptional values of α_0^{100} are either rejected or replaced by α_0^{357} , the justification of which is shown in the Bulletin.

The chart shows clearly, I think; that the alloys of platinum may be regarded as a class of materials possessing generic electrical properties: for the effect of alloying platinum with small amounts (<10 per cent) of any other metal, is a variation of temperature-coefficient in a way which is independent of the

TABLE III.—*Showing the electricities of platinum alloys.*

| No. | Metal alloyed to Platinum. | Δ_0 | s_0 | $10^3 \times \alpha_0^{100}$ | $10^3 \times \alpha_0^{367}$ |
|-----|----------------------------|------------|-------|------------------------------|------------------------------|
| A | Platinum | ---- | 12.0 | 2.90 | 2.65 |
| C | Platinum | ---- | 13.3 | 2.52 | 2.58 |
| B | Platinum | 21.31 | 14.9 | 2.30 | 2.22 |
| 1 | Gold | 21.29 | 18.5 | 1.78 | 1.62 |
| 2 | Gold | 21.22 | 22.1 | 1.45 | 1.33 |
| 3 | Gold | 21.17 | 24.7 | 1.27 | 1.09 |
| 4 | Silver | 21.16 | 19.1 | 1.80 | 1.61 |
| 5 | Silver | 20.99 | 22.3 | 1.46 | 1.02 |
| 6 | Silver | 19.40 | 34.0 | 1.02 | 0.71 |
| 7 | Palladium | 21.01 | 18.9 | 1.75 | 1.62 |
| 8 | Palladium | 20.54 | 20.9 | 1.53 | 1.48 |
| 9 | Palladium | 19.91 | 23.9 | 1.29 | 1.18 |
| 10 | Iridium | 21.27 | 19.4 | 1.72 | 1.61 |
| 11 | Iridium | 21.28 | 20.4 | 1.63 | 1.50 |
| 12 | Iridium | 21.32 | 23.6 | 1.28 | 1.21 |
| 13 | Copper | 20.68 | 31.8 | 0.89 | 0.83 |
| 14 | Copper | 20.60 | 33.6 | 0.80 | 0.72 |
| 15 | Copper | 18.80 | 63.6 | 0.20 | 0.20 |
| 48 | Copper | 20.92 | 25.3 | 1.27 | 1.14 |
| 49 | Copper | 19.56 | 53.6 | 0.29 | 0.15 |
| 16 | Nickel | 20.69 | 21.7 | 1.68 | 1.46 |
| 17 | Nickel | 19.89 | 26.8 | 1.34 | 1.19 |
| 18 | Nickel | 18.75 | 32.8 | 1.05 | 0.87 |
| 19 | Cobalt | 20.59 | 28.6 | 1.09 | 1.04 |
| 20 | Cobalt | 19.84 | 39.6 | 0.89 | 0.74 |
| 21 | Cobalt | 19.33 | 30.7 | 1.57 | 1.36 |
| 40 | Cobalt | 19.10 | 44.6 | 1.30 | 0.83 |
| 41 | Cobalt | 20.99 | 24.0 | 1.39 | 1.27 |
| 22 | Iron | 20.63 | 36.3 | 0.74 | 0.74 |
| 23 | Iron | 20.33 | 41.8 | 0.66 | 0.64 |
| 24 | Iron | 19.59 | 59.9 | 0.37 | 0.36 |
| 42 | Iron | 19.75 | 62.5 | 0.44 | 0.39 |
| 43 | Iron | 20.89 | 28.8 | 1.12 | 0.98 |
| 50 | Steel | 19.58 | 60.2 | 0.44 | 0.39 |
| 51 | Steel | 19.95 | 49.2 | 0.77 | 0.64 |
| 25 | Chromium | 20.91 | 27.4 | 1.14 | 1.06 |
| 26 | Chromium | 20.51 | 40.9 | 0.65 | 0.62 |
| 27 | Chromium | 20.16 | 52.4 | 0.56 | 0.49 |
| 44 | Chromium | 20.76 | 31.1 | 0.95 | 0.87 |
| 28 | Tin | 21.11 | 21.5 | 1.55 | 1.49 |
| 29 | Tin | 20.97 | 25.6 | 1.27 | 1.20 |
| 30 | Tin | 20.45 | 39.8 | 0.69 | 0.66 |
| 31 | Aluminium | 20.46 | 25.3 | 0.85 | 1.32 |
| 32 | Aluminium | 20.72 | 21.2 | 1.56 | 1.50 |
| 33 | Manganese | 20.81 | 25.6 | 1.28 | 1.14 |
| 34 | Manganese | 19.43 | 48.9 | 0.52 | 0.43 |
| 35 | Molybdenum | 21.26 | 16.0 | 2.13 | 1.94 |
| 36 | Molybdenum | 21.26 | 19.0 | 1.76 | 1.69 |
| 45 | Molybdenum | 21.30 | 16.4 | 2.06 | 1.88 |
| 37 | Lead | 21.18 | 14.6 | 2.28 | 2.23 |
| 46 | Lead | 21.24 | 17.0 | 2.02 | 1.82 |
| 38 | Antimony | 20.75 | 29.5 | 1.11 | 1.09 |
| 39 | Bismuth | 21.18 | ---- | ---- | ---- |
| 47 | Bismuth | 21.33 | 15.83 | 2.10 | 2.03 |
| 52 | Zinc | 20.10 | 44.2 | 0.51 | 0.32 |
| 54 | Zinc | 20.98 | 24.5 | 1.34 | 1.14 |
| 53 | Cadmium | (21.3) | ---- | ---- | ---- |

special ingredients of the alloy, and which depends only on the resistance-position of this alloy in the class. I venture to assert therefore that the arrangement of points is in accordance with a definite underlying law, with reference to which exceptional data are to be interpreted. The law in question appears to me particularly noteworthy as being among those which spe-

1.

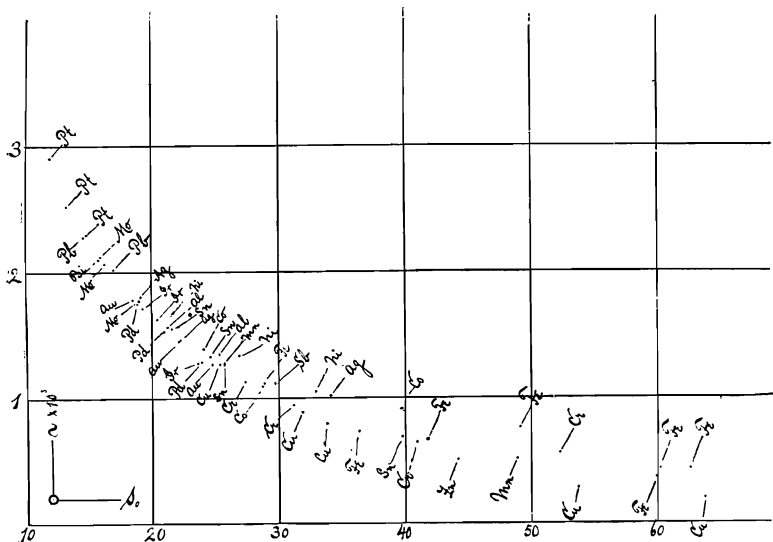


FIGURE 1.—Showing the relation between temperature-coefficient (α) and electrical resistance (s_0), in case of platinum alloys.

cially hold for the solid state. In his experiments on the conductivity of solid mercury, C. L. Weber* found its resistance to increase fourfold in virtue of fusion. Simultaneously with this variation, the temperature-coefficient of solid mercury (0.00455) falls to the relatively very low value (0.000927 between -30° and $+45^{\circ}$) which holds for the liquid metal. Weber points out the close approximation of the temperature coefficient of solid mercury to that of the other solid metals, and infers even closer agreement at temperatures sufficiently below the melting point of mercury. It is in a similar sense that in §1 I referred the properties to be investigated in this paper to a class of alloys characterized by high melting points.

* C. L. Weber, Wied. Ann., xxv. p. 245, 1885. The large variation of resistance at the melting point, observed in case of mercury and other metals and alloys (K, Na, etc.), suggests the striking adaptability of these substances for experiments on the relation between melting point and pressure; or in general on the continuity of solid and liquid state. Change of resistance is here the criterion of fusion.

7. Having thus obtained some general notions of the dependence of $f'(0)/f(0)$ on $f(0)$, it is in place to inquire more fully into the form of this dependence. I will proceed in a manner similar to that employed in §4, and postulate the hyperbolic equation $(x+l)(y+m)=n$. Availing myself of the chart, figure 1, selecting for preliminary computation a set of coördinates as carefully as possible from it,

$$\begin{array}{rcl} x=11.7 & & y=0.00300 \\ & 20.0 & 164 \\ & 50.0 & 050 \end{array}$$

I find the constants l, m, n to be

$$l=-0.1360, \quad m=0.0002548, \quad n=0.03764.$$

The values found for l, m, n are exceedingly significant. Since x varies between 10 and 70, l is in general much less than one per cent of x . This observation at once suggests the assumption of a simpler form of equation in which $l=0$. Again the positive character of m indicates that larger values of $\alpha_0^{1.0.0}$ would tend still further to simplify the equation $(x+l)(y+m)=n$. But $\alpha_0^{1.0.0} > \alpha_0^{3.5.7}$ follows from the experiments; hence also

$$f'(0)/f(0) = \alpha > \alpha_0^{1.0.0},$$

and therefore the postulation of $x(y+m)=n$ is altogether warranted.

To obviate the necessity of a complete recalculation of α , I used the following method of passing from $\alpha_0^{1.0.0}$ and $\alpha_0^{3.5.7}$ to α . If the values s, s', s'' , correspond respectively to t, t', t'' , and if

$$\frac{s}{1+\alpha t+\beta t^2} = \frac{s'}{1+\alpha t'+\beta t'^2} = \frac{s''}{1+\alpha t''+\beta t''^2},$$

it follows that

$$\alpha = \frac{(s'-s)(st''^2-s't^2)-(s''-s)(st'^2-s't^2)}{(st'-s't)(st''^2-s''t^2)-(st''-s't)(st'^2-s't^2)},$$

from which it is easy to deduce $\alpha - \alpha_0^{1.0.0}$ in terms of $\alpha_0^{1.0.0} - \alpha_0^{3.5.7}$. Now $st''-s't=D''$ and $st'-s't=D'$ are already known from the earlier computations; and when a correction only is sought $s''t^2$ and $s't^2$ may here be neglected as compared with st''^2 and st'^2 , respectively, t being small in comparison with t' and t'' . Hence

$$\alpha - \alpha_0^{1.0.0} = \frac{\alpha_0^{1.0.0} - \alpha_0^{3.5.7}}{t''^2/t'^2 \cdot D'/D'' - 1},$$

which equation, since the fraction $(t''/t')^2$ is constant, is a convenient form, and much of the correcting may be done mentally. I may add that the three quantities $\alpha_0^{1.0.0}, \alpha_0^{3.5.7}, \alpha_0^{3.5.7}$

have similarly simple approximate relations to each other; for instance,

$$\alpha_0^{100} - \alpha_0^{357} = (t'' - t'/t'' - t) (\alpha_0^{100} - \alpha_0^{357}),$$

and since the fraction $(t'' - t)/(t'' - t)$ is constant, such reductions also are mental. I observe finally that the effect of these corrections is only a few units of the last figure. The methods are therefore sufficient.

8. Having made this preliminary survey, the data are available for the calculation of m and n by the method of least squares. It is expedient, however, before doing so, to put the postulated equation under the form

$$f'(0)/f(0) = n \cdot 1/f(0) - m,$$

where $1/f(0)$ is the zero value of the electrical conductivity of the alloy whose temperature-coefficient is α . This equation when operated on by the method of least squares does not give inordinate preference to high values of specific resistance; and since such high values can not be warranted with a greater degree of accuracy than the low values, the said equation may most expediently be made the basis of computation.

The following table contains the results and is intelligible without further explanation. The alloys 10, 11, 12 which I insert for completeness, were added subsequently to the calculation.

The probable errors of m and n indicate that the inaccuracy is largely incurred in the measurement of $f'(0)/f(0)$. The constant n is much more fully warranted.

9. Endeavoring to describe the platinum alloys as a class possessing generic electrical characteristics it is permissible to abstract from the minute and isolated behavior of the individual alloy. It appears that the electrical temperature-coefficient $(f'(0)/f(0))$, varies as a linear function of conductivity $(1:f(0))$, throughout the whole of the enormous variation of electrical resistance (10 to 65 microhms, c. c.), presented by platinum alloys not too highly alloyed (< 10 per cent). In other words, if at t' , the specific resistance of a platinum alloy be denoted by $f(\chi, t)$, where t symbolizes temperature and χ is a variable parameter, then

$$f(\chi, 0) (f'(\chi, 0)/f(\chi, 0) + 0.000194) = 0.0378.$$

It is perhaps not superfluous to remark in passing that if instead of the arbitrary temperature 0°C. , some other value more in keeping with the qualities of platinum alloys had been selected, the constants m and n would present different values; and it is conceivable that correlated values of $f'(t)$ and $f''(t)$ may exist for which the constant m is annulled, and for which the given equation takes the simple form $xy = n'$.

TABLE IV.—*Electrics of platinum alloys. Digest $f(0) (f'(0)/f(0) + m) = n$.*

| No. | $f(0)$. | Observed ($f'(0)/f(0)$) $\times 10^3$. | Calculated ($f'(0)/f(0)$) $\times 10^3$. | Error $\times 10^3$. | Metal alloyed to platinum. |
|-----|----------|--|--|--------------------------|-------------------------------|
| A | 12.0 | 2.96 | 2.94 | + 2 | Pt |
| C | 13.3 | 2.50 | 2.66 | - 16 | Pt |
| B | 14.9 | 2.33 | 2.34 | - 1 | Pt |
| 1 | 18.5 | 1.84 | 1.84 | - 1 | Au |
| 2 | 22.1 | 1.49 | 1.51 | - 2 | Au |
| 3 | 24.7 | 1.33 | 1.34 | - 1 | Au |
| 4 | 19.1 | 1.87 | 1.79 | + 8 | Ag |
| 7 | 19.4 | 1.76 | 1.75 | + 1 | Pd |
| 8 | 20.4 | 1.67 | 1.66 | + 1 | Pd |
| 9 | 23.6 | 1.30 | 1.40 | - 10 | Pd |
| 10 | 19.4 | 1.76 | 1.75 | + 1 | Ir |
| 11 | 20.4 | 1.67 | 1.66 | + 1 | Ir |
| 12 | 23.6 | 1.30 | 1.40 | - 10 | Ir |
| 13 | 31.7 | 0.91 | 1.00 | - 9 | Cu |
| 14 | 33.6 | 0.83 | 0.93 | - 10 | Cu |
| 15 | 63.6 | 0.21 | 0.40 | - 19 | Cu |
| 48 | 25.3 | 1.31 | 1.30 | + 1 | Cu |
| 49 | 53.6 | 0.34 | 0.51 | - 17 | Cu |
| 16 | 21.7 | 1.75 | 1.55 | + 20 | Ni |
| 17 | 26.8 | 1.39 | 1.21 | + 18 | Ni |
| 18 | 32.8 | 1.11 | 0.96 | + 15 | Ni |
| 19 | 28.6 | 1.11 | 1.13 | - 2 | Co |
| 20 | 39.6 | 0.93 | 0.76 | + 17 | Co |
| 41 | 24.0 | 1.43 | 1.38 | + 5 | Co |
| 22 | 36.3 | 0.74 | 0.81 | - 10 | Fe |
| 23 | 41.8 | 0.67 | 0.71 | - 4 | Fe |
| 24 | 59.9 | 0.37 | 0.44 | - 7 | Fe |
| 42 | 62.5 | 0.46 | 0.41 | + 5 | Fe |
| 43 | 28.7 | 1.21 | 1.12 | + 9 | Fe |
| 50 | 60.2 | 0.46 | 0.43 | + 3 | Steel |
| 51 | 49.2 | 0.81 | 0.58 | + 23 | Steel |
| 25 | 27.4 | 1.17 | 1.19 | - 2 | Cr |
| 26 | 40.9 | 0.66 | 0.73 | - 7 | Cr |
| 27 | 52.3 | 0.58 | 0.52 | + 6 | Cr |
| 44 | 31.1 | 0.98 | 1.02 | - 4 | Cr |
| 28 | 21.5 | 1.57 | 1.56 | + 1 | Sn |
| 29 | 25.6 | 1.29 | 1.28 | + 1 | Sn |
| 30 | 39.9 | 0.70 | 0.75 | - 5 | Sn |
| 32 | 21.2 | 1.58 | 1.59 | - 1 | Al |
| 33 | 25.6 | 1.33 | 1.28 | + 5 | Mn |
| 34 | 48.9 | 0.55 | 0.58 | - 3 | Mn |
| 35 | 16.0 | 2.20 | 2.18 | + 2 | Mo |
| 36 | 18.9 | 1.78 | 1.80 | - 2 | Mo |
| 45 | 16.4 | 2.12 | 2.11 | + 10 | Mo |
| 37 | 14.6 | 2.30 | 2.38 | - 8 | Pb |
| 46 | 17.0 | 2.09 | 2.03 | + 6 | Pb |
| 38 | 29.5 | 1.12 | 1.09 | + 3 | Sb |
| 47 | 15.8 | 2.12 | 2.19 | - 7 | Bi |
| 52 | 44.2 | 0.57 | 0.66 | - 9 | Zn |
| 54 | 24.5 | 1.41 | 1.35 | + 6 | Zn |

$$m = 0.0001939 \pm 0.0000233$$

$$n = 0.03778 \pm 0.00054$$

10. It is desirable finally to give as graphic an exhibit of the results taken collectively, as possible. Unfortunately any scale which clearly presents the results for gold, silver and copper, will crowd the results for platinum and the iron-carburets; and vice versa. Perhaps the following chart, fig. 2, will

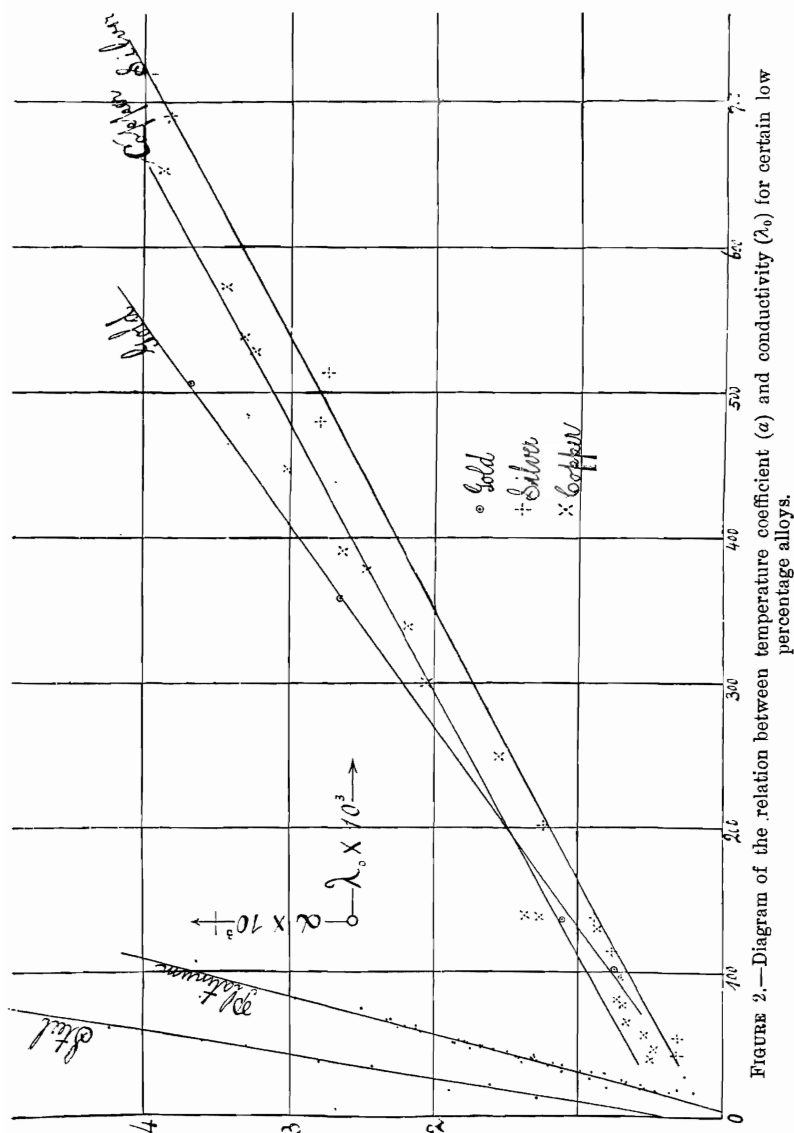


FIGURE 2.—Diagram of the relation between temperature coefficient (α) and conductivity (λ_0) for certain low percentage alloys.

represent the relation here involved. The constants of the lines drawn through the points are given at the end of the tables in §§ 3, 4 and 7. In the cases of silver, of gold, of platinum and of steel, the distribution of the points with reference to these lines is satisfactory, when the errors introduced by the mechanical treatment, by variations of hardness, and particularly by imperfect homogeneity are justly taken into account. In many cases, moreover, the percentage presence of foreign ingredient is greater than that specified in § 1. As all this is even more frequently the case with alloys of the oxidizable metal copper, the line computed by the method of least squares does not fairly represent these observations. The exceptional points here are the alloy of Cu with 22.4 per cent Ag, and the brasses with 23.6 per cent, 29.4 per cent and 42.1 per cent Zn. If these high per cents are rejected, the line for copper* will agree more nearly in character with the lines for gold and for silver, as it will tend more nearly to intersect the origin of coördinates (smaller numeric m). Applying the method of least squares for the case in which the inadmissible copper alloys are withdrawn, I find $m = -0.278$ and $n = +0.005655$, and of course a better agreement between observed and calculated α throughout. In figure 2, however, I have nevertheless inserted the line calculated for all the copper alloys in hand.

An interesting peculiarity of the steel line is that it leads to a larger value for the temperature-coefficient of iron† than that hitherto accepted. Comparisons of absolute values must however be made with caution, because of the great variety of electrical standards used by different observers. The high temperature-coefficient of iron is in conformity with relatively high values usually shown by alloys containing iron (cf. fig. 1.)

I desire finally to advert to the occurrence of the relatively *small* values of the constant, m , as computed for each of the series of silver, copper, gold, platinum and steel alloys. There is a marked tendency in all the cases stated to intersect the coördinate axes very near the origin. Inasmuch therefore as (§ 1) $\alpha = f'(\chi, 0)/f(\chi, 0)$ and $\lambda_0 = 1/f(\chi, 0)$, the slopes of these lines are very nearly equal to $f''(\chi, 0)$; or more rigorously to $f''(0, 0)$, since their true nature is that of an initial tangent (cf. § 3.) In § 11 it appears that I am not asserting, however, that these lines do pass through the origin.

* Those who have worked with copper alloys, will know the extreme difficulty encountered in making the individual points conform to any uniform curve. The data usually make up a diagram of very broken lines, as in the above work of Matthiessen, and in results of Dr. Strouhal and myself. Further comment is made in the Bulletin.

† In his research on the conductivity of iron, Auerbach (Wied. Ann., viii, p. 479, 1879), discusses reasons for the exceptionally high value of the temperature-coefficient of iron.

11. Taking the results collectively, they point to a limit below which in the case of solid metals and at ordinary temperatures, neither electrical conductivity nor temperature-coefficient can be reduced; whence it appears that a lower limit of both conductivity and temperature-coefficient is among the conditions of metallic conduction, not to say of metallic state.* These considerations are suggestive and I shall therefore endeavor to make what I have in mind clearer. In the case of conduction in metals (solid or liquid) the effect of temperature is a decided decrease of conductivity, continuing apparently, as temperature increases, indefinitely.† In the case of conduction in non-metallic elements‡ or in electrolytes (solid or liquid) on the other hand, the effect of temperature is a decided increase of conductivity, which supposing the liquid state to be retained, continues as temperature increases. Hence conduction in metals is distinguished from conduction in electrolytes in this respect, that if the temperature coefficient in the one case (electrolytes) be regarded positive, its value in the other case (metals) must be negative. This leads me to inquire into the possible occurrence or the nature of a class of substances whose temperature-coefficient is zero; a class of substances in other words in which the metallic and the electrolytic modes of electric conduction may be supposed to converge.§

The point which I have in view, viz: the possibility of a continuous transition from metallic to electrolytic conductivity gains much in reasonableness by associating with good metallic conductivity the correlative property of optic opacity. Relations between electricity and light have been investigated and many experimental facts are known. Maxwell's electro-mag-

* Recent researches of v. Ettingshausen and Nernst and of C. L. Weber (Wied. Ann., xxxiv, p. 582, 1888), show that the resistance-temperature coefficient of bismuth is often negative between 0° and 100°. Edward Weston has made alloys of copper, ferro-manganese and nickel of which this temperature-coefficient is nearly zero or even negative (Science, xii, p. 56, 1888). These exceptions, the underlying cause of which is probably secondary and to be referred to structural or crystalline modification, emphasize the vast amount of evidence in favor of the normal behavior given in the text. I may add, for instance, that the temperature-coefficient of glasshard steel between 0° and 100°, would be nearly zero because of annealing.

† Following Benoit (C. R., lxxvi, p. 342, 1873) the electrical resistance of all metals increases with temperature at an accelerated rate, except in the case of platinum and palladium, where the rate of increase is retarded. Benoit observes at temperatures limited by the boiling point of zinc.

‡ Matthiessen (Pogg. Ann., ciii, p. 428, 1858), W. Siemens (Wied. Ann., x, p. 560, 1880) and others (Bergmann, Kemlein, Muraoka) find this to hold for modifications of carbon. Similar increases of conductivity are usually observed in the case of selenium and tellurium (Hittorf, W. Siemens, Mattheissen, and many others): but the relations here are complicated. Quite recently Duter (C. R., March 19th, 1888) has shown that sulphur conducts at its boiling point. It is this investigation which I have specially in mind in the text.

§ Something of the kind may perhaps occur in the case of some natural sulphides, but it is not open for systematic study and its nature is obscure.

netic theory of light furnishes a theoretical basis for the fact that true conductors are exceedingly opaque. The resistance of solid metals, however intensely they may be heated, is found to increase so long as temperature increases. Nevertheless the careful experiments which Govi* made to interpret an erroneous result of Secchi,† prove that solid metals even in extreme states of white heat remain opaque. In the case of liquid metals at extreme white heat the case is not so definitely established; and the question relative to the ultimate transparency of liquid metals at very high temperatures is an open one.‡ It is in the direction of ultimate transparency that the observed continuous increase of resistance with temperature seems definitely to point.

It is reasonable to infer that the transition from opaque to transparent§ will take place in the region of the critical temperature. At least such transition must ultimately occur; and I am led to conjecture that the said transition from opaque to transparent will be accompanied by a change of the values of the electrical temperature coefficient, passing from the negative value which holds for the liquid metal, to the positive value which will probably hold for the gaseous metal, continuously through zero. The fact that conduction in gases is of an electrolytic nature was proved by Varley,|| who showed that after the polarization of the electrodes is overcome, gases obey Ohm's law. The electric *strength* of air is known to diminish rapidly as temperature is increased. Working with hot gases carefully insulated and protected from flames, Maxwell¶ was unable to obtain conduction either in hot gases like air or in hot metallic vapor like Hg or Na. At higher temperatures (red heat) the researches of Blondlot,** confirming the observations of E. Becquerel,†† prove that hot gases are conductors, and that at temperatures sufficiently high $\frac{1}{1000}$ volt is enough to set up a current. Hence in their thermal relations also, gases ultimately partake of the nature of an electrolyte, and the occurrence zero value of the temperature coefficient may be reasonably associated with the critical temperature of the metallic liquid, passing continuously from the liquid into the gaseous state.

* Govi, Comptes Rendus, lxxxv, p. 699, 1877.

† Secchi, Comptes Rendus, lxiv, p. 778, 1867.

‡ W. Ramsay, Chem. News, lv, pp. 104 and 175, 1887; Turner, *ibid.*, p. 163, 1887; Professor T. Sterry Hunt has given the question some attention. Kundt's recent experiments (Wied. Ann., xxxiv, p. 469, 1888), on the refractive index of metals will doubtless lead to more definite results than the data now in hand.

§ The jet of liquid hydrogen escaping from Pictet's apparatus appeared steel-blue, and was opaque for a distance of about 12^{cm}.

|| Varley, Proc. Roy. Soc., xix, p. 236, 1871.

¶ Maxwell, Elementary Treatise on Electricity, ed. by Garnett, 1881, §§138, 139.

** Blondlot, Comptes Rendus, xcii, p. 870, 1881; *ibid.*, civ, p. 283, 1887.

†† E. Becquerel, Comptes Rendus, lv, p. 1097, 1867.