THE ELECTRICAL RESISTIVITY OF DILUTE METALLIC SOLID SOLUTIONS.

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INTRODUCTION.

It is not possible to obtain very much theoretical knowledge from the study of alloys in which the components are mutually insoluble, for, as the work of Matthiessen (29) some sixty years ago showed, in these systems electrical conductivity is usually practically a linear function of the composition. In systems, however, where solid solutions are formed, very much more interesting results are obtained. Small additions of solute cause a relatively enormous increase in the electrical resistivity of the metallic solvent.

In the case of aqueous solutions, definite laws governing the effect of the solute on the solvent have been discovered and are now well established. Only a very superficial analogy exists, however, between aqueous solutions and metallic solid solutions, and little is known of the laws governing the effect of a solute on a metallic solvent.

Studying this question from the electrical resistivity point of view, Benedicks (2), in 1901, put forward the hypothesis that equiatomic quantities of foreign elements dissolved in iron increase the electrical resistivity to the same amount. In a recent paper (32), however, it was shown that this hypothesis is not borne out by more recent work, which indicates on the contrary that equiatomic quantities of foreign elements dissolved in iron do not increase the resistivity to the same amount. Nickel and cobalt, for instance, have markedly lower atomic effects than any of the other elements quoted.

The present interpretation of the subject is essentially of a qualitative nature. In order to attach an accurate quantitative significance to the data quoted, for purposes of inter-comparison, it is necessary to estimate the exact significance of various relatively minor factors.

The paper is divided into three sections. In the first, the general interpretation of resistivity data is discussed.

. In the second section, resistivity data relating to various dilute metallic solid and molten solutions are tabulated and plotted.

In the third section the general significance of the results is discussed.

I. GENERAL INTERPRETATION OF ELECTRICAL RESISTIVITY DATA.

Very good accounts of the historical and general aspects of the present subject are given by Guertler in his numerous papers. (Also by Broniewski (6).)

a. *Mutually Insoluble Components.*

Le Chatelier's interpretation of Matthiessen's results obtained for this type of binary alloy system was that if the electrical *conductivities* of the alloys are plotted against their percentage compositions, the results lie on a straight line. Roozeboom and Guertler, however, raised objections to this and showed that in some cases it appeared as if a more linear relationship was obtained by plotting electrical *resistivity* against composition.

Working on the same problem, Schleicher (40) "made experiments to determine the influence of the mechanical arrangement of the constituents in a conglomerate on the electrical conductivity. In one series amalgamated copper wires were threaded through a glass tube and the spaces between them filled with mercury. In such a composite mass the conductivity is a linear function of the composition by volume. In the second series short lengths of amalgamated copper were placed in a tube and this was filled up with mercury. In this case the resistance of the mass is a linear function of the composition by volume. The latter condition approaches more nearly to the state of things occurring in alloys which consist of conglomerates."[1] It is thought, however, that Schleicher's second series represent an extreme, rather than a typical case of metallic conglomerates. A similar explanation to that suggested by Edwards for the copper-bismuth alloys, probably applies to a certain extent in the above case. Edwards (12) says: "With the addition of comparatively small quantities of bismuth" (to copper) "the conductivity rapidly falls to the value for bismuth. This, however, is due to the fact that the crystals of copper become completely surrounded by bismuth, and when this occurs the resistance of the mass is virtually governed by that of the element which exists at the boundaries of the crystals." Moreover, the fact that copper amalgamates so readily with mercury indicates that there is a certain "affinity" between the two and consequently, from the general conclusions arrived at in the present paper, one would expect an increased resistivity in the amalgamated layers.

In Fig. 1 the curve (a) represents the calculated resistivity values for copper mercury conglomerates, assuming Le Chatelier's linear *conductivity*-composition relationship (Schleicher's first series). The dotted line (b) represents *resistivity* as a linear function of the composition (Schleicher's second series).

That Schleicher's second series of conglomerates does not represent a universal condition in conglomerate alloys is shown by Stepanow's (44) results for magnesium-tin alloys reproduced in Fig. 2. The compound Mg_2Sn exists throughout and behaves like a pure component.

In Fig. 2a, the lines $a'b$ and bc' indicate that two nearly linear conductivity-composition relationships exist between the three components: a' = solid solution of Mg_2Sn in magnesium, b' = Mg_2Sn, and c' = solid solution of Mg_2Sn in tin.

It is thought that a great advantage in plotting the results as resistivities is that a correct idea of the variations due to experimental error is obtained. Conductivity values, on the other hand, give a fictitious idea.

In Fig. 2b a comparison of the two resistivity curves meeting in a peak at Mg_2Sn, with the two possible types of curves (a) and (b) in Fig. 1, indicates that conductivity, much more nearly than resistivity, is a linear function of the composition in this particular case. The fact that

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[1] *Journal of the Institute of Metals*, 1913 (i), p. 222. (Abstract.)

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conductivity is more nearly a linear function of the composition than resistivity, is also indicated in Stepanow's (43, 44) results for the magnesium-lead and other systems.
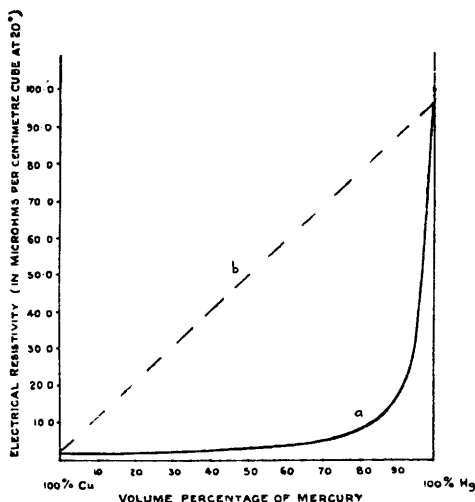

FIG. 1.—Resistivity-Composition Curves Calculated for Copper-Mercury Mixtures.

a. Assuming *Conductivity* is a linear function of the composition.
b. Assuming *Resistivity* is a linear function of the composition.

It seems probable that each crystal grain in a mechanical mixture may be considered as a separate conductor. In so far as the arrangement
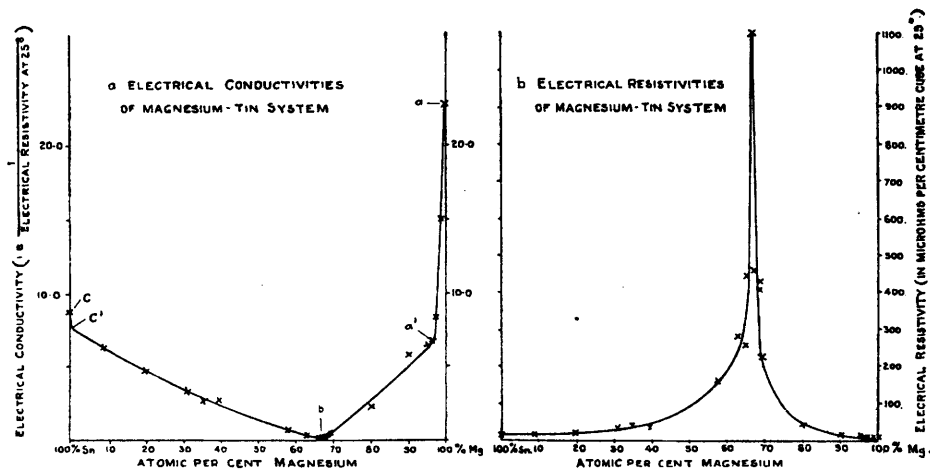

FIG. 2.—Magnesium-Tin System.
(From Stepanow, *loc. cit.*)

of the crystal grains tends to be in the nature of a number of conductors arranged in *parallel*, the *conductivity* will tend to be a linear function of the composition. In so far as the arrangement of the crystal grains

tends to be in the nature of a number of conductors arranged in *series*, the *resistivity* will tend to be a linear function of the composition (see also section I*e*). Every intermediate condition between the two ideal types seems possible in alloys made up of two mutually insoluble components.

b. Mutually Soluble Components.

Types of resistivity-composition curves for two components that are mutually soluble and form a continuous series of solid solutions are shown in Fig. 3.

Guertler proposed the following formula for calculating resistivity-composition curves of the above nature: He says (*loc. cit.*) "We can consider the resistance R of a solid solution as being made up of two parts, of which R_1 = original resistance *a priori*, and R_2 = solution resistance due to solid miscibility ". For R_2 he gives: " $R_2 = K.C(1-C)$,
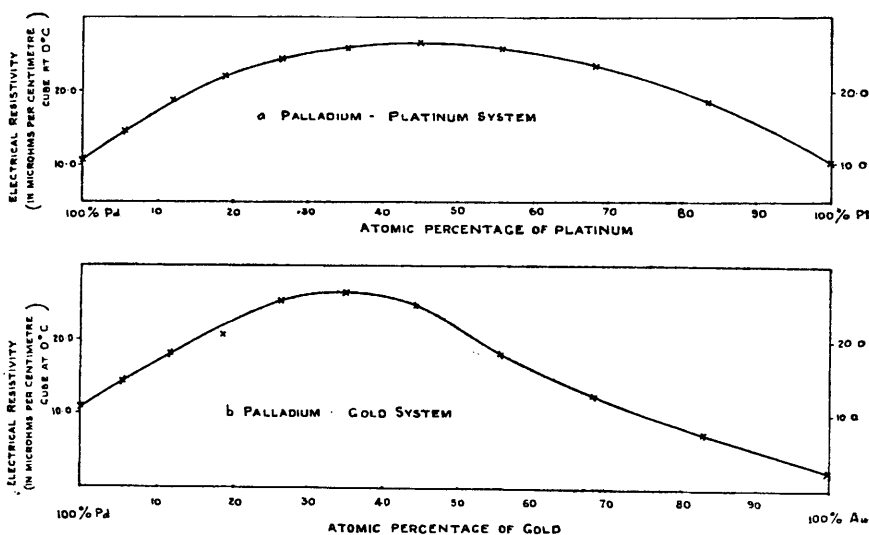

FIG. 3.—Electrical Resistivity of Continuous Solid Solutions.
(From Geibel, *loc. cit.*)

where C is the concentration of one component, and K is a constant for the series ".

The assumption that R may be considered as being made up of the two quantities $R_1 + R_2$ is made from considerations regarding the effect of temperature. Temperature influences the resistivities of solid solutions in such a way that they behave as if their resistivities were made up of two independent quantities R_1 and R_2 as above, of which R_1 is strongly influenced by temperature while R_2 is practically uninfluenced (see Section I*d*). This method of treatment appears to yield approximately correct results at all events. Assuming that this is so, a difficulty arises in calculating R_1, if the component metals have very different resistivities. It is not known to what extent the atoms in a solid solution (supposing complete mutual indifference) would partake of the nature of a number of conductors arranged in series or in parallel, or how the resistivities of such atomic mixtures would have to be calculated.

By making certain assumptions ;and working backwards it appears as if mixtures of the above type would approximate more nearly to the conductivity-composition linear relationship than to the resistivity-composition linear relationship. This difficulty only arises, however, when the two component metals have decidedly different resistivities. In many cases the value of R_1 is, relatively speaking, not very important.

The two types of curve, the symmetrical and the unsymmetrical, reproduced in Fig. 3, appear to be typical of simple continuous solid solutions. The curve shown in Fig. 3*b* indicates, it is thought, that Guertler's type of formula is not sufficiently general. By having only one constant K for a binary system he assumes that the R_2 curve is symmetrical on either side. It would appear from Fig. 3*b*, however, that each component requires a separate constant K of its own.

Curves of the simple types shown in Figs. 3*a* and 3*b* may be calculated by making certain assumptions of the above nature. It does not seem probable, however, that many curves for continuous solid solutions will admit of calculation by any simple formula. Further complications usually arise due to the formation of intermetallic compounds or the partial precipitation of one of the components from solid solution. The former case is shown in Kurnakow's (27) resistivity data for the copper-nickel solid solutions, where a discontinuity at about 50·0 atomic per cent. is apparent. The latter case is shown by Kurnakow's (28) work on concentrated copper-gold solid solutions where annealing at certain temperatures was found to precipitate one of the components from solution.

The point, however, which it is wished to make at present, is that (apart from complications of the above-mentioned nature) these resistivity curves for continuous solid solutions are of a fairly simple mathematical character. Moreover, the typical constants K_A and K_B for each component, from which the whole of the R_2 curve may be calculated, are approximately represented by the initial resistivity increases on either side.

Assuming that $R = R_1 + R_2$, it will be seen that if the solute has a higher resistivity value than the solvent, the initial resistivity increase will tend to represent too large a relative value for the constant K. Conversely, if the solute has a lower resistivity value than the solvent, the initial resistivity increase will tend to represent too low a relative value for the constant K in this case. In view of the fact that R_1 seems to approximate more nearly to the linear conductivity composition relationship, it will be seen that cases in which the solute has a higher resistivity than the solvent will yield more approximately correct values by the above method of interpretation than will the converse cases. All the data quoted in the present paper refer to cases in which the solvent metal has a relatively low resistivity value. Consequently, the difference between the resistivities of the solvent and solute is often small enough to make corrections of the above nature so relatively small (in comparison with the magnitude of the solution resistivity R_2) that they are within the limits of experimental error of the figures quoted. It is obvious, however, that corrections of the above nature must be made in order to obtain values which can be compared quantitatively.

c. *The Initial Addition of Solute in Dilute Solid Solutions.*

Reasons for thinking that the initial additions of solute cause an almost linear (as represented by the tangent to the initial stages of the curve) increase in the resistivity of the solvent, have been given in the preceding

sub-section.   This linear type of relationship has been found in all the
experimental results examined so far, with only one or two exceptions of
the following type.   For instance, in the cases of the copper-arsenic and
copper-antimony dilute solutions a slightly concave upwards type of curve
is usually obtained.   The form of this curve is reminiscent of curve *a* in
Fig. 1 and is thought to be due to the same cause, namely, duplexity of
structure, in this case in the solid solutions.   This is in accordance with
the cored structures observed under the microscope.

A typical normal case showing the usual linear nature of the initial
resistivity increase is reproduced in Fig. 4, where Clay's (11) results for
dilute solutions of silver in gold, measured at various temperatures, are
plotted.

d. The Effect of Temperature.

The general truth of Guertler's deduction "that the solution resistance"
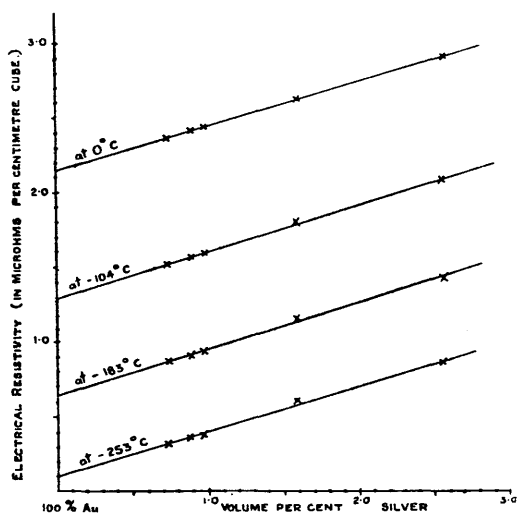(R_2, see Section 1b) "does not vary with the temperature" is confirmed by

FIG. 4.—Electrical Resistivity of Dilute Solid Solutions of Silver in Gold.
(From Clay, *loc. cit.*)

Clay's figures plotted in Fig. 4.   It will be seen that the slope of the
resistivity-composition lines is the same when measured at 0° C. as it is
when measured at − 104° C., − 183° C., and − 253° C.   If the solution
resistivity is affected by temperature, the effect must be very small and
would require exceedingly accurate measurements to detect it in this
particular case.

In comparison, it will be noted that the resistivity of pure gold varies
from 2·15 microhms at 0° C. to 0·09 microhm at − 253° C.   At still lower
temperatures Kammerlingh Onnes has found that pure metals exhibit a
"super-conductivity".

There appear to be indications, however, that the solution resistivity
is not altogether independent of temperature, even in solid solutions.   In
cases of solid solutions quoted in Section 2, where measurements on the
same alloys were made at, say, 0° and 100°, a slight variation in the value

of the solution resistivity is sometimes discernable.   In Fig. 6 it will be seen that the values for various elements in solid and molten solution in copper are by no means identical, and Bornemann's (3, 4, 5) other data indicate that temperature undoubtedly affects the solution resistivity values in the case of molten alloys.   In the case of solid solutions, however, the influence appears to be relatively very small, unless temperature has the effect of altering the amount of solute in solution, or altering the relative arrangement of the atoms in the alloy in any way.   The solid solutions quoted in Section 2 were in all cases measured at temperatures lying between 0° and 30° and for this range the effect of temperature on the solution resistivity appears in all cases to be within the limits of experimental error.

e. The Effect of Cold Work and Grain Size.

The following figures [1] illustrate the relatively small effect of cold work, and incidentally of grain size, on the electrical resistivity of pure metals :—

	Silver.	Copper.	Gold.	
Annealed :	1·47	1·56	2·04	Electrical resistivity in microhms
Hard drawn :	1·62	1·62	2·08	per centimetre cube at 0° C.

A still more striking instance is given by Campbell (9) for iron.   He found that the effect of drastic cold-hammering on annealed, pure iron (carbon 0·04 per cent.), was to increase the Brinell hardness from 76 to 240 whereas at the same time the electrical resistivity only increased from 10·50 to 10·63 microhms per centimetre cube.

Apart from the other effects of cold working, the difference in grain size between the worked and the unworked specimens would be very great, the attendant small alteration in electrical resistivity is consequently the more noteworthy.

That the effect of cold work on the resistivity of solid solutions is similarly very small is shown by Münker's data (31).   Although the effect of grain size is small in the case of pure metals, it becomes more important in the case of duplex alloys and increasingly so as the degree of dispersion of the components increases.   At the crystal boundary between a crystal grain of metal A and a crystal grain of metal B, in a duplex alloy, there must presumably exist a region where atoms of A are adjacent to atoms of B. It seems reasonable to suppose, therefore, that a large but local increase in resistivity will take place at such a crystal boundary, just in the same way as it does in solid solutions where atoms of A and atoms of B are adjacent to one another.   The grain size in a duplex alloy has, however, to become exceedingly small before the number of the atoms comprising these crystal boundaries becomes comparable with the total number of atoms present. When, however, this degree of dispersion is reached, the resistivity increases very rapidly.

It is thought that this point is well illustrated by the progressive fall in resistivity which takes place on tempering martensitic steels at progressively higher temperatures.   Temperature has the effect of causing a progressive diminution in the degree of dispersion of the carbides—consequent on coalescence—and the electrical resistivity falls correspondingly. The reason that this coalescence takes place so readily is thought to be that, whereas in austenite the carbon is in true solid solution in the γ-iron,

[1] *Metal Industry Handbook*, 1920.

in martensite it is equally highly dispersed but is not in solid solution in the α-iron. If the quenching is sufficiently rapid the $\gamma \rightarrow \alpha$ change, and consequent precipitation of the carbide from solution, does not take place until the system has practically reached the temperature of the quenching medium. At this temperature the very highly dispersed (probably atomically dispersed) carbon atoms are thrown out of solution. Although they have a strong tendency to approach one another and coalesce, they are unable to move owing to the fact that they are wedged in between the iron atoms, for at this low temperature the system has not sufficient inter-atomic mobility to permit the necessary atomic rearrangement to take place. The fact that the dispersed system is metastable and that the carbon atoms—with attendant iron atoms—are trying to approach one another and coalesce is clearly shown by the readiness with which this takes place when the temperature—and consequently the inter-atomic mobility—is slightly raised. Campbell (9) has shown that tempering at 100° causes a very large drop in the resistivities of martensitic carbon steels; and finds that the resistivities are slowly dropping in some cases even at ordinary temperatures (10). In austenitic steels, on the other hand, in so far as the carbon is in true solid solution in γ-iron, it does not coalesce on tempering until the temperature is sufficiently high to cause first of all the austenite $\rightarrow$ martensite (i.e. the $\gamma \rightarrow \alpha$) transformation to take place.

The conclusions arrived at in what precedes are in some cases incomplete, but it is thought that they give a general working idea of the relative importance of the various factors which go to determine the resistivity of a solid solution. In comparison with most of the factors already discussed the influence of 1·0 atomic per cent. added element entering into solid solution is relatively very large.

2. COLLECTION AND DISCUSSION OF EXPERIMENTAL DATA SHOWING THE ATOMIC EFFECTS OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITY OF CERTAIN METALS.

In the present section experimental data dealing with the electrical resistivity of various dilute metallic solid and molten solutions, are collected. They have been interpreted in the light of the generalisations discussed in the preceding section.

Composition is expressed in atomic percentages, and specific resistivity is defined throughout in microhms per centimetre cube. The exact temperature of measurement is relatively unimportant from the present point of view—as has been discussed in section 1d—but was, in all the cases of the solid solutions quoted, somewhere between 0° and 30°.

It would take up too much space to give a detailed account for every set of experimental determinations of the methods used and the probable accuracy of the results in each case. An attempt to indicate the possible experimental errors has, however, been made by giving, in the columns showing "Increase in resistivity due to 1·0 atomic per cent added element," a maximum and a minimum possible value, deducible in doubtful cases from an investigator's plotted results. Furthermore, the "Remarks" columns show the number and the compositions of the alloys from which the above mentioned maximum and minimum values have been calculated. By taking into account the details given in these two columns, a good idea

may be obtained of the probable accuracy of the value obtained from each set of experimental determinations.

As an illustration of the way in which the figures showing the "increase in resistivity due to 1·0 atomic per cent. added element" were actually obtained, Clay's results in Fig. 4 may again be utilised. It will be seen that the addition of 1·0 per cent. by volume of silver has raised the specific resistivity of the gold from 2·15 to 2·45 microhms at 0° C. This amounts to an increase of 0·3 microhm for 1·0 atomic per cent. of silver (since the atomic volumes of gold and silver are approximately equal). In some cases—as for example in most of the data quoted from Geibel's papers (13, 14) on palladium and platinum solid solutions—there are no figures given for very dilute solid solutions. Since, however, these solid solutions are more or less continuous, it is possible to deduce the initial increase by interpolation from the experimental values obtained for more concentrated solutions. Cases in point are shown in Figs. 3a and 3b. All the other values quoted have been interpreted in an exactly similar way and represent the difference between the resistivity of a 1·0 atomic per cent. solid solution and the resistivity of the pure solvent.

a. Solid Solutions in Iron, Nickel and Cobalt.

The solid solutions in iron shown in Table 1 have been taken direct from the previous paper (32). These data (Table I.) are shown diagrammatically in Fig. 5a where the atomic resistivity increases are plotted against the positions the added elements occupy in the Periodic Table.

In three cases (e.g. Al, Cu, Au) the solute has a decidedly lower resistivity than the solvent ; the values for these three elements are therefore (for reasons discussed in Section 1b) to be considered as being somewhat lower than they really would be if they were calculated to a more strictly comparable basis. Apart from this, however, it will be seen that the two elements cobalt and nickel—in the same group and period as iron—have markedly lower atomic effects than any of the other elements quoted. Further, cobalt has a smaller effect than nickel. The largest atomic effects are caused by elements in the most distant groups, while the elements in the intermediate groups have more or less intermediate effects. The nitrogen and vanadium values are doubtful and, especially ⸰ in the case of nitrogen, are probably too low. The manganese value is probably fairly accurate, but is considerably higher than would have been anticipated in view of the general relationship brought out more clearly in Figs. 6 and 7.[1] The nickel alloys collected in Table 2a and plotted in Fig. 5b show the same general relationship, and it will be seen that the value showing the effect of manganese on nickel is much more "normal".

b. Solid Solutions in Palladium and Platinum.

In Tables II.c and II.d some palladium and platinum alloys, which are plotted in Figs. 5c and 5d, are shown. It will again be observed that the elements palladium and platinum, in the same sub-group (8c), have smaller effects on one another than any of the other elements shown. As

[1] In view of the general explanation of the results suggested in Section 3, however, it is noteworthy that manganese has such a marked power of retaining iron in the γ form, indicating that some strong forces must be operating between the two. Similar remarks probably apply to some of the other iron alloys.

a matter of interest, Wolf's (47) data for the palladium-hydrogen alloys have been calculated to the same basis, and give the relatively high value of 16·0 microhms for the atomic effect of hydrogen. This case is, however, not necessarily strictly comparable.
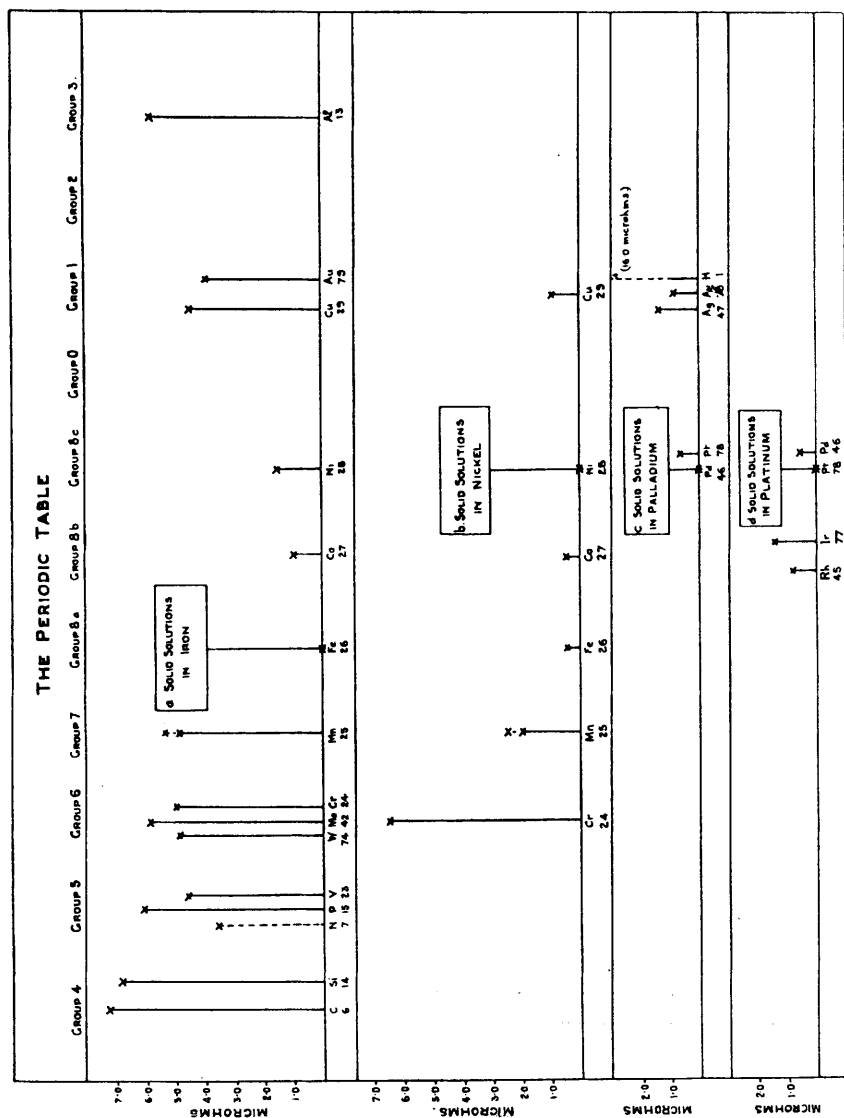
FIG. 5.—The Atomic Effects of Various Elements on the Electrical Resistivities of Iron, Nickel, Palladium and Platinum. (Tables I. and II.).

(The uprights indicate : Increase in the Resistivity of the pure Solvent (in microhms per centimetre cube) due to the Presence in Solid Solution of 1·0 Atomic per cent. Added Element.)

c. Solid Solutions in Copper, Silver and Gold.

In Table III. data relating to solid solutions in copper are collected. In column 4a of this table the effect of 1·0 per cent. by weight added element is also given. The atomic effects are plotted (thus ×) in Fig. 6.

It will be seen, on studying the results, that they ought really to be
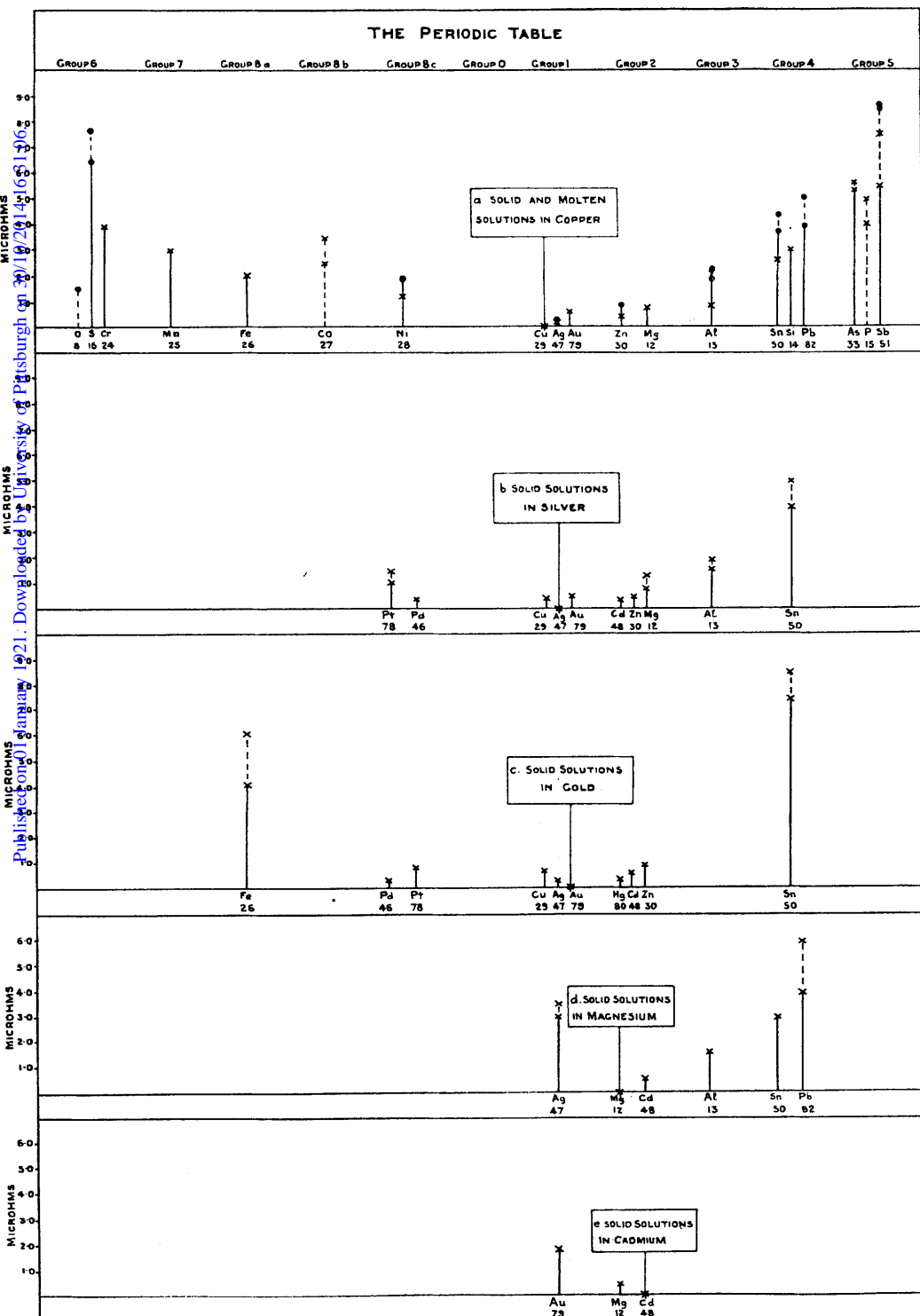
FIG. 6.—The Atomic Effects of Various Elements on the Electrical Resistivities of Copper, Silver, Gold, Magnesium and Cadmium. (Tables III. to V.)

(The uprights indicate: Increase in the Resistivity of the pure Solvent (in microhms per centimetre cube) due to the Presence in Solution of 1·0 Atomic per cent. Added Element. Solid Solutions thus **x**, Molten Solutions thus ● at 1100°—1400°.)

plotted in three dimensions, the dimension not indicated being that showing the vertical arrangement of the elements in the Periodic Table.   In order, however, that the vertical positions may be more readily imagined, the atomic numbers are written in under each of the solute elements.   The same remarks apply also to the silver solid solutions (in Table V.*a* and Fig. 6*b*) and the gold solid solutions (in Table V.*b* and Fig. 6*c*).

Considering the plotted results in Figs. 6*a*, 6*b*, 6*c*, it is interesting to study the remarkably close relationship existing between the magnitudes of the atomic effects and the distances (horizontal and vertical) separating the solute from the solvent in the Periodic Table.

The horizontal relationship is well brought out in all the plotted results. The effects, however, of Cr, Mn, Fe, Co (doubtful, see Table III.), Ni, Zn and As on Cu are already sufficiently regular to indicate that exact values would be very interesting.

The vertical relationship is best brought out by comparing the relative effects of :—

i. (*a*) Au and Ag on Cu; with (*b*) Au and Cu on Ag; with (*c*) Cu and Ag on Au.
ii. (*a*) Mg and Zn on Cu; with (*b*) Mg, Cd and Zn on Ag; with (*c*) Zn, Cd and Hg on Au.

Here again the indication is that exact values would be very interesting. Incidentally, it is to be noted that the data plotted in Figs. 5*c*, 5*d* and the palladium and platinum values in Fig. 6*c* do not show a similar vertical relationship.   It is possibly significant, however, that if the positions palladium and platinum occupy in the Periodic Table were interchanged, the results in Figs. 5*c*, 5*d* and 6*c* (but not 6*b*), would conform to the above vertical relationship.

d. Molten Solutions in Copper.

In Table IV., data are shown which have been calculated in exactly the same way, from the results obtained by Bornemann and his co-workers for molten copper alloys.   The values obtained from resistivity measurements on the alloys at $1100°$, $1200°$, $1300°$ and $1400°$ are shown in columns 3 to 6.   Column 7 shows the variation of these values between $1100°$ and $1400°$.

The maximum and minimum values, between $1100°$ and $1400°$, are therefore plotted (thus ●) in Fig. 6*a*, side by side with the values of the respective solid solutions.   With the exception of the oxygen value (which it will be seen from Table IV. is admittedly the most variable and doubtful), these values for the molten solutions are in marked general conformity with the respective solid solution values, the former being, roughly speaking, once or twice as great as the latter.

It will be observed in Table IV. that temperature has apparently an appreciable influence on the solution resistivity of these molten alloys. The fact, however, that the atomic increases for these molten solutions are only about twice the respective solid solution values, is thought to be rather noteworthy.   Moreover, it is quite possible that the solution resistivity may jump discontinuously on melting just as the resistivity of a pure metal does.

e. Solid Solutions in Magnesium and Cadmium.

Data referring to a few magnesium and cadmium solid solutions are given in Tables VI.*a* and VI.*b*, and are plotted in Figs. 6*d* and 6*e*.   So far as they go they confirm the above general relationship.   They also indicate,

it is thought, a further cross-relationship between the results.   The effects of silver and gold on magnesium and cadmium respectively are, for example, considerably greater than the converse effects of magnesium
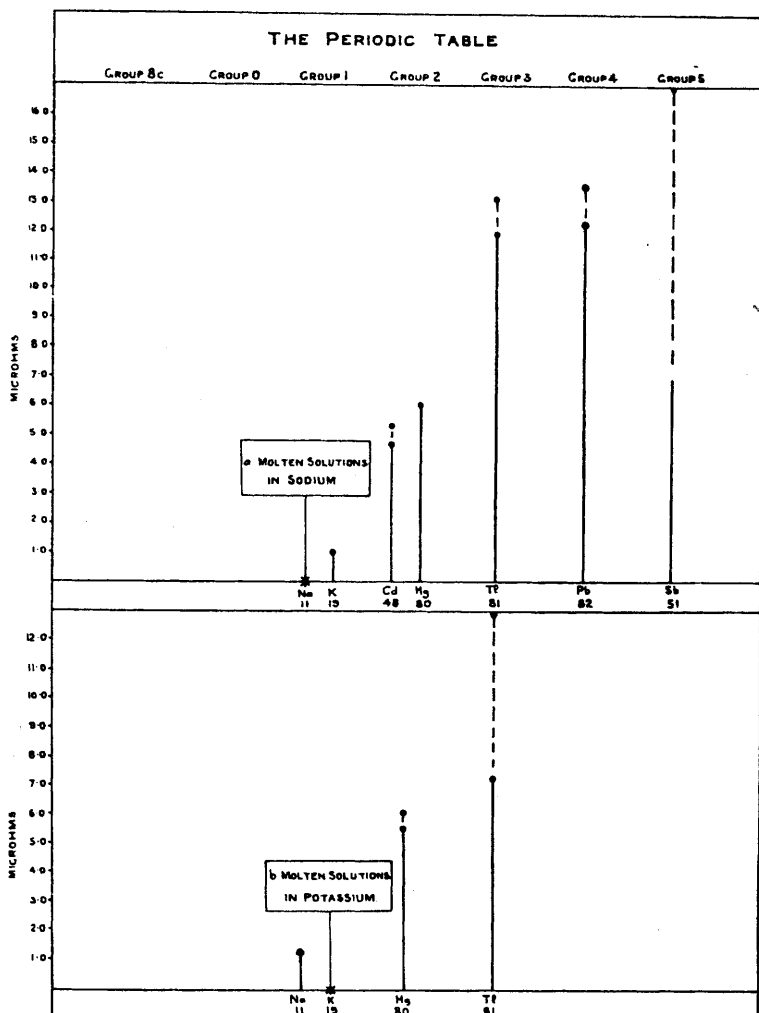
FIG. 7.—The Atomic Effects of Various Elements on the Electrical Resistivities of Sodium and Potassium.   (Table VII.)

The uprights indicate : Increase in the Resistivity of the pure Solvent (in microhms per centimetre cube) due to the Presence in Molten Solution of 1·0 Atomic per cent. Added Element.)

and cadmium on silver and gold respectively.   The existence of a similar type of cross relationship is also apparent in most other cases where data showing the effect of A on B, and the effect of B on A, are in both cases available.

f. Molten Solutions in Sodium and Potassium.

In Tables VII. *a* and VII. *b* and Figures 7*a* and 7*b*, data for various molten sodium and potassium alloys—taken from papers by Bornemann, etc. (3, 4, 5), and Müller (30)—are collected and plotted. In many cases the solutions were very dilute and, therefore, the experimental difficulties of obtaining very accurate results would be considerable. They nevertheless serve to bring out the same general relationship.

Kurnakow's (25) data for solid solutions showing that rubidium has a very small atomic effect on potassium (and vice versa) are also included.

The foregoing data all refer to solutions in which the solvent has a comparatively low resistivity value. In cases where the solvent has a high resistivity value the interpretation is more difficult. In many cases, on the solute going into solution it actually lowers the resistivity of the solvent. It seems, however, that in most cases, in spite of this lowering, the solution has a higher resistivity than it would have were the components mutually indifferent—as discussed in Section 1*b*.

3. DISCUSSION OF THE RESULTS.

It is thought that the first inference to be drawn from the foregoing results is that there is—from the electrical resistivity point of view—no very obvious analogy between solid solutions and aqueous solutions.

The results indicate that the atomic resistivity effects of various elements in solid or molten solution in a metallic solvent are relatively large or small according as the solute is far from or near to the solvent in the Periodic Table. In other words, the atomic effects are large or small according as the solute differs from, or resembles the solvent, in some atomic property. It is obviously the properties of the solute in relation to those of the solvent that have to be considered.

The fact that most of the atomic properties of the elements vary periodically suggests several possible explanations.

a. Comparison with some of the Atomic Properties of the Elements.

An examination of the atomic volumes of the elements concerned shows that the above results cannot be explained as being directly due to differences of atomic volume between the solvent and the solute. For example, the differences between the following atomic volumes : Ag = 10·23, Au = 10·20, Mn = 7·44, Ni = 6·64, etc., and that of copper (Cu = 7·08) are not in the same order as the resistivity effects of these elements on copper (see Fig. 5). In the same way the data collected by Smith[1] for the intrinsic pressures of the elements (*viz.* Ni = 306,300, Fe = 239,000, Cu = 236,100, Au = 178,500, Ag = 161,900, Zn = 108,900, Al = 119,300, Sn = 68,700 megabars, etc.) are equally incapable of direct application.

Similarly with the electrical resistivities, thermo-electric properties and decomposition potentials of the elements.

As a matter of fact, the exceedingly close way in which the resistivity increases follow the relative positions of the elements in the Periodic Table, itself tends to preclude many of the atomic properties, since most of them do not follow the Periodic Table nearly so closely. The closeness of the above relationship is in fact thought to be very significant. It

[1] *Journal of the Institute of Metals*, 1917 (i), p. 78.

suggests that the above results may be explained by assuming that the relative atomic effects are small, when there is little "affinity" between atoms of solute and solvent, and large according as the "affinity" between the two is greater. It is thought that this explanation is substantiated when the results are examined from various other points of view.

b. The Degree of Dispersion of the Solute.

It is obviously of primary importance to know the degree of dispersion of the solutes in the above cases (see Section 1e). It is thought that there is no experimental evidence indicating that the atoms of solute in a dilute metallic solid solution are associated. All available evidence indicates on the contrary that the solute is probably atomically dispersed. Unfortunately, however, the evidence on this point is not absolutely conclusive.

If the above results were to be explained by assuming that the atomic effects of various elements on a metallic solvent would be equal if the solutes were all dispersed to the same degree, it would be necessary to assume that the atoms of silver, gold, and zinc, for instance, in solid and molten solution in copper are associated to a highly improbable degree. In one case at all events direct comparison is possible. Cadmium is known to be atomically dispersed in boiling mercury, while resistivity data indicate that cadmium at 300° has relatively a very small atomic influence on the electrical resistivity of mercury compared, for instance, with sodium.

In what follows it will be assumed that the solutes in the dilute solid solutions quoted are in all cases atomically dispersed. It may be that in some cases there is a certain amount of association, but this does not seem probable and does not affect the general conclusions arrived at.

c. Space-Lattice Considerations.

It is thought that the foregoing explanation of the results receives support by considering the way in which the atoms of solute and solvent are arranged with respect to one another in the space-lattice.

If one atom of solute in a very dilute solid solution is pictured, and if, for example, the face-centred cube lattice is assumed, it is known from the work of W. H. and W. L. Bragg that this atom of solute will be surrounded by twelve equidistant atoms of solvent. It is thought that the solute atom will not be attached, providing the solution is sufficiently dilute, to any one of the twelve surrounding atoms in particular, although there may be strong "affinity" forces at work tending to cause such combination.

The above non-formation of inter-metallic compounds will, however, only occur in very dilute solutions. As the solutions become more concentrated some of the atoms of solute will tend to "combine with" (that is to say, a transference or re-grouping of electrons will take place) definite atoms of solvent to form inter-metallic compounds (compare Section 1b).

If the electrical forces between solute and solvent atoms normally tend to be more or less neutralised by inter-metallic compound formation, it seems that in the case of the dilute solid solution pictured above, these forces are not neutralised and are therefore still in existence between the solute atom and the electrons of the surrounding solvent atoms.

Incidentally, if the above picturing is correct, it follows that normal inter-metallic compounds do not exist as such in sufficiently dilute solid solutions and consequently it is correct to compare the atomic effects of various solutes on a solvent without taking into consideration the formulæ

of the inter-metallic compounds formed by solute and solvent under more favourable conditions. If this is the case, there should be some relationship between the atomic effect of metal A on metal B and vice versa. This type of cross-relationship seems to be appearing in the results (see Section 2e).

d. Electrical Conductivity Considerations.

The present generally accepted view on metallic conduction is that metals conduct an electric current by means of their " free " electrons. (By " free " electrons is meant such electrons as are shot off from one atom and temporarily attach themselves to a new atom.)

Temperature, it is assumed, has the effect of increasing the kinetic energy of these electrons and making them in consequence less easily deflected in the direction in which the electric current is flowing.

It seems in accordance, therefore, with the above view to explain the relatively enormous effects produced on a metallic conductor by the introduction of a few foreign atoms, by assuming that the increased resistivity is due to the solute atoms exerting forces on the electrons of the neighbouring atoms of the solvent (and vice versa) as suggested in the preceding sub-section.

To take an actual case, the fact that the addition of 1·0 atomic per cent. arsenic sends the specific resistivity of copper up by four or five microhms (this effect is apparently almost equally great near absolute zero where the resistivity of pure copper approaches 0·0) makes it seem very probable that each arsenic atom is exerting a very considerable influence on the resistivity of a large number of the surrounding copper atoms. It is thought that it would be difficult to explain such a relatively large influence unless it is assumed that the electrons in a large number of the copper atoms are being affected.

Conclusion.

Experiments are being carried out with the view of obtaining some more data of the above type. It is also hoped that a more quantitative interpretation may be possible in the future.

In conclusion, the author would like to express his appreciation of the encouragement and advice he has received from Professor C. A. Edwards, and acknowledge his indebtedness to the Commissioners for the 1851 Exhibition for a special grant made in view of a relinquished scholarship.

TABLE I.

THE EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITY OF IRON.[1]

Added element	.	C	N	Al	Si	P	V	Cr	Mn	Ni	Co	Cu	Mo	W	Au
Atomic weight	.	12·0	14·0	27·1	28·3	31·0	51·1	52·0	54·9	58·7	59·0	63·6	96·0	184·0	197·2
Increase in the resistivity of iron (in microhms per centimetre cube) due to the presence in solid solution of 1·0 atomic per cent. added element.		7·3[2]	3·6	5·8	6·9	6·1	4·6	5·0	4·9 to 5·4	1·5	1·0	4·5	5·8	4·9	3·9

[1] Journal of the Iron and Steel Institute, 1920 (i), pp. 640-641.
[2] Water-quenched at 1100° C., and relative to a 1·0 per cent. carbon steel.

TABLE II.

THE EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITIES OF NICKEL, COBALT, PALLADIUM AND PLATINUM.

Author, Date and Reference.	Element.	Atomic Weight.	Increase in Resistivity (in Microhms per Centimetre Cube) due to the Presence in Solid Solution of: 1·0 Atomic Per Cent. Added Element.	Remarks.
			a. Solid Solutions in Nickel.	
Hunter and Sebast: 1917 (22)	Cr	52·0	6·5	From alloys with 5·0, 10·0, 15·0 weight per cent. chromium. Initial slope taken.
Hunter and Sebast: 1917 (22)	Mn	54·9	2·0 to 2·5	From alloys with 5·0, 8·0, 10·0, 12·5, 15·0 and 20·0 weight per cent. manganese.
Burgess and Aston: 1910 (8) } Honda: 1918 (20) }	Fe	55·9	Below 0·5 (?)	The results appear to indicate that an inter-metallic compound Fe₂Ni is formed, which is fairly soluble in iron but practically insoluble in nickel.
Ruer and Kaneko: 1913 (38)	Co	59·0	0·5 (?)	Value deduced by interpolation.
Kurnakow: 1907 (27)	Cu	63·6	1·0	From alloys with 10·6, 20·0, 28·0, etc., weight per cent. copper. Initial slope taken.
			b. Solid Solutions in Cobalt.	
Honda: 1919 (21)	Fe	55·9	1·0 to 2·0	From alloys containing 10·0, 20·0, 30·0 weight per cent. iron. Value deduced by interpolation.
Ruer and Kaneko: 1913 (38)	Ni	58·7	Very low	Nickel appears to form an inter-metallic compound which is practically insoluble in cobalt.

TABLE II. (*continued*).

				Description
			c. Solid Solutions in Palladium.	
Wolf: 1914 (47) . . .	H	1·0	16·0	Calculated from Wolf's data showing the rise in resistivity of palladium wire, due to the occlusion of various volumes of hydrogen.
Geibel: 1911 (14) . .	Ag	107·9	1·4	From alloys with 9·90, 19·83, 29·77, etc., atomic per cent. silver. Initial slope taken.
Geibel: 1911 (14) . .	Pt	195·2	0·7	From alloys with 5·7, 12·0, 19·0, 26·7, etc., atomic per cent. platinum. Initial slope taken.
Geibel: 1910 (13) . .	Au	197·2	1·0	From alloys with 5·67, 11·9, 18·8, 26·5, etc., atomic per cent. gold. Initial slope taken.
			d. Solid Solutions in Platinum.	
Żemczużny: 1920 (24) . ' .	Rh	102·9	0·7 to 0·8	From alloys with 1·88, 4·63, 9·08, 17·40 atomic per cent. rhodium. Initial slope taken.
Geibel: 1911 (14) . .	Pd	106·7	0·55 to 0·60	From alloys with 16·7, 31·5, 43·8, etc., atomic per cent. palladium. Initial slope taken.
Żemczużny: 1920 (24) .	Pd	106·7	0·55 to 0·60	From alloys with 1·81, 4·48, 8·78 and 16·70 atomic per cent. palladium. Initial slope taken.
Geibel: 1911 (14) . .	Ir	193·1	1·5 to 1·6	From alloys with 5·05, 10·09, 15·13, 20·16 and 25·16 atomic per cent. iridium. Initial slope taken.
Żemczużny: 1920 (24) .	Ir	193·1	1·4 to 1·5	From alloys with 1·01, 2·53, 5·05 and 10·09 atomic per cent. iridium. Initial slope taken.

TABLE III.

The Effect of Various Elements on the Electrical Resistivity of Copper. (Solid Solutions.)

Author, Date and Reference.	Element.	Atomic Weight.	Increase in the Resistivity of Copper (in Microhms Per Centimetre Cube) due to the Presence in Solid Solution of:		Remarks.
			a. 1·0 Per Cent. By Weight, Added Element.	b. 1·0 Atomic Per Cent. Added Element.	
Stepanow: 1914 (44)	Mg	24·3	2·0	0·8	Doubtful whether all the magnesium is in solution even in the 1·7 and 2·0 atomic per cent. magnesium alloys quoted.
Broniewski: 1912 (6)	Al	27·1	1·9	0·8	From alloys with 6·0 and 14·0 volume per cent. aluminium.
Hampe: 1892 (18)	Si	28·3	7·0	3·0	From alloys with 0·53 and 3·47 weight per cent. silicon.
Münker: 1912 (31)	P	31·0	(9 to 11)	(4·0 to 5·0)	Seven alloys with phosphorus from 0·0 to 1·05 per cent. by weight examined. Not solid solutions, apparently. Increased resistivity probably due to segregation of phosphide at crystal boundaries (see Edwards, Section 1a).
Hunter and Sebast: 1917 (22)	Cr	52·0	4·0	4·0	One alloy with 0·5 weight per cent. chromium.
Münker: 1912 (31)	Mn	54·9	3·4	2·9	Ten alloys with 0·04 to 1·49 weight per cent. manganese examined, only slight resistivity differences found between alloys as: (a) untreated, (b) annealed at 700°, and (c) quenched at 500° and 700°.
Hunter and Sebast: 1917 (22)	Mn	54·9	3·5	3·0	From alloys with 4·5, 7·3, 12·0, etc., weight per cent. manganese.
Ruer and Fick: 1913 (37)	Fe	55·9	2·3	2·0	One alloy with 0·5 weight per cent. iron.
Reichardt: 1907 (36)	Co	59·0	2·5 to 3·8	2·5 to 3·5	Four alloys containing up to 3·0 per cent. by weight cobalt.

TABLE III. (*continued*).

			1·2 to 1·3	1·1 to 1·2	
Kurnakow: 1907 (27) .	Ni	58·7		1·1 to 1·2	Six alloys containing up to 30·0 per cent. by weight nickel. Linear increase up to about 40·0 per cent. nickel.
Gray: 1915 (15) .	Ni	58·7	1·2	1·1	From alloys with 10·0, 30·0 and 40·0 weight per cent. nickel.
Matthiessen: 1860 (29) .	Zn	65·4	0·25 to 0·30	0·26 to 0·31	From alloys with 1·6 and 3·2 weight per cent. zinc.
Haas: 1894 (17) .	Zn	65·4	0·28	0·29	From alloys with 0·71, 1·56, 3·07, 5·51, etc., weight per cent. zinc.
Puschin: 1913 (35) .	Zn	65·4	0·29	0·30	From alloys with 3·0, 5·0, 8·0, etc., atomic per cent. zinc.
Matthiessen: 1860 (29) .	As	75·0	4·0 to 5·0	—	From alloys with 2·8 and 5·4 weight per cent. arsenic.
Hampe: 1892 (18) .	As	75·0	4·5	5·3	From alloys with 0·22, 0·35, 0·81 weight per cent. arsenic.
Hiorns: 1909 (19) .	As	75·0	4·8	5·6	From fifteen alloys with 0·05 to 2·58 weight per cent. arsenic.
Puschin: 1913 (34) .	As	75·0	4·7	5·5	From alloys with 0·25, 0·50, 0·75, 1·00, 1·50, etc, weight per cent. arsenic.
Matthiessen: 1860 (29) .	Ag	107·9	0·13	0·22	From alloys with 1·22 and 2·45 weight per cent. silver.
Kurnakow: 1910 (26) .	Ag	107·9	0·08 to 0·13	0·13 to 0·22	From alloys with 0·5, 1·0, 2·0, 3·0, etc., atomic per cent. silver.
Matthiessen: 1860 (29) .	Sn	118·7	1·4	2·6	From alloys with 1·33, 2·52 and 4·90 weight per cent. tin.
Münker: 1912 (31) .	Sn	118·7	1·4	2·6	From ten alloys containing 0·3 to 1·46 per cent. by weight tin. Only slight resistivity differences found between alloys as : (*a*) untreated, (*b*) annealed at 700°, and (*c*) quenched at 500° and 700°.
Hampe: 1892 (18) .	Sb	120·2	2·0 to 2·3	4·0 to 5·0	From alloys with 0·26 and 0·53 weight per cent. antimony.
Hiorns: 1909 (19) .	Sb	120·2	2·8 to 3·8	5·5 to 7·5	From six alloys with 0·10 to 0·61 weight per cent. antimony.
Matthiessen: 1860 (29) .	Au	197·2	0·15 to 0·25	0·5 to 0·65	From alloys with 1·64 and 3·53 volume per cent. gold.
Kurnakow: 1916 (28) .	Au	197·2	0·21 to 0·23	0·60 to 0·64	From alloys with 5·0, 10·0, 15·0, etc. atomic per cent. gold. Initial slope taken.

TABLE IV.

THE EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITY OF COPPER. (MOLTEN SOLUTIONS.)

Added Element.	Atomic Weight.	Increase in the Resistivity of Molten Copper (in Microhms per Centimetre Cube) due to the Presence in Molten Solution of 1·0 Atomic Per Cent. Added Element, at:—				Variation between 1100° and 1400°.	Remarks.
		1100°.	1200°.	1300°.	1400°.		
(Resistivity of Pure Copper)	—	21·52	22·41	23·29	24·17)	—	All the data given in this table are calculated from the results of : Bornemann and Rauschenplat (4) and Bornemann and Wagenmann (5).
Oxygen	16·0	0·4	0·7	1·2	1·5	0·4 to 1·5 ?	Calculated from alloy containing 0·667 atomic per cent. oxygen.
Aluminium	27·1	2·0	1·9	1·8	1·8	1·8 to 2·0	Calculated from alloy containing 10·99 atomic per cent. aluminium.
Sulphur	32·1	6·3	6·3	6·4	6·5	6·3 to 7·6	Calculated from alloy with 0·43 atomic per cent. sulphur.
Sulphur	32·1	7·5	7·5	7·6	7·6	—	Calculated from alloy with 0·90 atomic per cent. sulphur.
Nickel	58·7	—	1·6	1·7	1·8	1·6 to 1·8	Calculated from alloy with 20·22 atomic per cent. nickel. (N.B.—In solid solutions the increase is linear up to about 40·0 atomic per cent. nickel.)
Zinc	65·4	0·6	0·7	0·8	—	0·5 to 0·8	Calculated from alloy with 0·88 atomic per cent. zinc.
Zinc	65·4	0·5	0·5	0·6	—	—	Calculated from alloy with 3·41 atomic per cent. zinc.
Silver	107·9	-0·1	0·0	0·2	0·3	-0·1 to 0·3	Calculated from alloy with 1·01 atomic per cent. silver.
Tin	118·7	3·7	3·8	3·9	4·0	3·7 to 4·3	Calculated from alloy with 1·08 atomic per cent. tin.
Tin	118·7	4·3	4·3	4·3	4·3	—	Calculated from alloy with 2·60 atomic per cent. tin.
Antimony	120·2	8·4	8·7	8·7	8·6	8·4 to 8·6	Calculated from alloy with 1·04 atomic per cent. antimony.
Lead	207·2	4·0	4·3	4·6	5·0	3·9 to 5·0	Calculated from alloy with 0·62 atomic per cent. lead.
Lead	207·2	3·9	4·1	4·5	4·8	—	Calculated from alloy with 0·92 atomic per cent. lead.

TABLE V.

THE EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITIES OF SILVER AND GOLD. (SOLID SOLUTIONS.)

Author, Date and Reference.	Added Element.	Atomic Weight.	Increase in Resistivity (in Microhms per Centimetre Cube) due to the Presence in Solid Solution of 1·0 Atomic Per Cent. Added Element.	Remarks.
			a. Solid Solutions in Silver.	
Smirnow: 1911 (42) .	Mg	24·3	0·8 to 1·3	From alloys with 0·17, 0·38, 0·74, 1·03 atomic per cent. magnesium.
Broniewski: 1912 (6) .	Al	27·1	1·6 to 2·0	From alloys with 4·9 and 9·7 volume per cent. aluminium.
Beckmann: 1914 (1) .	Al	27·1	1·6 to 2·0	From alloys with 3·3, 4·45 and 7·6 atomic per cent, aluminium.
Matthiessen: 1860 (29) .	Cu	63·6	0·1	From alloy with 2·01 volume per cent. copper. Doubtful if copper is all in solution.
Kurnakow: 1910 (26) .	Cu	63·6	0·4 to 0·5	From alloys with 2·0, 4·0, 8·0 and 10·0 atomic per cent. copper.
Sedström: 1919 (41)	Zn	65·4	0·5	From alloys with 5·7 and 11·6 atomic per cent. zinc. Initial slope taken.
Geibel: 1911 (14) .	Pd	106·7	0·4	From alloys with 10·1, 20·2, 30·2, etc., atomic per cent. palladium. Initial stope taken.
Sedström: 1919 (41) .	Cd	112·4	0·4	From alloy with 4·0 atomic per cent. cadmium.
Matthiessen: 1860 (29) .	Sn	118·7	4·0 to 5·0	From alloys with 0·93 and 2·01 volume per cent. tin.
Matthiessen: 1860 (29) .	Pt	195·2	0·6 to 0·7	From alloys with 5·0 and 9·8 volume per cent. platinum.
Thompson & Miller: 1906 (45)	Pt	195·2	1·0 to 1·5	From alloys with 10·5, 20·5, 31·5 weight per cent. platinum. Initial slope taken.

TABLE V. (*continued*).

Matthiessen: 1860 (29)	Au	197·2	0·4 to 0·6	From alloys with 1·17, 1·74, 2·68, 5·84, etc., volume per cent. gold.
Sedström: 1919 (41)	Au	197·2	0·3	From alloys with 5·0, 9·7, etc., atomic per cent. gold. Initial slope taken.
			b. Solid Solutions in Gold.	
Matthiessen: 1860 (29)	Fe	55·9	4·0 to 6·0	From alloys with 4·7, 5·0, 10·0 and 15·0 weight per cent. iron.
Matthiessen: 1860 (29)	Cu	63·6	0·35 to 0·4	From alloys with 2·28, 4·33, 8·46, etc., volume per cent. copper.
Kurnakow: 1916 (28)	Cu	63·6	0·74	From alloys with 5·0, 10·0, 15·0 atomic per cent. copper. Initial slope taken.
Sedström: 1919 (41)	Zn	65·4	0·85 to 0·95	From alloys with 4·9, etc., atomic per cent. zinc. Initial slope taken.
Geibel: 1910 (13)	Pd	106·7	0·3	From alloys with 17·0, 31·6, etc., atomic per cent. palladium. Initial slope taken.
Matthiessen: 1860 (29)	Ag	107·9	0·2 to 0·3	From alloys with 1·19, 1·77, 2·73, etc., volume per cent. silver.
Clay: 1911 (11)	Ag	107·9	0·30	From alloys with 0·726, 0·872, 0·960, 1·586 and 2·550 volume per cent. silver.
Sedstrom: 1919 (41)	Ag	107·9	0·36	From alloys with 4·9, etc., atomic per cent. silver.
Saldau: 1915 (39)	Cd	112·4	0·35	From alloys with 5·05, 14·4, etc., atomic per cent. cadmium.
Sedström: 1919 (41)	Cd	112·4	0·64	From alloys with 5·4, 8·7, etc., atomic per cent. cadmium.
Matthiessen: 1860 (29)	Sn	118·7	7·5 to 8·5	From alloys with 1·17 and 2·11 volume per cent. tin.
Geibel: 1911 (14)	Pt	195·2	0·8	From alloys with 10·09, 20·26, 30·21, 40·25 atomic per cent. platinum. Initial slope taken.
Parravano: 1919 (33)	Hg	200·6	0·4	From numerous alloys containing 0·5 to 3·0 weight per cent. mercury.

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TABLE VI.

THE EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITIES OF MAGNESIUM AND CADMIUM. (SOLID SOLUTIONS.)

Author, Date and Reference.	Added Element.	Atomic Weight.	Increase in Resistivity (in Microhms Per Centimetre Cube) due to the Presence in Solid Solution of 1·0 Atomic Per Cent. Added Element.	Remarks.
			a. Solid Solutions in Magnesium.	
Broniewski: 1912 (6)	Al	27·1	1·6	From alloy with 4·7 volume per cent. aluminium. Doubtful if all aluminium is in solution.
Smirnow: 1911 (42)	Ag	107·9	3·0 to 3·5	From alloys with 0·44, 0·88, etc., atomic per cent. silver.
Urascow: 1911 (46)	Cd	112·4	0·5 to 0·6	From alloys with 5·0, 10·0, 15·0, 20·0, etc., atomic per cent. cadmium. Initial slope taken.
Stepanow: 1914 (44)	Sn	119·0	3·0	From alloys with 1·18, 2·5, 3·56, etc., atomic per cent. tin.
Stepanow: 1908 (43)	Pb	206·9	4·0 to 6·0	From alloys with 0·75, 1·76, 3·03, 3·43, etc., atomic per cent. lead.
			b. Solid Solutions in Cadmium.	
Urascow: 1911 (46)	Mg	24·4	0·40 to 0·45	From alloys with 5·0, 10·0, 15·0, 17·5, etc., atomic per cent. magnesium.
Saldau: 1915 (39)	Au	197·2	1·7 to 1·9	From alloy with 0·95 atomic per cent. gold.

TABLE VII.

EFFECT OF VARIOUS ELEMENTS ON THE ELECTRICAL RESISTIVITIES OF SODIUM AND POTASSIUM. (MOLTEN SOLUTIONS.)

Added Element.	Atomic Weight.	Temperature of Measurement.	Increase in Resistivity (in Microhms per Centimetre Cube) due to the Presence of 1·0 Atomic Per Cent. Added Element.	Remarks. All the Values in this Table have been Calculated from the Results of Bornemann and Rauschenplatt: 1912 (4), unless the Contrary is Stated.
			a. Molten Solutions in Sodium.	
K	39·1	100° C.	0·95 or 1·1	From alloys with 4·2 and 8·0 atomic per cent. potassium.
		150° C.	1·0 or 1·1	
		200° C.	1·1	
Cd	112·4	150° C.	5·1	From alloy with 0·93 atomic per cent. cadmium.
		250° C.	4·6	
		350° C.	5·3	
Sb	120·2	150° C.	7·0	From alloy with 0·1 atomic per cent. antimony. (In consequence of the small amount of solute there is a large possible error.)
		250° C.	11·0	
		350° C.	17·0	
Hg	200·0	100° C.	6·0	From alloys with 7·0, etc , atomic per cent. mercury.
		150° C.	5·9	
		200° C.	5·9	
Tl	204·1	150° C.	11·9	From alloy with 0·92 atomic per cent. thallium.
		250° C.	12·1	
		350° C.	13·1	
Pb	206·9	250° C.	12·3	From alloy. with 0·99 atomic per cent. lead.
		300° C.	12·9	
		350° C.	13·6	
			b. Molten Solutions in Potassium.	
Na	23·0	100° C.	1·3	From alloys with 7·0, etc., atomic per cent. sodium.
		150° C.	1·3	
		200° C.	1·3	
Rb	85·5	0° and 25° C. (Solid Solutions)	0·1	Kurnakow: 1914 (25), alloys with 14·29, etc., atomic per cent rubidium.
Hg	200·0	100° C.	5·5	From alloys with 4·75, etc., atomic per cent. mercury.
		150° C.	5·8	
		200° C.	6·1	
Tl	204·1	150° C.	7·3	From alloy with 1·06 atomic per cent. thallium.
		250° C.	9·8	
		350° C.	13·2	

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(38) Ruer and Kaneko : *Ferrum*, 1913, Vol. 10, p. 258.   (Ni-Co and Co-Ni.)

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