THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

THE ELECTRICAL RESISTIVITY OF MOLTEN METALLIC MATERIALS

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Nomenclature

a = lattice constant

a_o = first Bohr orbit radius

A = constant

b = radius of cell to which an atom motion is restricted

B = constant

c = ionic constant of the metal

c_b = atomic fraction of component b

C = constant

d = atom group diameter

e = electronic charge

E_F = kinetic energy of an electron at the maximum Fermi distribution point

$\overline{E}_m$ = mean energy of vibration per atom

E_o = rest position energy

E'_o = lowest atom energy value

E_x = (potential) energy in x-direction

f = partition function

f_l = liquid state partition function

f_s = solid state partition function

f' = functional relationship

f'' = functional relationship

$f(r)$ = function of container radius

g = dimensionless factor determined by the ionic structure arrangement

$g(h')$ = structural factor relationship

$g(h')_l$ = structural factor relationship for the liquid state

$g(h')_s$ = structural factor relationship for the solid state

G = constant

h = Plank's constant

h' = dimensionless number

$\hbar$ = modified Plank's constant

H' = magnetic field intensity

H_∞ = electron constant at infinite dilution

I = electric current

j = scattering coefficient of one atom and a unit solid angle

J = scattering coefficient of a unit volume and unit solid angle

k = Boltzmann's constant

K = wave number of an electron at the maximum Fermi distribution point

l = electron mean free path

L = latent heat of fusion

L' = resistance ratio of lead to material

m = electronic mass

M = torque

dM = increment of torque

$\bar{M}$ = atomic mass

n = number of electrons per unit volume

n' = number of free electrons per atom

n_f = number of free electrons per unit volume

N = total number of atoms

$\bar{N}$ = constant

N_D = ionic density (number of free electrons per atom)

N_l = total number of atoms in the liquid state

N_s = total number of atoms in the solid state

p $\cong$ atom concentration of solute

P = denotes constant pressure

q_∞ = resistivity constant at infinite dilution

Q = effective scattering cross-section

r = a dimension measured radially outward from the container center

r_o = separation distance of two atoms (potential energy minimum)

R = container radius

s = distance

s' = dimensional scale factor (length)

$\bar{s}'$ = average distance of separation between atom groups

t = time

$\bar{t}$ = average time between electron collisions

T = absolute temperature

T' = denotes constant temperature

T_{mp} = melting temperature

u_∞ = viscosity constant at infinite dilution

v = electron velocity

v' = final electron velocity

$\bar{v}$ = average electron velocity

V = volume

V' = denotes constant volume

V_{rs} = potential energy at the surface of the atomic sphere

w = atomic cross-section for all-directional electron scatter

$\bar{w}$ = number of individual atom group contacts

$W(v,v')d\Omega$ = probability that an electron of initial velocity v is scattered

x = displacement in one direction from the equilibrium position

$\bar{x}$ = screening constant

x_l^2 = mean square atom displacement in the x-direction in the liquid

x_s^2 = mean square atom displacement in the x-direction in the solid

z = apparent electron charge number

α = temperature coefficient of resistivity

α_T = coefficient of thermal expansion

β = temperature coefficient of resistivity

β' = isothermal compressibility coefficient

γ = temperature coefficient of resistivity

η = viscosity

θ = coordinate

θ' = scattering angle at an inclination to the motion of the electron

θ'' = scattering angle

θ_D = Debye characteristic temperature

θ_E = (Einstein) characteristic temperature

λ_F = electron wave-length at the Fermi surface

μ = average frequency of group contacts

μ' = attenuation coefficient

ν = oscillation frequency

ν_l = atom oscillation frequency in the liquid

ν_s = atom oscillation frequency in the solid

ρ = resistivity

ρ_a = resistivity of pure component a

ρ_b = resistivity of pure component b

ρ_l = resistivity of the liquid

ρ_o = resistivity at 0^oK

ρ_s = resistivity of the solid

ρ_T = resistivity at a temperature T (absolute)

ρ_{ab} = resistivity of an a-b alloy

σ = conductivity

ϕ = coordinate

ω = (constant) rotary field angular velocity

ω_f = angular velocity of the rotary field

Ω = solid angle for scattering

Ω = resistance

$\Delta\bar{\Omega}$ = total resistance increase

I. INTRODUCTION

At the present time the literature contains a considerable amount of data on the resistivity of liquid metals and alloys. The data are scattered rather uniformly over the past seventy years and have never been summarized in a comprehensive survey. Consequently, it is quite difficult to locate specific data which may be available.

This report is presented in an effort to offer a fairly complete survey of liquid metal resistivities. It presents a compilation of published data and summarizes existing theories. It includes the following material: a review of the historical background in the resistivity field; theoretical derivations for liquid state resistivity; major experimental techniques used in liquid resistivity investigations; and a complete compilation of metallic resistivity data for liquid elements, binary alloys, and amalgams. The last section includes some tabular data on the temperature-resistivity-composition relationship.

II. Historical Review[1]

It had been noted in the 19th century that when a metal passed through a change of state the various physical properties underwent a discontinuous change. Early investigators of this discontinuity were primarly interested in the breakdown of the solid structure upon melting; thus, the variation of the physical properties, including electrical resistivity, were first studied in much detail at temperatures near the melting point.

The first recorded investigator was Matthiessen in 1857. He reported a sharp change in electrical resistivity near the melting point of potassium and sodium. In 1872, Matthiessen (with Vogt) made the first report on the resistivity of an amalgam in the liquid state. These two studies were soon followed by those of de la Riva (1863), who studied a few of the common metallic elements. For all metals investigated de la Riva noted resistivity increases through the solid-liquid transformation, except for bismuth and antimony which displayed decreases. In the years 1884-1887 Weber made rather extensive studies on several liquid pure metals and liquid amalgams. Vicentinni and Omodei, investigating tin, bismuth, thallium, cadmium, and lead found that the liquid resistivity of these metals at their melting temperatures were proportional to the atomic weight. They observed a relationship between

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[1] This subsection was taken from several sources: (26, 30, 69, 76, 101, 111, 113-117, 139, 147-148). Numbers refer to ref. in the bibliography.

the resistivity and the specific volume at the melting temperature: those metals which expanded upon melting showed increases in resistivity; those which contracted showed resistivity decreases. A few additional observations on pure metals were made before 1902, the most well-known and useful being those of Vassura and Guillaume, both in 1892. A complete listing of all investigations on the resistivity of molten metals published before 1902 is given in Table I.

The first extensive and systematic data obtained for pure molten metals and for liquid binary alloys, was reported in a series of papers by Bornemann, Muller, et al. (14-16, 83) in 1910-1914. The accurate investigations of Northrup (87-94) on pure metals and binary alloys followed shortly thereafter. Northrup developed a theory of liquid metallic resistivity based upon the Drude-Lorentz electron theory of metals (87). The first studies conducted on the resistivities of molten metals at high pressures were carried out by Bridgeman (20-22) in great detail between 1907 and 1921. Three Japanese investigators, Tsutsumi (139), Konno (69), and Matsuyama (76), did considerable research on binary alloy resistivities over the years 1918 to 1927. Skaupy (129-132) continued the work done by Bornemann on liquid amalgams. He presented both experimental data and the first theoretical interpretations in this field in a series of papers, published from 1916-1920. Basing experimental work on Skaupy's theories, Williams and Evans, et al. (26, 30, 147-148) reported extensive data for amalgams in the 1920's. This group also made initial investigations of the effect of magnetic fields on resistivity, following up some preliminary work

Table I. Early Reports on Resistivity of Molten Metals

Investigator	Year	Material
Matthiessen	1857	K, Na
Siemens	1861	Sn
Matthiessen and Vogt	1862	Ag, Au amalgams
de la Riva	1863	Bi, Cd, Pb, Sb, Sn, Zn
Benoit	1873	Hg
Michaelis	1883	Cu amalgams
Weber	1884, 1885, 1887	Bi, Hg; Ag, Bi, Cd, Pb, Sn amalgams
Cailletet and Bouty	1885	Hg
Batelli	1887	Ag, Au, Cu, Cd, Na amalgams
Grimaldi	1887	Na amalgams
Vicentini and Omodei	1889	Bi, Cd, Pb, Sn, Th; Cd amalgams
Jaeger and Kreichgauer	1892	Hg
Müller	1892	Hg
Vassura	1892	Bi, Cd, Sn
Guillaume	1892	Hg
Cattaneo	1893	amalgams
von Schweidler	1895	Cd amalgams
Dewar and Fleming	1896	Hg
Willows	1899	Cd amalgams
Larsen	1900	Cd amalgams

by others (85, 98-99). Braunbek (17-19) constructed the first practical apparatus for obtaining resistivity data by indirect measurements involving sample rotation in a magnetic field.

The next 15 years produced relatively little experimental work; however, in 1934 Mott (82) presented a useful theory on resistivity changes at the melting point. In addition, Harasima's later theory (48-49) for alkali metal resistivities attempted to extend Mott's analysis to more fundamental metal properties. A third extensive theory of metallic resistivity at the melting point was offered by Gerstenkorn (40-41) in two papers about 10 years ago. These investigators were among the first to recognize atomic scattering influences on resistivity and to mention the micro-crystalline structure in the liquid state. Soviet scientists, among them Mokrovski and Regel (78-81, 109), have made many investigations in the last 10 years, particularly on semiconductor elements and compounds. These authors have also theorized on a quasi-crystalline structure in liquids (5). Recent research in the resistivity field includes the efforts of Roll and his co-workers (111-117) who redeveloped and improved the indirect magnetic apparatus for resistivity determinations. They have also presented much material on molten pure metals and binary alloys at high temperatures. Scala and Robertson (121) recently reported data on metals and binary alloys.

III. Theoretical Review

Most of the experimental resistivity studies before 1900 were of limited accuracy due primarily to inaccurate measuring devices and the lack of suitably pure metals. The theoretical interprelations of this period were of very little value. However, with the discovery of the electron and the introduction of the Drude-Lorentz theory of "electron gases" in metals an elementary interpretation of resistivity became possible.

The devolopment of a theory for molten metals has been slow. At the present time only the change in resistivity upon melting has been treated theoretically; there is no theory which adequately explains the effect of either temperature or composition on the resistivity of molten alloys. In the three subsections below, a brief description of most of the more important theoretical treatments of resistivity of molten pure metals, binary alloys, and liquid amalgams is given.

Theories of Resistivity of Pure Metals

Drude-Lorentz Theory[2]. After the discovery of the electron, various theories of metals were put forth, culminating in what is now known as the Drude-Lorentz theory. A theoretical relation for the electrical conductivity of metal was developed from this theory.

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[2] From Northrup (87).

Although derived for solid metals, it should also apply to liquid metal systems.

If there are a number of "free electrons" in a unit volume of metal in the absence of an external applied field, the average velocity of the electrons is identical in all directions. Applying a field introduces a perturbation upon electrons and acceleration occurs:

$$d^2s/dt^2 = F'e/m \tag{1}$$

Collisions between electrons occur, and after each such collision, the electrons involved lose all velocity in the direction of the field. Assuming the electric field is applied at time zero, integration of Equation (1) gives:

$$v = ds/dt = F'et/m \tag{2}$$

The average velocity between two electron collisions is then:

$$\bar{v} = F'e\bar{t}/2m \tag{3}$$

The current is a function of the number of electrons present and their velocity:

$$I = ne\bar{v} = ne^2\bar{t}F'/2m \tag{4}$$

Application of Ohms's Law to Equation (4) gives for the resistivity:

$$\rho = 2m/ne^2\bar{t} \tag{5}$$

By defining the mean free path, ℓ, as the average distance traversed by the electrons between collisions Equation (5) may be written as:

$$\rho = 2\bar{v}m/lne^2 \qquad (6)$$

Although the derivation of Equation (6) was more or less rigorous within the framework of the assumptions of the Drude-Lorentz theory, some objections were stated:

1. No explanation was given for the change in resistivity through a change in state.
2. No explanation was given for the different experimental resistivities of different metals at the same temperature.
3. The temperature dependence of the resistivity was difficult to explain.
4. Experimental changes of resistivity with external pressure were not explained correctly.

Electric Transport Theory. Northrup, in his experimental studies on the resistivities of materials, had rejected the original Drude-Lorentz theory for some of the reasons offered above, and attempted (87) to explain the experimental behavior of resistivity on the basis of the empirical form:

$$\rho_T = \left|_{o}^{T_{mp}} \rho_o(1 + \alpha T + \beta T^2) + \right| _{T_{mp}}^{T} \gamma(T - T_{mp}) \qquad (7)$$

Northrup's reasoning is based on the assumption that at reasonable temperatures all electrons are normally attached to atom groups. Under ordinary applied electric fields, electrons can only be detached from their groups when the groups approach each other due to heat motion or pressure application. This idea results in the concept of perfect conductor atom groups surrounded by perfect insulator

spaces. Under an electric potential, the atom groups move within "contact distance" of each other and a transferrence of electrons takes place in such a manner to produce an electric field opposite in direction to the applied field.

A result of Northrup's derivation is general for both solids and liquids:

$$\rho \propto 1/\overline{w}_{\mu} de \tag{8}$$

Upon further assumption that the material is a metal in the liquid state, the resistivity can be written as:

$$\rho \propto (\overline{s}' - d)\sqrt{m}/nd^3e\sqrt{T} \tag{9}$$

Equation (9) maintains that at constant volume, the resistivity decreases with temperature[3].

Although some experimental verification of Equation (9) was possible, no explanation was given for metals which did not have linear temperature dependencies in the liquid state, as assumed by Equation (7).

Resistivity Ratio Group Theories. One of the early attempts to consolidate in a regular fashion the various data on resistivity was initiated by Wagner (144) in 1910, and extended (independently) by Perlitz (101) in 1926. Although these efforts were comprised of experimental observation rather than purely theoretical interpretation,

[3] A result experimentally verified later (44, 70).

they represent the first work done on the systematic change of resistivity at the melting point. This change in resistivity, usually expressed as a ratio of the resistivity of the liquid to that of the solid, has dominated most of the theoretical interpretations of molten resistivity to date.

It was first noted experimentally by Vicentini and Omodei about 1890 that the change in resistivity at the temperature of melting was such that the state of matter with the larger specific volume possessed the larger resistivity. Wagner, collecting experimental data on resistivity ratios, classified various pure elements into four groups by showing that these resistivity group numbers were in the ratio of small integers. A further extension was made by assuming that the resistivity ratios were proportional to the number of "structural" atom groups in both the solid and liquid states (see Table II, page 16).

Bridgeman in 1921 reiterated Vicentini and Omodei's observations in his work with metals at high hydrostatic pressures (20). Noting the observations made by these previous researchers, Perlitz (101), investigating the disappearance of the regular crystalline lattice, sought to obtain a relation between the (solid) crystalline structure of a metal and the change in resistivity during melting.

Examining some 19 metals for crystalline structure (lattice classification) and resistivity ratio at the melting temperature, Perlitz observed that the values for the ratios were not uniformly distributed numerically, but tended to cluster about several mean values (see Table II, page 16). At the time of Perlitz's observations,

not all of the 19 metal lattice structures had been determined. Even so, Perlitz identified the first group (1/2) as those metals of the rhombohedral-hexagonal solid type; the second group (3/2) as structures of the BCC metals; and the (4/2) group as the close-packed types (FCC and HCP). On this basis Perlitz then postulated that certain given structural lattice groups would have approximately the same resistivity ratio at the melting point. Perlitz noted only one exception to his rule, namely, that aluminum should have possessed a BCC-type structure (mercury was classified separately and hence was not included as an exception).

Although the postulate held reasonably well at the time it was stated, it can be seen (Table II, page 16) that with more information available on lattices, other discrepancies are introduced.

Latent Heat-Vibration Theory. One of the most important theories of the resistivity change in the solid-liquid transformation was proposed by Mott (82) in 1934 and is still used by many experimenters to interpret results. In this theory an expression is derived which holds reasonably well for most metals. The results can also be extended by various hypotheses to account for the resistivity ratio anomalies in bismuth and mercury.

Mott's derivation is as follows: from the electron theory of metals, the solid state is characterized by atomic vibrations occuring about fixed positions. Similar vibrations occur in liquid which are superimposed upon the shifting mean atomic positions. This shifting is of much smaller magnitude than the oscillation-vibration

Table II. Wagner and Perlitz Classifications of Resistivity Ratio Groups[4]

Metal	Resistivity Ratio[5]	Wagner Group	Structural Classification[6]	Resistivity Ratio[7]	Perlitz Group
Bismuth	0.465	1/2	Rhombohedral	0.48	1/2
Gallium	0.476		(Orthorhombic)	0.53	
Antimony	-----		Rhombohedral	0.69	
Sodium	1.37-1.70	3/2	Body-centered cubic	1.45	3/2
Lithium	-----		Body-centered cubic	1.48	
Potassium	1.44-1.62		Body-centered cubic	1.50	
Rubidium	1.58		(Body-centered cubic)	1.54	
Aluminum	-----		Face-centered cubic	1.65	
Cesium	1.7		(Body-centered cubic)	1.71	
Silver	-----	4/2	Face-centered cubic	1.86	4/2
Cadmium	~1.92		Hexagonal close-packed	1.91	
Lead	1.92		Face-centered cubic	1.97	
Thallium	2.0		Hexagonal close-packed	2.0	
Copper	-----		Face-centered cubic	2.03	
Zinc	~2.0		Hexagonal close-packed	2.05	
Tellurium	~2.10		Rhombohedral (hexagonal)	2.1	
Tin	~2.17		(Tetragonal)	2.13	
Gold	-----	8/2	Face-centered cubic	2.28	
Mercury	~4.07		Hexagonal (rhombohedral)	4.23	

[4] From (101, 144).

[5] Tabular data from (144).

[6] Lattice structures in parentheses are from L.S. Darken and R.W. Gurry, The Physical Chemistry of Metals, p. 50-7. The other structures are from (101).

[7] Tabular data from (101).

velocity; the average distance of movement of the mean position is about one percent of the interatomic distance.

Neglecting this mean position motion in liquid metals, each atom oscillates with a certain frequency. Mott assumes that the frequencies for all atoms are identical, and that the characteristic temperature for the solid is given by Einstein's model as:

$$\Theta_E = h\nu_s/k \tag{10}$$

If the melting temperature satisfies the condition,

$$T_{mp} \gg h\nu_s/k \tag{11}$$

the work required to move one atom (initially at rest) in the solid to an equilibrium position in the liquid is given by the latent heat of fusion for the metal. Using a statistical mechanical approach, Mott finds the free energy for a given number of atoms as:

$$F = N(kT \ln f + E_o) \tag{12}$$

If the total number of atoms is constant and is distributed in some manner between the solid and liquid states, the free energy in Equation (12) becomes:

$$F = N_s(-kT \ln f_s) + N_l(-kT \ln f_l + E_o) \tag{13}$$

At the melting temperature, the free energy in Equation (13) is minimized to zero and hence:

$$kT_{mp} \ln f_s = kT_{mp} \ln f_l - E_o \tag{14}$$

Equation (14) may be expressed as:

$$(f_l/f_s)\exp\ (-E_o/kT_{mp}) = 1 \tag{15}$$

The partition functions used in Equation (13) are of the form:

$$f = A(kT/\nu)^3 \tag{16}$$

A substitution of Equation (16) into Equation (15) yields:

$$\nu_l/\nu_s = \exp\ (-E_o/3kT_{mp}) \tag{17}$$

Mott, noting the relations developed above between the work required for movement across the solid-liquid boundary and the latent heat of fusion, substituted numerical values into Equation (17) and obtained the result:

$$\nu_l/\nu_s = \exp\ (-40L/T_{mp}) \tag{18}$$

Mott next develops a relation between the vibration ratio ν_l/ν_s and the resistivity. From Block's theory of conductivity in solids, perfect crystallinity produces ideal solids impervious to electronic motions. The ideal conductivity is modified for real bodies, however, since these structures possess irregularities due to either thermal atom motion or the presence of foreign atoms. In addition, resistivity depends upon the freedom of electronic motion from atom to atom. A resistivity equation in the solid state, due to Berthe, is:

$$\rho_T = 1/\sigma = (\pi^2 mhKa_o T/2n'\bar{M}k\theta_D^2)(c\ dE_F/k\ dK)^2 \tag{19}$$

Considering the possible changes in the variables of the last equation upon melting, Mott concludes that:

1. $\overline{M}$, m, a_o, c, n' remain constant.

2. K is a function of the specific volume and should not change greatly.

3. dE/dK, while a structural factor, is a function of the Fermi distribution energy and as such is dependent only upon the specific volume, and should not change greatly.[8]

Thus, Mott concludes that only the variation in atomic vibration is influenced greatly upon melting. From the characteristic temperature term in Equation (19), and from Equations (10) and (18), the resistivity ratio becomes:

$$\rho_l/\rho_s = (\nu_s/\nu_l)^2 = \exp\ (80L/T_{mp}) \qquad (20)$$

The derivation of Equation (20) relies on Equation (11); however, if this is not justified, i.e., if:

$$T_{mp} \leq h\ \nu_s/k \qquad (21)$$

which is especially true for the alkali metals and aluminum, Mott replaces Equation (10) by:

$$(\exp\ [h\ \nu_s/kT_{mp}] - 1)/(\exp\ [h\ \nu_l/kT_{mp}] - 1) = \exp\ (E_o/3kT_{mp}) \qquad (22)$$

A comparison between Mott's theory and experimental values of various resistivity ratios may be found in Table III, page 23. In the table are included the original calculations of Mott from Equation (20) and his values of experimental ratios. Also included are the writer's

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[8] "Abnormal melts" or those in which an increase of dE/dK exhibits itself in the disappearance of diamagnetism, are expected in this connection.

recalculated values of resistivity ratios using recent thermodynamic data on the basis of Equation (20).

Mott considered his theoretical calculations in reasonable agreement with experimental resistivity ratio values, except for mercury, antimony, bismuth, and gallium. He explains this discrepancy by assuming that in these particular cases the factor dE/dK does not remain constant during the liquid-solid phase change. For mercury, a decrease occurs; for the other metals above, an increase of about 10 takes place. (Note that the only metals which undergo contraction upon melting are the latter three: bismuth, antimony, and gallium. Cf. Perlitz theory of groups, page 10.) This theory requires that the additional resistivity in the liquid state is due mainly to the greater atomic oscillation amplitude and not to any great irregularity of the atomic structure. Hence, Mott introduces the important concept that over large distances (in comparison to the atomic distance), the atoms in a liquid possess regularity of position.

Extensions of the Latent Heat Vibration Theory. Harasima (48-49), in an attempt to extend the Mott theory of resistivity ratio to more fundamental quantities than the heat of fusion, has derived equations for the ratio in the alkali metals. A brief description of the derivation follows; Harasima postulated that from a knowledge of the mechanism of melting, the atomic distribution, and the state of motion the resistivity ratio can be calculated. This derivation assumes that the electrons in the melt can be considered to be identical to "free" electrons in the solid, and that the atom distribution remains un-

Table III. Resistivity Ratios Using Mott's Vibration Theory[9]

Metal	Theoretical Resistivity Ratios[10]		Experimental Ratios
Bismuth	5.0	5.04	0.43
Gallium	4.5	4.24	0.58
Antimony	5.6	5.94	0.67
Sodium	1.58	1.77	1.45
Potassium	1.67	1.76	1.55
Rubidium	1.76	1.75	1.61
Aluminum	1.8	1.55	1.64
Cesium	1.75	1.74	1.66
Lithium	1.57	2.58	1.68
Silver	2.0	2.08	1.90
Cadmium	2.3	2.46	2.0
Thallium	2.3	1.82	2.0
Copper	1.97	2.42	2.07
Lead	1.87	1.98	2.07
Zinc	2.3	2.17	2.09
Tin	3.0	3.07	2.1
Gold	2.22	2.14	2.28
Mercury	2.23	2.22	3.2-4.9

[9] From (82).

[10] The first set of calculations are from Mott: data on aluminum, lithium, potassium, and sodium are based upon Equation (22); all other calculations are from Equation (20). The second column contains calculations from Equation (20) using data from Selected Values of Chemical Thermodynamic Properties.

changed upon melting. Hence, Harasima states that the ratio of resistivities is related to atom displacements by:

$$\rho_l/\rho_s = (\overline{x}^2)_l/(\overline{x}^2)_s \tag{23}$$

To develop the idea of a potential energy-distance relationship, Harasima notes that a potential curve is quite different in the liquid than in the solid state; the curve has a flat portion in the former. Thus, the deviation of an atom from an equilibrium position in the liquid is larger than a similar deviation in the solid. There is one general relation for the atomic displacements:

$$x^2 = \int_0^\infty x^2 \exp(-E_x/kT)dx / \int_0^\infty \exp(-E_x/kT)dx \tag{24}$$

Further reduction of Equation (24) yields expressions for both the liquid and solid states of the form:

$$(\overline{x}^2)_l = 1.81B^2r_o^2 \tag{25}$$

$$(\overline{x}^2)_s = 1.24B^2r_o^2 \tag{26}$$

By substitution of Equations (25) and (26) into (23), the resistivity ratio for alkali metals is found to be:

$$\rho_l/\rho_s = 1.81/1.24 = 1.46 \tag{27}$$

The result is reasonably close to the experimental resistivity ratio values for lithium, potassium, and sodium (see page 18).

Perturbation Theory. In addition to the work done on the resistivity ratios of the alkali metals, Harasima (49) employed a different approach

for the calculation of an absolute resistivity of molten sodium at its freezing point.

In this calculation for resistivities, Harasima considers that the resistivity arises from the scattering of electrons in the interior of the metal. This scattering is due to atom displacements in a periodic lattice--the displacements caused either by thermal activity or by foreign atom presence.

In employing this basis for calculation, a perturbation method is selected for the electron scattering coefficients, with the assumptions that an atom motion is independent of other such motions, and that the potential-distance relation remains constant with changing atom displacement. Using an analysis similar to that by Mott and Jones,[11] the resistivity of sodium is derived to be:

$$\rho = 2.06m^2\overline{x}^2(V_{r_s} - E_o')^2/ne^2\hbar^3 \qquad (28)$$

Where, the mean square atom displacement is given by:

$$\overline{x}^2 = \int_0^b \int_0^\pi \int_0^{2\pi} 3(r \sin\theta \cos\theta)^2 r^2 \sin\theta \, dr \, d\theta \, d\phi/4\pi b^3 = b^2/5 \qquad (29)$$

Substitution of numerical equivalents in Equations (28) and (29) gives a resistivity for molten sodium at its freezing point of 7.1×10^{-6} ohm-centimeters. This is slightly less than the experimentally observed value.

Harasima found that this calculation on the basis of electron scattering in a periodic lattice gives a value in better agreement with that observed than does the previous derivation based on Mott's analysis

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[11] N. Mott and H. Jones, The Theory of the Properties of Metals and Alloys, p. 249ff.

(page 17). Harasima cautioned, however, that this second analyses uses experimental values to fit a cell distribution function, while previous models have no such dependency.

Electron Scattering Models of Resistivity. In general, theories of resistivity of liquid metals based upon the scattering of electron waves in a metal body are extensions of similar theories developed for the solid state.

Schubin (124), in 1934, was one of the first to apply this concept of scattering to liquid state resistivity. He considers that the scattering proceeds without loss of energy and that the nature of the ion changes during the process. By analogy with an "almost free electron", Schubin investigates behavior in both constant and varying potential fields. He concludes that the probability of both the scattering process and the ionic change is independent of temperature. Similar to a conclusion of Mott's (see page 17)Schubin states that the resistivity of a liquid metal as compared to that of a solid is scarcely influenced by a change from the ordered crystalline state to a (supposed) disordered liquid condition. This implies that a quasi-crystalline state exists in the liquid.

Two Indians, Krishnan and Bhatia (72), further extended the points outlined above. They define an attenuation coefficient as being that fraction of the electron wave scattered in all directions in a given unit volume. The coefficient is hence the reciprocal of the electron mean free path. Thus, according to the electron theory of

metals, the resistivity is:

$$\rho = h\mu'/nn'e^2\lambda_F \tag{30}$$

Furthermore, it can be shown that for the solid alkali metals, the wave-length in Equation (30) is sufficiently large so that the scattering coefficient can be obtained from the following:

$$J\mu = \epsilon n' j\mu \tag{31}$$

where

$$\epsilon = n'kT\beta' \tag{31a}$$

For Equation (30) and (31) to hold, the absolute temperature in Equation (31a) is assumed to be much greater than the characteristic temperature.

By integrating $J\mu$ over a solid scattering angle, the attenuation coefficient becomes:

$$\mu' = 2\pi\int_0^\pi J\mu \sin\theta' d\theta' \tag{32}$$

Also:

$$w = 2\pi\int_0^\pi j\mu \sin\theta' d\theta' \tag{33}$$

From Equations (31), (32), and (33), the scattering coefficient is:

$$\mu' = \epsilon n' w \tag{34}$$

Application of the last equation to the alkali metals gives results for the wave length in Equation (30) larger than the wave-length for the

first diffraction maximum occurring in the backward direction. The diffraction in these instances is diffuse compared to the solid diffraction, and the scattering angle is less than 90°. This causes additional scattering in the back plane besides that given in Equation (31). Thus Equation (34) gives a greater scattering coefficient and, according to Krishnan and Bhatia, this is observable through the resistivity increases of the alkali metals at the melting point. For other metals, an analogous treatment of X-ray scattering data, intensity distributions, and atomic structure factors can yield values of resistivity. In these cases, the diffraction pattern of the liquid must be studied. The intensity majority included in the inclination angle $0<\theta'<\pi$ completely determines the attenuation coefficient and, hence, the resistivity. In the derivation of Equation (34) for alkali metals, the intensity majority is limited by Equation (31). This majority, however, being a function of the valency, is only partly included in the given range for other metals. The attenuation coefficient in polyvalent metals is much larger than given in Equation (34). It is given by:

$$\mu' = n'w \tag{35}$$

Krishnan and Bhatia state that the above calculations have been checked with the "abnormal" metals, and that Equation (35) gives reasonable explanation for experimental resistivities.

Gerstenkorn (40) has recently published a detailed article on the change of electrical resistivity at the melting point, which was based on free electron scattering probability and a structural influence.

A rough translation of this paper is given below.

The electrical resistivity results from the scattering of electrons in motion in the metal interior. Hence, the resistivity in solids as well as in liquid may be represented as:

$$\rho = m/n_f e^2 \tau \tag{36}$$

and:

$$1/\tau = \int W(v,v')(1-\cos\theta'')d\Omega'^4 \tag{36a}$$

The scattering angle and the electron wave length are combined to produce a dimensionless variable:

$$h' = 2a/\lambda \sin(\theta''/2) \tag{37}$$

If one considers the maximum Fermi energy level as fixed, the integration variable in Equation (36a) may be replaced by Plank's constant. The wave-length under this substitution becomes:

$$\lambda^3 = 8\pi/3n_f \tag{38}$$

The scattering probability in Equation (36a) can also be expressed in the form:

$$W = N_d v Q g \tag{39}$$

An exact theoretical determination of the effective electron scattering cross-section becomes very complex:

$$\begin{aligned} Q &= (ze^2/2mv^2)^2(\sin^2[\theta''/2] + [\lambda/4\pi\bar{x}a]^2)^{-2} \\ &= (2zme^2a^2\bar{x}^2/\hbar^2)^2([2\pi\bar{x}h']^2 + 1)^{-2} \end{aligned} \tag{40}$$

With further analysis on the structural factor appearing in Equation (39), Gerstenkorn is able to combine Equations (36), (36a), (37), (38), (39), and (40) to obtain an equation representing the absolute value of the resistivity:

$$\rho = (N_d/3\pi n_f^2)(4z^2m^2e^2/\hbar^6)(4\pi\bar{x})^4 I \tag{41}$$

where:

$$I = (1/16) \int_0^{2a/\lambda} g(h')h'^3 dh'/([2\pi\bar{x}h']^2 + 1)^2 \tag{41a}$$

The ratio of the resistivities of the solid and liquid at the melting point from Equation (41); all factors except that defined in Equation (41a) cancel:

$$\rho_l/\rho_s = I_l/I_s = \int_0^{2a/\lambda} g(h')_l h'^3 dh'/([2\pi\bar{x}h']^2 + 1)^2 / \int_0^{2a/\lambda} g(h')_s h'^3 dh'/([2\pi\bar{x}h')^2 + 1)^2 \tag{42}$$

For high temperatures, the resistivity of pure metals, as seen from Equation (41), is influenced only by an electron scattering probability and a structural factor. This is true for any state of aggregation. It is most difficult to calculate structural factors for liquid metals, and Gerstenkorn deduces some of the needed information from X-ray diffraction results for the alkali metals. In the solid, however, the factor can be obtained directly. The substituted values for both the solid and liquid alkali metals at their melting points agree rather closely with experimental values:

Table IV. Theoretical Resistivity Ratios of Gerstenkorn[12]

Metal	$n_f = 1$	$n_f < 1$	Experimental
Lithium	1.62	2.04	1.68-1.96
Potassium	1.61	1.59	1.34-1.6
Sodium	1.74	1.77	1.39-1.56

Gerstenkorn calculates the resistivity ratios for elements with one or less free electrons per atom. As can be seen, the calculated values are not at great variance with the experimental ratios.

Theories of Resistivity of Binary Metallic Alloys

Although there have been a number of attempts to derive a theory of resistivity for pure molten metals, the lack of literature on similar theories dealing with binary molten alloys suggests little progress. A survey of the published information yields not one theoretical derivation relating resistivity and composition at a given temperature or resistivity and temperature at a given composition, much less a general resistivity-composition-temperature relationship. The reason probably stems from the lack of understanding of liquid state, particularly of the liquid state in alloys. The small number of experimental investigations relating to binary alloy resistivity presents a restriction to the development of theoretical conclusions. The few experimental-theoretical observations of binary alloy resistivities noted by various experimenters are discussed below.

One of the earliest experiments with liquid alloy resis-

[12] From (40).

tivities, that of Bornemann and van Rauschenplot (15), produced some original observations. These workers noticed that if the solute added had a strong tendency to form an intermetallic compound with the solvent metal, the resistivity decreased over that of the pure solvent. In general, resistivity-temperature curves were found to be linear at a given concentration. Resistivity-composition curves, however, were in most cases not linear over extended composition ranges.

Japanese investigators at Tohoku Imperial University (69) found that simple "series" and "parallel" resistivity-composition relationships held for some of the alloy resistivity data taken. Thus, either of the following relations were approximately obeyed:

$$\rho_{ab} = \rho_a + c_b(\rho_b - \rho_a) \tag{43}$$

$$1/\rho_{ab} = 1/\rho_b + c_b\,(1/\rho_b - 1/\rho_a) \tag{44}$$

In a few alloys, the arithmetic mean of Equations (43) and (44) seemed to work well:

$$\rho_{ab} = (1/2)(\rho_a + c_b[\rho_b - \rho_a] + \rho_a\rho_b)/(\rho_b - c_b[\rho_b - \rho_a]) \tag{45}$$

In a recent investigation of dilute alloy resistivities, made by Scala and Robertson (121), the liquid and solid states were postulated to have almost complete correspondence of thermal, structural, and compositional relationships. With dilute concentrations of various metallic solutes in a copper solvent, the resistivity change for a unit atomic solution was the same as the change found in solid copper solutions. Also, this resistivity change was always an increase,

and the increase per unit of solute concentration was proportional to the difference in electronic charge of the solute and solvent. This relationship was independent of temperature. In the case of solutions of dilute metallic solutes in zinc, however, no resistivity increases were noted in most cases.

Theories of Resistivity of Liquid Metallic Amalgams

Only one researcher, Skaupy, published articles in the literature on the theoretical derivation of resistivities of liquid amalgams. The theory was presented in a series of papers (129-132) published before and after the advent of the Drude-Lorentz electron theory of metals, and was based upon an analogy to the electrolytic conduction concepts. This viewpoint was adopted for interpretations of liquid amalgam resistivities by most of the subsequent experimenters (26, 30, 147-148). A brief description of this theory follows.

The first assumption of Skaupy[13] in deriving his theory is that the electrical resistivity of pure substances can be expressed in terms of the electron concentration and the liquid internal friction. Actually, the relation is:

$$n = C\eta/\rho \qquad (46)$$

After expressing Equation (46) in logarithmic form and differentiating:

$$\Delta n/np = \rho\Delta(1/\rho)/p + \Delta\eta/\eta p \qquad (47)$$

From Equation (47) Skaupy notes that a substitution of the values for the pure solvent (mercury) could be used, since the Δ expresses small

[13] The following analysis is from (30, 148).

yet finite concentrations.

Hence, by setting:

$$\Delta n/np = H \tag{48a}$$

$$\rho\Delta(1/\rho)/p = q \tag{48b}$$

$$\Delta\eta/\eta p = u \tag{48c}$$

Substitution in Equation (47) gives:

$$H = q + u \tag{49}$$

At infinite dilution, Equation (49) becomes:

$$H_\infty = q_\infty + u_\infty \tag{50}$$

Although Skaupy first postulated (and showed experimentally) that the resistivity constant at infinite dilution, q_∞, was approximately the same for different amalgams, it was later shown by a co-worker to be only the same order of magnitude.

This later conclusion was found in investigations on a number of amalgams.[14]

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[14] As for instance, the investigations of (26, 30, 146-148).

IV. Resistivity Apparatus Review

In the effort to experimentally determine the resistivity of liquid metals several different types of apparatus have evolved. Early investigators utilized electrode cells to make direct measurements. Later investigations avoid the need for electrodes by employing magnetic fields.

Electrode-type Measuring Devices

Resistivity, or specific resistance, is defined as the ratio of the voltage to the current for some standardized state. With solid materials, particularly around room temperature, the measurement of resistivity presents no unusual problems. However, obtaining measurements in molten systems introduces such problems as: proper size and shape of container, suitable contact (electrode) and container materials, and uniform temperature distribution.

Tube Resistivity Devices[15] Early investigators, used low melting non-corrosive metals and inert containers in order to minimize the above difficulties. The typical experimental apparatus consisted of a long, narrow-bore tube ending in two large, low resistance contact wells; the molten metal under study filled the interconnected well-tube-well device. Four electrodes, two to serve as current leads and two as voltage leads, were contacted to the bath in the large wells. The tube portion, or more generally the entire device, was either placed

[15] Taken from (2-4, 10, 13, 23-24, 26-27, 30, 32, 36, 45-47, 50-51, 53-54, 56, 69, 71, 73, 76, 88-94, 107, 110, 119, 121, 125, 127, 133, 138-139, 142-143, 145, 147-148).

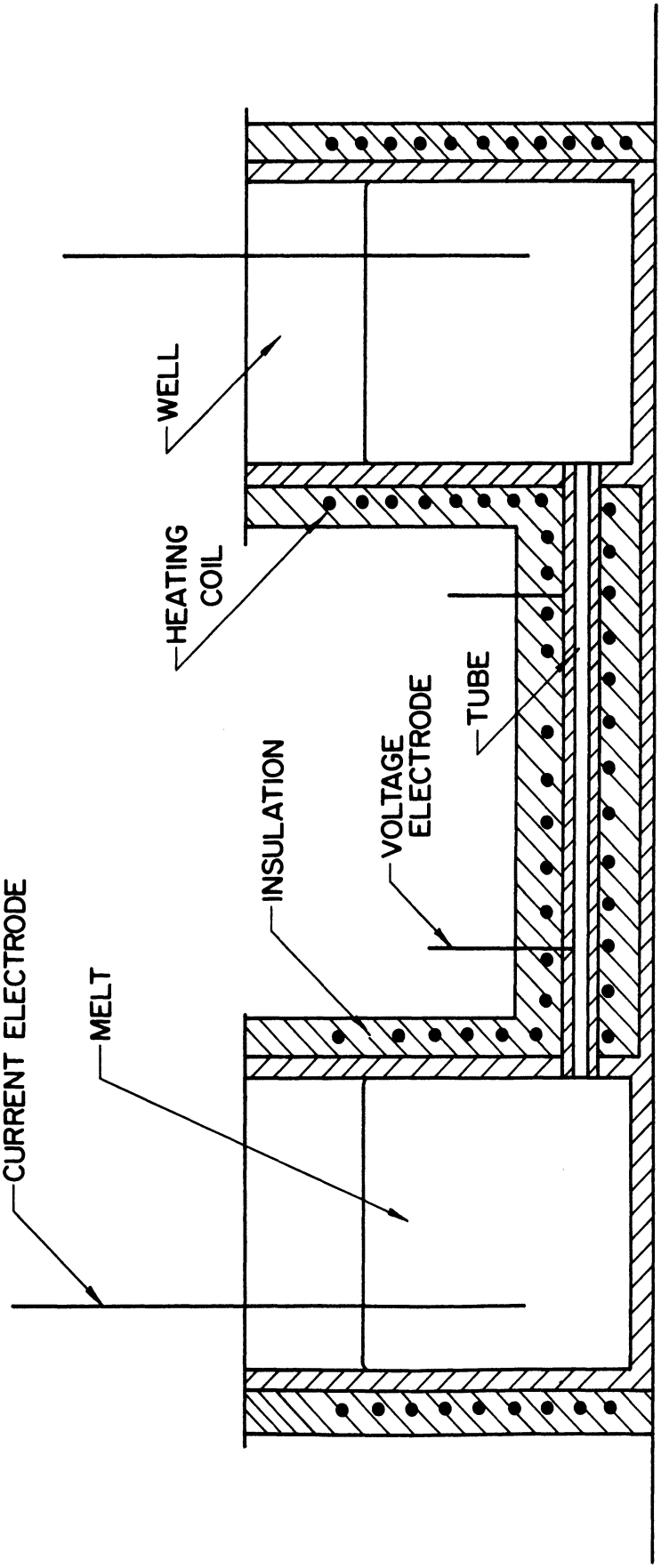

Figure 1. Typical Tube Resistivity Device.

into a constant temperature region, or surrounded by heating coils.

Figure 1, page 32, illustrates a typical resistivity device of early design. In some equipment particularly in work with liquid amalgams the tube portion was varied, being either vertical, U-shaped, or even helical shaped. In a few cases the contact wells were either partially or entirely eliminated, and contact with the material was made through the normal tube sides or ends. The two electrode sets were generally of platium wire, although tungsten, iron, and copper wire or rod have also been successfully employed. The placement of the electrode sets relative to each other and to the contact wells was important to insure measurements in constant electrical density regions. For this reason, the set of voltage electrodes were usually placed far enough inside of the path of current introduced by the current electrodes to be in a region of constant current density. The current electrodes were constructed of larger diameter wire than the voltage electrodes. This procedure reduced the temperature fluctuation in the molten material and gave lower electrical circuit resistance, thereby resulting in more accurate resistivity measurements.

The current electrodes were usually connected to a source of direct current such as a battery or small generator. A few experimenters have successfully used alternating current, usually at 60 cycles or less; although withstudies of the resistivity in the semi-metals frequencies of 1000 were not uncommon. The voltage circuits in direct current applications were usually connected to high-precision voltage measuring devices such as Wheatstone or Kelvin-

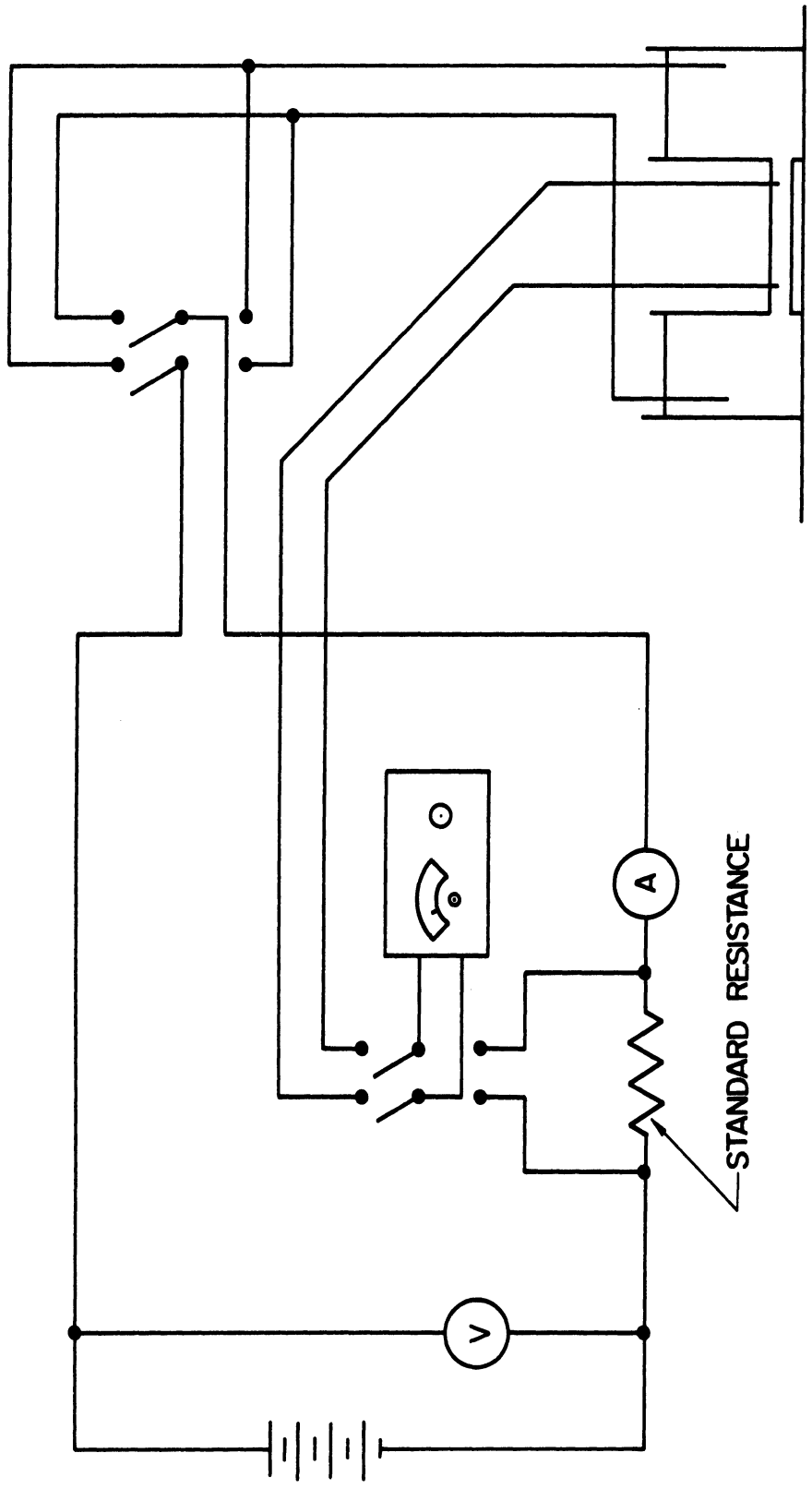

Figure 2. Typical Electrical Measuring Circuit.

double bridges, or precision potentiometers and galvanometer indicating instruments. In alternating current circuits the voltage was usually measured with either of the devices noted above plus a galvanometer type indicator suitable for use on alternating current. With direct currents provision also had to be made for inclusion of a reverse switch in the current circuit, so that polarization effects could be eliminated by reading the normal and reversed currents and averaging the readings. With alternating current, this procedure was not necessary. Figure 2, page 34, illustrates a typical direct current circuit used for measuring with high precision the current and voltage of resistivity devices.

In addition to the associated electrical equipment, either a protective atmosphere or a vacuum was employed when working at high temperatures or with easily oxidizable materials. Provision was usually made in the container tube to permit the introduction of an inert gas.

Bath Resistivity Devices.[16] One of the main difficulties experienced with the tube resistivity devices was that the resistivity circuit in the molten material passed through nearly the entire volume of the material. The devices employing this construction were hard to control at a uniform tube temperature.

The introduction of the bath resistivity device offered an advance in accuracy and convenience of handling. These devices were based on the concept of immersing a suitable open-ended tube in a large bath of the molten material. Consequently, the resistivity device

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[16] See footnote 15.

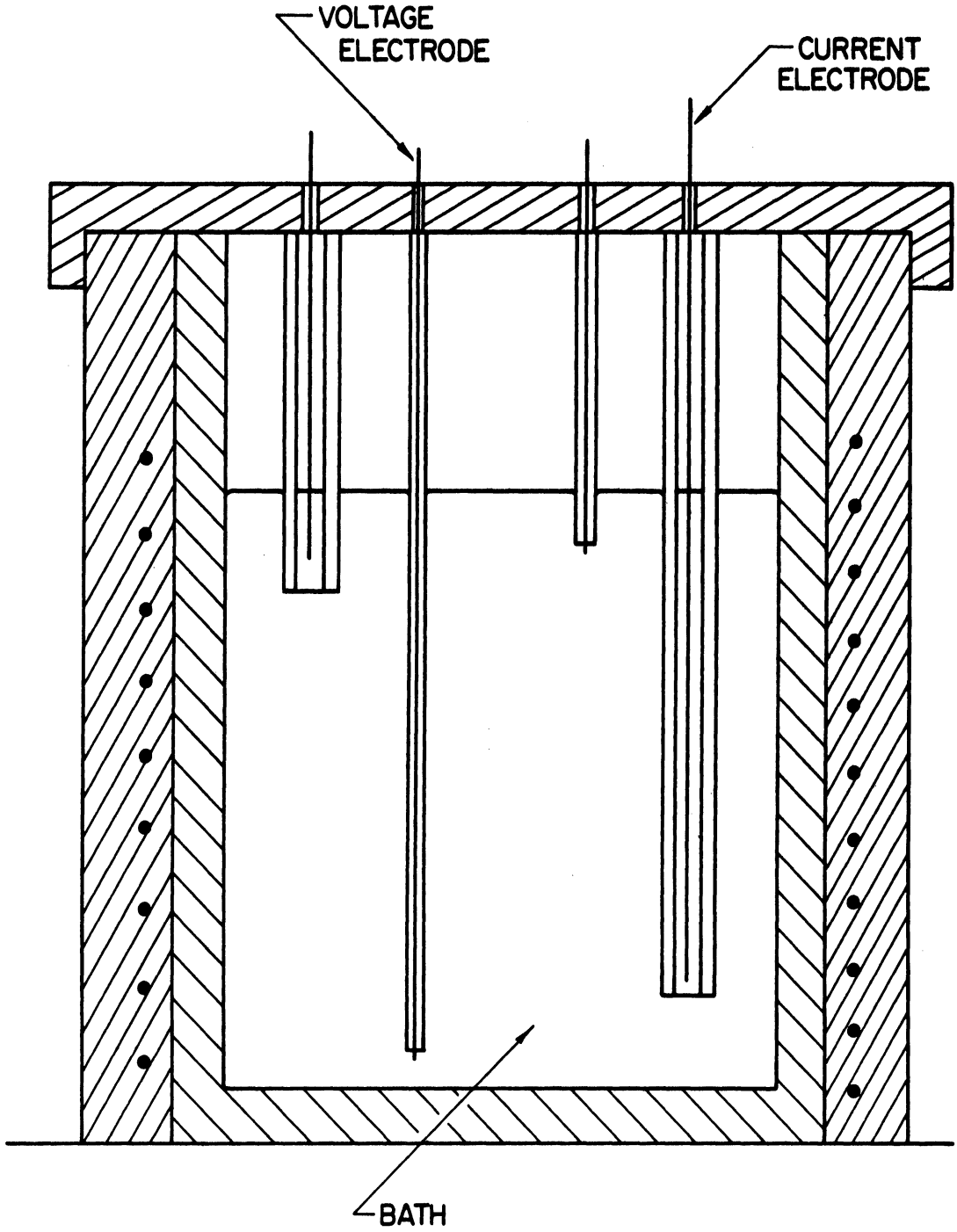

Figure 3. Typical Bath Resistivity Device.

was a unit in itself completely independent of the container and heating units. In most cases the bath resistivity devices consisted of two or more inert open-ended tubes connected together in a rigid manner. Platinum or tungsten electrodes, two to serve as current leads and two as voltage leads, were fastened rigidly to the tubes. This interconnected apparatus was placed into a large bath of molten material. Temperature regulation was accomplished by heating coils surrounding the large bath container.

Figure 3, page 36, shows a suitable bath resistivity device. As with the previously described tube device the voltage measuring electrodes were so placed to assure a homogeneous current density. In some cases the current leads were placed in inert tubes, but these were usually left free to contact the bulk of the bath in order to minimize total circuit resistance.

The same types of electrical circuits employed with tube resistivity devices were also used with bath resistivity equipment (see above, page 34).

Likewise, the methods employed to provide protective atmospheres over molten materials were similar to those used with tube devices (see above, page 35).

Electrodeless-type Measuring Devices[17]

Due to difficulties experienced with the standard types of electrode contact resistivity apparatus the indirect devices were

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[17] Taken from 17-19, 38, 64-68, 111-117).

developed. With these devices effects such as polarization, localized heating near electrodes, electrode contact problems, extraneous electromotive forces, etc., could be completely avoided.

All of the indirect electrodeless methods of resistivity measurement depend upon the interaction of a molten sample with a magnetic field. This interaction produces an eddy currents in the sample; these eddy currents can be examined by studying the "drag" or magnetic friction effect in a rotating magnetic field. Theory shows that such rotation can be related to the resistivity of the molten material by measurements of friction effects, and for similarly shaped molten material masses resistivities may be evaluated.

Most of the indirect magnetic apparatus are variations of a basic device consisting of a suitable furnace surrounded with one or more cylindrical coils. The sample, placed in a small crucible, is freely suspended to hang in the center of both the furnace and the coils (see Figure 4, page 39). The application of a rotating magnetic field on the molten sample causes eddy currents to be induced in the mass, and because of internal friction this induction results in a torque transmitted to the free suspension, thus causing rotation. The rotation momentum is obtained through the use of bucking coils or mirror arrangements. With some types of apparatus the molten material is freely suspended in an inhomogeneous magnetic field, and the interaction of the original and produced fields are measured and related to the resistivity.

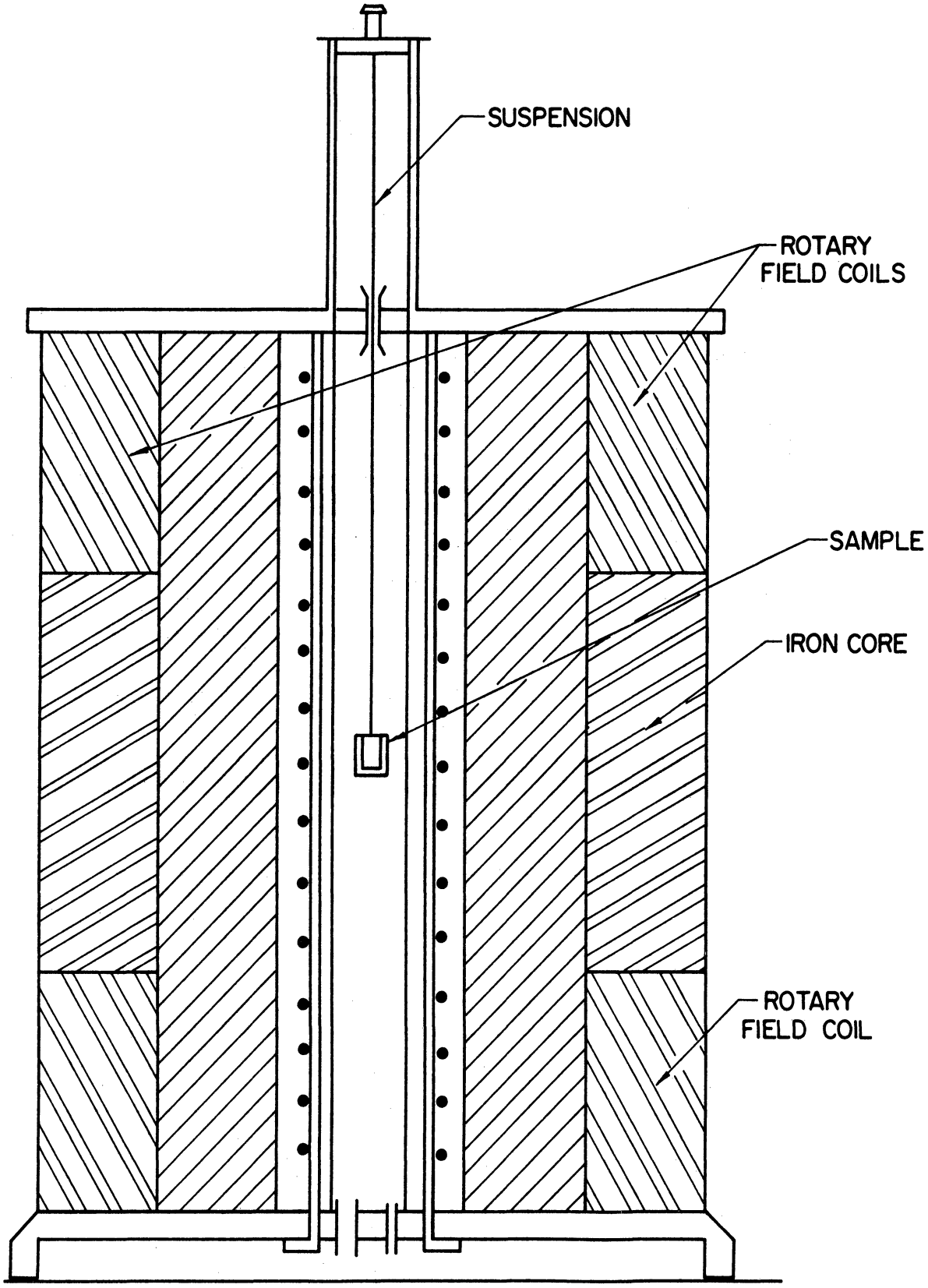

Figure 4. Electrodeless Resistivity Device.

Liquid Wire Measuring Apparatus

An unusual and ingenious device, differing in form from both the direct and indirect apparatus was used in a study on several pure, low-melting metals.

Pietenpol and Miley (103-106) first studied a phenomenon noticed earlier: certain metal wires, when suspended in air, could be heated by electric current to temperatures above melting without separation. The conclusion was that an elastic oxide coating was formed on the wire; the strength of the coating being sufficient to support an inner core of molten metal. By conducting measurements of the current and potential drop along the wire, and knowing the volume of the molten zone the resistivity-temperature relationship could be found.

The wire to be tested was first heated in air or oxygen to form and strengthen the oxide coating. It was then introduced into an inert atmosphere to prevent further oxidation. Currents, voltage, and temperature reading were taken and a small correction factor was applied for both the wire and coating to account for thermal expansion. Supplementary investigation showed that the current shunting effect through the oxide coating and the thickness of the coating were negligible in calculations of resistivity.

V. Calibration of Resistivity Apparatus Review

Electrical resistance is a measure of that property of a material which limits the amount of electrical current it can carry under a given voltage gradient. The unit of resistance is defined as the ratio of the unit of voltage to the unit of current. Resistance is an extensive property and the corresponding intensive property is the specific resistance or resistivity. Resistivity is generally defined as the resistance of a material of a specific shape: the resistivity is numerically equal to the resistance of a material measured between opposite sides of a cube of unit edge of material. With this basic definition, measurements of resistivity are further qualified with increasing temperature as:

1. Resistivity at constant pressure
2. Resistivity at constant mass
3. Resistivity at constant volume.

In general resistivity at constant property Z means that Z is held constant with temperature in the volume defined between the measuring electrodes.

Electrode-type Measuring Apparatus.[18] In the experimental measurement of resistivity values with electrode devices all values of resistance must be reduced into terms of resistance for a specifically shaped volume; i.e., the unit cube. The actual dimensions of the space between the voltage electrodes may be computed and reduced to that of the unit cube, and this reduction factor applied to all measured values.

[18] See footnote 15.

However, it is difficult to calibrate precisely the volume between the electrodes at a given temperature. Thus it has become common to first calibrate the electrode apparatus with a material of known resistivity. The ratio of the resistance values measured on the known material to the resistivity of the known material is a "correction factor" which can be applied reciprocally to experimental data resistances.

Mercury has usually been employed for such calibration measurements because of its well-known resistivity-temperature relationship; however, other pure metals such as tin have also served as calibration materials.

In addition to the resistance-resistivity correction factor a small correction has sometimes been employed to compensate for the thermal expansion at high temperatures of the measuring cell itself; if the calibration was made near room temperature.

Electrodeless-type Measuring Apparatus.[19] Braunbek (19) was the first to present a derivation of the theoretical aspects of the indirect magnetic apparatus. He noticed that the torque exerted on the molten material by the magnetic coil of the apparatus causes the crucible and suspension to rotate. The contents of the crucible also rotate, but with less angular velocity. The liquid immediately adjacent to the container walls rotates with nearly the velocity of the rotary field itself, and conducts this motion to the container wall:

$$\omega_f = f(r) \qquad (51)$$

[19] See footnote 17.

The eddy current drag on the molten cylinder is:

$$dM = \pi\rho(\omega-\omega_f)H'^2r^3dr \tag{52}$$

From the above and from a basic equation in hydrodynamics for frictional liquids, the eddy current torque is also:

$$dM = -2\pi\eta(d/dr)(r^3d\omega_f/dr)dr \tag{53}$$

Equating Equations (52) and (53):

$$(d/dr)(r^3d\omega_f/dr) = -\rho H'^2(\omega-\omega_f)r^3/2\eta \tag{54}$$

To the first approximation in Equation (54), ω_f in the right-hand term can be neglected in comparison to ω; the solution of this simplified equation can be formed assuming the following boundary conditions:

$$\left.\begin{aligned} &r = 0 \\ &d\omega_f/dr = 0 \end{aligned}\right\} \tag{55a}$$

$$\left.\begin{aligned} &r = R \\ &\omega_f = 0 \text{ (at container wall)} \end{aligned}\right\} \tag{55b}$$

as:

$$\omega_f = \rho H'^2\omega(R^2 - r^2)/16\eta \tag{56}$$

This result in Equation (56), when substituted into Equation (52) and integrated over $0 < r < R$, yields as the torque on the cylindrical material:

$$M = (\pi\rho\omega l'R^4H'^2/4) - (\pi\rho^2\omega l'R^6H'^4/192\eta) \tag{57}$$

or:

$$M = M_o(1 - \rho R^2 H'^2/48\eta) \tag{58}$$

where:

$$M_o = \pi\rho\omega l' R^4 H'^2/4 \tag{58a}$$

Then since:

$$V = lR^2 \tag{59}$$

by substitution of Equation (59) into Equation (58):

$$M = M_o(1 - M_o/12\eta\pi\omega V) \tag{60}$$

Either Equation (60) or Equation (57) is in suitable form to obtain resistivity values from measurements of angular velocity, material viscosity, magnetic field strength, and total torque.

VI. Resistance in Magnetic Field Review[20]

The influence of a magnetic field on the resistance of pure molten metals and liquid binary alloys has attracted long interest, the first work being done on this subject in 1891. The early workers in this area found that the application of such a field to liquid bismuth and mercury increased the resistance by small amounts. Orginally, this increase was considered to stem from secondary effects and probably due to the heating of the metal by the current passage. Later Berndt and others (6, 85, 118) discovered that the container size affected the change of resistance: the smaller the diameter of the capillary tube used, the smaller the resistance change. It was thought that the observed change was due mainly to unknown effects and that the actual resistance difference was close to zero.

Williams (146) has given a theoretical treatment of the problem in which the change in resistance is assumed to be caused by:

1. An actual resistance change.
2. A change dependent upon the energy required to maintain hydrodynamic currents set up in the liquid by the interaction of the magnetic field and the electrical current in the material.

An expression for the latter effect was calculated dimensionally, and shown to predominate over true resistance change in all experimental cases except mercury, bismuth, and bismuth amalgams. The variation of the change in resistance with current was found to be due to a

[20] Taken from (6, 34-35, 60-61, 85, 98, 118, 146).

turbulent motion of the material. In general, the total increase of resistance is:

$$\Delta\overline{\Omega} = G\overline{\Omega} + \overline{N}H'^{2}s'f'(\eta^{2}/H'Is'\rho)f''(L')/\eta \qquad (61)$$

Equation (61) was considered further for cases both of steady and turbulent liquid motion.

The experimental equipment for detecting the change of resistance in magnetic fields usually consisted of capillary spiral tubes or even straight tube sections which were placed between the poles of a magnet, and the resistance change noted with and without the field present by a type of standard electrode apparatus. The data were usually reported in terms of this resistance change with no standardized state given for conversion to absolute resistivities.

VII. Resistivity under Pressure Review[21]

A few early determinations on the resistivity of liquid mercury were conducted at relatively low pressures (under 200 atmospheres) in 1882, 1897, and 1898. Braunbek (18) and Birch (11) also experimented in limited fashion with the resistivity of mercury at various pressures and temperatures. Conclusions by these experimenters as to the nature of the change of resistivity with pressure (a decrease with increasing pressure) were not satisfactorily explained; furthermore, the resistivity-pressure relation did not seem to follow any simple law. Bridgeman (20-22) did the most extensive and accurate work on the resistivity-pressure-temperature relationship of mercury, and also experimented with other molten metals at high pressures: gallium, lithium, potassium, and sodium. Several "abnormal liquids" studied by Bridgeman underwent an increase in resistivity with both increasing temperature at constant pressure and increasing pressure at constant temperature. The normal metals had opposite behavior, similar to that found for mercury.

The entire experimental apparatus was generally contained in a pressure "bomb" with resistivity measurements conducted on capillary tubes which were subjected to hydrostatic pressure. Standard electrode-type devices were employed. The data reported are given mainly in terms of relative mass or volume resistivities with the standard taken as the resistivity at 0°C and at 0 atmosphere pressure.

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[21] Taken from (11, 18, 20-22)

VIII. Resistivity at Constant Volume Review[22]

All of the experimental studies reported in the literature have consisted of the determination of resistivity at constant pressure for different temperatures, i.e., the molten material is not constricted but is free to expand in the electrode region. Kraus (70) in 1914 considered the electron theory of metals as applied to the liquid state and calculated temperature coefficients of resistivity for mercury at constant volume from assumptions of the number of conducting charges per atom. He found that at constant volume the resistivity actually decreased with temperature--that the temperature coefficient was negative. Gubar and Kikoin (44) in a recent article also performed calculations on the resistivity of mercury at constant volume. These researchers stated that due to the widespread use of constant volume resistivities in theoretical work, experimental measurements should either be measured directly in terms of constant volume or should be converted from measurements at constant pressure to constant volume by:

$$1/\rho = (\partial\rho/\partial T)_V, = (\partial\rho/\partial T)_P/ - (\partial\rho/\partial P)_T, \alpha_T/\beta' \qquad (62)$$

These latter investigators also experimentally confirmed Kraus's contention on the negative temperature coefficient in mercury with constant volume.

The experimental apparatus (44) consisted of a standard capillary electrode-type device filled completely with the molten material at room temperature and sealed. Under increasing temperature

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[22] Taken from (44, 70).

the material was constrained to the capillary bore and the resistivity at constant volume was determined in the usual manner.

IX. Resistivity Data Compilation

This section presents a complete listing of most experimental resistivity data from 1902 to the present (early 1961). These data have been taken entirely from the entries in the Bibliography (see pages 243ff) and are presented separately for pure molten metals, molten binary alloys, and liquid amalgams. The experimental data are presented in tabular form whenever possible.

Discussion of Literature Resistivity Presentation

Among the articles of resistivity of various materials reported in the literature some ambiguity has occurred with the forms of presentation, particularly involving units of measurement.

Resistance is an electrical property of a material which is expressed as the ratio of the voltage across a body to the current through it. In the practical system of units, where voltage is expressed in terms of the volt, current as the ampere, resistance has the unit of ohms.

The resistivity, or specific resistance, is most commonly used in comparison of resistive properties of different materials. Resistivity is a measurement of the resistance of a substance of unit cross-section area and of unit length at a temperature of 0°C. Under these conditions the resistivity is numerically equal to the resistance offered by a cube of unit edge where the resistance is measured across two opposed faces. Although the unit of resistivity is the ohm-centimeter (resistance times cross-section area divided by length), many

hybrid units have been used and reported which are (incorrectly) based upon the above definition. Particularly common is the term "ohm per centimeter cube". In reality this unit is identical to the ohm-centimeter unit.

In an analgous manner a system of units based upon conductance and conductivity, the reciprocals of resistance and resistivity, are defined and have received some usage.

In consulting references on electrical resistivity the units in which the data are reported must be viewed with care. Most of the data are taken and reported in terms of resistivity at a constant pressure with temperature and composition varying. In a few articles relative resistivities are reported; if the standard value is also given a simple multiplication can yield true resistivities.

Form of Data Compilation

In each of the following subsections, the literature data are arranged as follows:

1. Pure Metals. Arranged alphabetically according to chemical symbol.
2. Binary Alloys. Arranged alphabetically according to chemical symbol of individual component.
3. Amalgams. Arranged alphabetically according to chemical symbol of non-mercuric component.

For each subsection listing, all appropriate sources of data are given in tabular form by reference number (referenced to listings in the Bibliography, pages 243ff). Those sources consulted by the writer and available from the University of Michigan Libraries are

indicated by an asterisk preceeding the number. These tables also contain information on investigator, year of investigation, type of apparatus employed,[23] and form of experimental data.[24]

A tabular listing of most of the available data is also given; each data set is identified by its reference number. In most cases, only reference data obtained from original tabular presentations are included; data taken from graphically-presented sources are enclosed between parentheses. Unless otherwise noted resistivity values are in units of microhm-centimeter (ohm-centimeter x 10^{-6}) at constant pressure, temperature values in degrees Centigrade, and composition values in weight percent.

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[23] E indicates measurement by a standard electrode-type device;
M indicates measurement by an indirect magnetic device; and
O indicates some other measurement method.

[24] T indicates tabular data;
G indicates graphical data.

DATA COMPILATION

PURE MOLTEN METALS

Table V . Literature Data on Resistivity of Silver

Temp	*16	*76	*92	*112	*139
960		17.3		17.25	
961			16.6		
962	18.7				
971					16.2
978					16.6
980		17.8			
996					16.7
1000	19.22		17.01	17.6	
1010		17.9			
1028		18.3			
1030					17.2
1050	19.86				
1083					17.8
1100	20.48		18.19	18.45	
1108		19.2			
1150	21.29				
1152		20.6			
1200	21.67		19.36	19.35	
1220		21.4			
1235					19.7
1250	22.24				
1257		21.7			
1300	22.79		20.54		
1340			21.01		
1350	23.30				
1400	23.80				

Table VI . Literature Data on Resistivity of Aluminum

Temp	*16	*76	*87	*112	*139
653	27.11		20.13		
654					20.1
658				24.2	
659		25.5			
662					19.6
670					20.5
686		26.0			
695					20.9
700	27.80			24.75	
710					21.0
715		26.4			
735					21.3
745		26.8			
765					21.7
774		26.8			

Table VII . Literature Data on Resistivity of Gold

Temp	*91	*112
1063	30.82	31.25
1077	31.00	
1100	31.34	31.8
1140	32.00	
1200	32.76	33.15
1217	33.00	
1218	33.00	
1300	34.76	
1400	35.58	
1500	37.00	

Table VIII . Literature Data on Resistivity of Bismuth

Temp	*25	*76	*94	*103	*112	*139
263			127.50			
269	141.7					
271		126.7			130.2	
278				124.430		
279		128.				
282						138.
289						127.
300			128.90	125.316	131.9	
301						128.
320				126.282		
324						128.
325		130.				
340				127.310		
350			131.55			
360				128.376		
375		133.				
376						129.
380				129.486		
396						131.
400		135.	134.20	130.711	137.6	
414						131.
420				132.000		
440		136.		133.513		
450			137.00			
460				135.224		
500			139.90		143.3	
526		141.				
550			142.50			
590		144.				
600			145.25		149.0	
639		147.				
650			148.00			
700			150.85		154.7	
709		151.				
750			153.55			
800					160.4	
900					166.1	
1000					171.8	

Table X . Literature Data on Resistivity of Cadmium

Temp	*16	*76	*94	*112	*121
321		32.2		34.7	
322	33.76				
325			33.76		
350			33.60		33.6
351		32.8			
392		32.8			
400	33.70		33.70	34.7	33.5
419		33.0			
450			33.90		33.6
457		33.2			
494		34.7			
500	34.12		34.12	35.2	33.8
528		34.2			
550		33.4	34.44		34.0
596		34.2			
600	34.82		34.82	36.3	34.4
650	35.26		35.26		
700	35.78		35.78		

Table XII . Literature Data on Resistivity of Cesium

Temp	*46	*47
28	37.2	
30		36.6
34		36.6
37		37.0
59	40.6	

Table XIII . Literature Data on Resistivity of Copper

Temp	*15	*16	*90	*112	*121	*139
1082			12.090			22.0
1083				21.1		
1084	20.36	21.38				
1088			13.210			
1092						22.0
1093			14.820			
1097			16.110			
1100	20.45	21.52	17.400	21.2	22.9	
1103			19.340			
1117			21.270			
1124						22.2
1143			21.880			
1150	20.81	21.97			24.0	
1157						22.4
1184						22.6
1200	21.19	22.41		22.1	25.1	
1202						22.9
1250	21.59	22.24			26.2	
1300	22.05	23.29			27.3	
1350	22.60	23.29				
1400	23.15	24.17				
1450	23.69					
1500	24.24	25.05				
1550	24.80					

Table XIV . Literature Data on Resistivity of Iron

Temp	*16	*107
1505	131.1	
1550	133.3	139
1600	135.7	139
1650	138.1	

Table XV . Literature Data on Resistivity of Gallium

Temp	*27	*46	*125
0	27.23		
18		28.0	
30		27.2	25.84
46		28.4	

Table XVI . Literature Data on Resistivity of Germanium

Temp	*28	*62
937	63.	60.

Table XVII . Literature Data on Resistivity of Mercury

Temp	*15	*19	*30	*57	*76	*83	*139	*147	*148
-39					93.1		85.4		
-35							90.1		
-32							91.0		
-25							92.8		
-23							93.2		
-19					94.8				
-18							93.4		
-11					95.2				
-6							93.8		
0		94.074	94.074	94.074	96.4		94.3	94.074	94.074
10				94.920					
12									95.047
13					97.5				
15			95.328						
17								95.507	
20				95.784			95.6		
26		96.238							
30				96.668					
35							96.6		
40				97.569					
44					100.				
50	98.54			98.490		98.30			
60				99.429					
63							99.4		
70				100.387					
77							100.6		
80				101.364					
90				102.359					
100	103.32		103.361	103.373	105.7	103.20		103.351	103.361
103							103.9		
109		103.952							
129								106.415	
145					110.7				
150	108.48					108.50			
169			110.863						
184								112.655	
187		112.607							
200	114.27				118.0	114.20			
217									116.742
221								117.194	
245		120.132							
250	123.44					120.70			
256			121.797					121.820	
258									121.975
275					128.8				
288								126.188	
297								127.509	
300	127.70		127.876			127.50			127.876
320					136.7				
350						135.50			
389		145.156							

Table XVIII . Literature Data on Resistivity of Indium

Temp	*112	*121	*133
154	33.1		29.10
157			29.28
167			29.66
182			30.11
199			30.84
200		33.8	
220			31.87
230			32.29
250		35.0	
261			33.31
280			34.87
300	36.75	36.2	
350		37.4	
400	39.3	38.7	
450		39.9	
500	41.9	41.2	
550		42.4	
600	44.45	43.7	
650		44.9	
700	47.0		
800	49.6		
900	52.2		
1000	54.75		

Table XIX . Literature Data on Resistivity of Potassium

Temp	*8	*15	*73	*83	*87
63	13.3647				13.35
63	13.7534				
64	13.8272	13.16		12.98	
64	13.4266				
65	13.7317				
65	13.8647				
68	14.2516				
69	13.8926				
75			14.43		
81	14.3580				
83	15.1419				
90	15.6052				
90	15.3748				
95	15.0089				
100		15.49	15.80	15.3	
105	15.5712				
106	16.2528				
109	16.6647				
115	16.7547				
120	16.3675				
122	16.6193				
129	17.6652				
130	17.5475				
130	17.1995				
150		18.70		18.53	
200		21.80		21.78	
250		25.00			
300		28.20			
350		31.40			

Table XX . Literature Data on Resistivity of Lithium

Temp	*7
181	40.5553
181	40.2933
183	40.3368
185	40.6002
186	40.9231
191	41.8586
196	41.8256
200	43.0012
200	42.8753
201	42.2989
208	43.5525
217	44.3250
219	44.4988
229	45.2603
232	45.6321
234	45.8281

Table XXI . Literature Data on Resistivity of Magnesium

Temp	*112	*121
650	27.4	
700	27.7	28.8
750		28.6
800	28.2	28.4
850		28.2
900	28.7	28.0

Table XXIII . Literature Data on Resistivity of Sodium

Temp	*9	*15	*47	*83	*87
98		9.60		9.75	9.656
99	8.8002				
100	9.0395	9.65		9.8	
111	9.3045				
116			10.2		
125	9.5037				
131	9.3216				
150		11.40		11.7	
200		13.18		13.58	
250		14.90			
300		16.70			
350		18.44			

Table XXIV . Literature Data on Resistivity of Nickel

Temp	*15
1451	108.0
1500	108.8
1550	109.9
1600	110.5
1650	111.5

Table XXV . Literature Data on Resistivity of Lead

Temp	*15	*16	*69	*76	*83	*94	*103	*112	*139
327	94.6	94.6		95.8	94.6			95.0	
328			66.6						
329			50.8						
330							96.735		
331			67.6						
332									48.7
333						95.00			
337									96.4
338			81.5						
340							97.867		
345			83.0						
346			82.9						
348				96.9					
349									101.
350	95.6								
358									100.
360							99.000		
365				97.6					
373									101.
380							100.255		
392			85.0						
400	98.0				98.0	98.30	101.418	98.2	
404			85.2						
408									102.
420				100.			102.563		
433			86.8						
440							103.716		
450	100.3		87.4			100.55			
453									104.
460			88.2				104.878		
463			87.9						
468									103.
468									105.
473				103.					
493									105.
500	102.6				102.6	102.85		102.9	
510			90.4						
524									106.
527				105.					
536									107.
550	104.9					105.05			
551			91.8						
561									107.
577			93.0						
578				108.					
600	107.2				107.2	107.25		107.6	
650	109.5					109.51			
682				112.					
700		111.8			111.8	111.75		112.35	
731				114.					
750						114.00			
776				117.					
800		116.4			116.4	116.20		116.9	
856				120.					
900		121.1			121.1			121.6	
1000		125.7			125.7			126.3	
1100		130.2							
1200		134.8							

Table XXVI . Literature Data on Resistivity of Rubidium

Temp	*46	*47	*73
40	24.5	19.6	
43		20.9	
50			23.15
64	26.5		
75			25.32
100			27.47

Table XXVII. Literature Data on Resistivity of Antimony

Temp	*15	*76	*94	*112	*139
627			117.00		
630		115.0		113.5	
631	127.80				
634					111.
638					110.
650			117.07		
656					111.
658		115.5			
690					110.
700	128.98		117.65	115.4	
708		116.1			
721					111.
746		116.4			
750	129.88		118.53		
755					113.
778					112.
800	130.76		120.31	118.1	
808		117.4			
810					113.
843					115.
850	131.70		123.54		
900	132.74			120.8	
910					119.
913		120.0			
938					120.
950	133.86				
990		121.9			
1000	134.98				
1009		122.1			
1050	136.20				
1100	137.62				
1150	139.07				
1200	140.49				

Table XXVIII . Literature Data on Resistivity of Selenium[28]
Data are in ohm-centimeter units.

Temp	*100
390	76650.
412	38925.
437	22340.
465	12300.
540	2247.
582	992.
645	237.
690	88.

Table XXX . Literature Data on Resistivity of Tin

Temp	*15	*16	*76	*94	*103	*112	*121	*121	*139
232	47.6	47.83	48.1		47.250	48.0			
235				47.60					45.
240					47.580				49.
250	47.9						48.3	45.4	
255									48.5
260					48.331				
265			48.6						
270									49.7
280					49.142				
295			49.5						
300	49.1	49.45		49.44	49.961	49.7	49.6	46.7	50.5
320					50.782				
325			50.1						
340					51.506				
350	50.3			50.76			50.8	47.8	
360					52.331				
379			51.3						
380					53.154				
385									52.2
400	51.4	51.60		52.00	53.980	52.2	52.0	49.1	52.8
420					54.807				
432			52.6						
440					55.633				
450	52.6			53.30			53.2	50.3	
460					56.458				
471									54.6
485			54.1						
500	54.0	53.85		54.62		54.7	54.5	51.5	55.5
550	55.5			55.94			55.7	52.7	
563			56.0						
600	56.8	56.05		57.22		57.2		54.0	
650	58.2			58.58				55.2	
668			59.0						
700		58.26		59.88		59.6		56.4	
718			60.0						
750				61.22				57.7	
783			62.1						
800		60.45				62.1		58.9	
837	61.21								
840	61.28								
850	61.50							60.1	
900		62.67				64.5		61.3	
987	64.60								
1000		64.98				67.0			
1100		67.20				69.5			
1200		69.45				72.0			
1218	69.80								
1300		71.70							
1370	73.20								
1390	73.62								
1400		73.98							
1435	74.65								
1472	75.49								
1500		76.24							
1600		78.51							
1617	78.81								

Table XXXI . Literature Data on Resistivity of Tellurium

Temp	*31	*46	*71
450	550.		
451			600.
460		17000	
464			564.
483			523.
500			496.
550	400.		

Table XXXII . Literature Data on Resistivity of Thallium

Temp	*112	*133
302	73.1	83.38
303		83.60
306		83.61
309		83.89
321		84.32
347		84.84
356		85.35
367		85.34
382		85.95
400	76.25	
402		86.78
422		87.54
500	79.1	
600	81.9	
700	84.8	
800	87.75	

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Table XXXIII . Literature Data on Resistivity of Zinc

Temp	*16	*69	*76	*94	*103	*112	*121	*139
418		32.8						36.7
419	35.30	33.3	37.0			37.4		
420		23.5						
423					36.955			
424								36.2
425								36.2
426		33.8						
427				37.30				
432		33.4						
436		33.7						
440					37.349			
445			37.1					
450				37.08			37.1	
460					37.783			
484			36.9					
491								36.2
499		33.4						
500				36.60		36.8	36.5	
519								36.2
539			36.7					
540		33.0						
549								36.2
550				36.20			36.2	
555		32.9						
570			36.5					
595		32.5						
600	35.65			35.90		36.3	36.0	
601		32.4						
623								36.2
627			36.7					
650				35.72			35.9	
669			36.8					
695			36.6					
700	35.70			35.60		36.4	36.1	
750				35.59			36.2	
800				35.60		36.7	36.4	
850				35.74			36.7	
900	35.75							

Table XXXV .

Literature Data on Resistivity of Silver-Copper Alloys

Temp	*16 1.70Ag
1073	21.16
1100	21.45
1150	21.95
1200	22.46
1250	22.96
1300	23.47
1350	23.97
1400	24.48

Table XLI .

Literature Data on Resistivity of Aluminum-Copper Alloys

Temp	*16 5.0Al	*16 10.0Al	*16 12.3Al	*16 15.0Al	*16 18.0Al	*16 22.3Al
925						73.91
989					72.57	
1021				67.57		
1027		58.52				
1065	43.00					
1100	43.18	58.22	62.50	66.72	70.08	70.27
1200	43.33	57.82		65.67	68.00	68.47
1300	43.57	57.40		64.61	66.22	66.95
1400	43.81			63.57		

Temp	*16 30.0Al	*16 45.0Al	*16 50.0Al	*16 67.2Al	*16 80.3Al	*16 95.0Al
542				38.21		
578			45.32			
592		48.30				
596					30.82	
600		48.32	45.45	39.03	30.87	
638						26.98
700		48.59	46.00	40.43	31.68	28.05
798	65.43					
800	65.44	48.85	46.57	41.83	32.52	29.78
900	65.52	49.11	47.11	43.22	33.34	31.49
1000	65.61	49.37	47.67	44.60	34.14	33.22
1100	65.70	49.64	48.22	45.97	34.95	34.96
1200	65.81	49.90	48.78	47.34	35.77	36.68
1300	65.92	50.16	49.33	48.73	36.57	38.39

Table XLVI .

Literature Data On Resistivity of Bismuth-Cadmium Alloys

Temp	*76 10.0Bi	*76 30.0Bi	*76 50.0Bi	*76 70.0Bi	*76 90.0Bi
201			108.4		
224				124.9	
245			109.3		
255				125.5	
264					131.0
270		78.6			
287				127.4	
295					132.2
300			111.0		
305		78.9	111.1		
325	48.4				
336				128.6	
342	48.5				
350					134.8
352		79.6			
376				129.5	135.3
378	48.3				
384			112.5		
399			114.5		
400	48.8				137.0
408		80.4			
431	49.0				
438			115.4		
443					139.3
471				133.5	
474	49.6				
479		80.7			
496				134.5	

Table XLVIII .

Literature Data on Resistivity of Bismuth-Lead Alloys

Temp	*83 1.2Bi	*76 10.0Bi	*76 30.0Bi	*76 50.0Bi	*76 70.0Bi	*76 90.0Bi
180				111.0		
213				112.9		
224					117.8	
250			108.6			
264						126.7
272					120.0	
275				116.0		
285						127.9
315		111.8				
318			118.1			
325		105.5				
326						129.7
357						131.6
358			114.1			
375				120.6	124.8	
376		108.8				
397						133.4
400	97.8					
405			116.0			
421				123.6		
428		112.7				135.0
438			118.8			
471		115.5				
480			121.5			
490					130.3	
498		116.8				
500	102.4					
600	107.0					
700	111.6					
800	116.2					
900	120.8					
1000	125.4					

Table XLIX .

Literature Data on Resistivity of Bismuth-Antimony Alloys

Temp	*76 30.0Bi	*76 60.0Bi	*76 90.0Bi
355			126.0
387			128.4
425			130.3
463			132.0
486			133.5
519		126.6	
530			135.6
562			136.5
563		128.4	
587	122.0		
608		129.7	
614	122.8		
630	123.6		
635		130.5	
664	124.4		
675	124.8		
677		132.4	

Table LI .

Literature Data on Resistivity of Bismuth-Tin Alloys

Temp	*76 10.0Bi	*76 30.0Bi	*76 50.0Bi	*76 70.0Bi	*76 90.0Bi
202		62.2	74.6		
224	52.2				
233			75.5		
235		63.4		96.6	
244	52.8				
260		63.8			
264				97.7	
265			76.8		
270					119.2
274	53.1				
285	53.5				
289		64.4			
290					120.3
291				98.6	
295		64.5	77.7		
302					120.7
305	53.9				
320					121.7
325			79.0	99.5	
344		67.2			
352					123.5
365			79.6		
375	55.8				
376				101.8	
392					124.1
407			81.1		
417				102.8	
455	58.0				
515		71.6			

Table LV . Literature Data on Resistivity of Carbon-Iron (Steel) Alloys

Temp	*16 0.2Fe	*16 1.2Fe	*16 3.8Fe	*43[29] 3.3Fe	*23[30] 3.8Fe	*23[31] 3.9Fe	*23[32] 3.9Fe
1060						200.	
1090							136.
1115					152.		
1123						200.	
1132						192.	
1135						180	
1137						169.	
1140					155.	148.	
1150						145.	142.
1155					153.		146.
1170							146.
1180							150.
1190			148.0				
1200			148.2		150.		
1240						146.	
1250						148.	
1300			150.3				
1310				160.	150.		
1350					152.		
1400			152.6				
1416		149.1					
1450		150.1	153.7				
1495	136.4						
1500	136.6	151.5	154.8				
1550	138.7	154.3	157.0				
1600	140.8	154.3	157.0				
1650	142.9	155.7					

[29] Sample composition: 93.032Fe, 3.337C, 2.752Mn, 0.783Si, 0.061P, 0.035S.

[30] Sample composition: 3.8C, 0.2Si, 0.2Mn, 0.1P, 0.02S, remainder Fe.

[31] Sample composition: 3.9C, 1.3Si, 0.2Mn, 0.1P, 0.02S, remainder Fe.

[32] Sample composition: 3.9C, 1.3Si, 0.2Mn, 0.1P, 0.0055S, 0.05Mg, remainder Fe.

Table LVI .

Literature Data on Resistivity of Cadmium-Copper Alloys

Temp	*16 58.0Cd	*16 63.0Cd	*16 68.5Cd	*16 72.6Cd	*16 76.2Cd	*16 81.0Cd
540		43.68				
547						42.86
549	42.14					
559					44.65	
563				44.56		
564			45.17			
600	41.65	42.97	44.45	43.89	43.97	42.42
650	41.18	42.35	43.44	52.96	43.14	42.00
700	40.71	41.77	42.43	42.07	42.31	41.57

Temp	*76 43.0Cd	*76 55.0Cd	*76 65.0Cd	*76 75.0Cd	*76 80.0Cd	*76 90.0Cd	*76 95.0Cd
419							36.2
466							36.1
486						40.0	
512						39.7	
525							35.8
537						39.7	
564						39.3	
568					42.0		
570							36.0
579			44.9				
580		41.1					
593				44.6			
600		40.8					
601			44.6				
604						39.1	
618		40.7					
619					42.6		
620							35.8
628			44.2			39.1	
629				43.6			
641							36.0
642		40.3					
645			43.4				
650					42.9		
670				42.8			
672						39.7	
675			43.3				
680	33.2			42.5	43.3		36.2
681		39.9					
692		39.8					
700			43.3	42.5			
703	35.5						
705		39.8					
719					42.6		
720				42.3			
731	36.7		43.3				
732				41.7			
745	37.7						
757	38.1						
812	39.9						
850	41.9						

Table LVII .

Literature Data on Resistivity of Cadmium-Sodium Alloys

Temp	*15 4.4Cd
122	15.30
150	16.18
200	17.71
250	19.25
300	21.24
350	23.36

Table LVIII . Literature Data on Resistivity of Cadmium-Lead Alloys

Temp	*83 1.4Cd	*83 2.9Cd	*76 10.0Cd	*76 30.0Cd	*76 50.0Cd	*76 70.0Cd	*76 90.0Cd
300		92.0					
302					68.5		
308						54.2	
314	93.2						
315			92.6				
324				80.9			
344					69.9		
350			93.8	81.8			
353							38.7
375						55.1	
390					71.2		
392				82.9			38.9
395			95.7				
400	97.1	96.5					
417					72.0		
419							38.7
420						55.7	
445							38.8
450					73.0		
454			97.9				
457				84.6			
460						56.4	
484						56.9	
489							38.7
493					74.2		
500	101.6	100.9					
515						57.0	
520				85.1			
521			101.7				
539						57.7	
557			102.8				
600	106.1	105.4					
700	110.6	109.8					
800	115.1	114.3					

Table LIX . Literature Data on Resistivity of Cadmium-Antimony Alloys

Temp	*76 20.0Cd	*76 30.0Cd	*76 40.0Cd	*76 50.0Cd	*76 60.0Cd	*76 70.0Cd	*76 80.0Cd	*76 90.0Cd
378							89.9	
387						130.0		
417						128.4		
428							89.6	
438						126.7		
451							89.5	
462						125.7		
470					161.5			
495							90.0	
496			169.6					
505							89.5	
513		149.6						
515				187.5				
516						123.2		
519					153.5			
524				183.6				
532								
535		146.9						62.6
541						122.7		
545		145.3						
550			160.0					
553				179.7				
570					148.0			
574	141.2							
585		143.3						
591						122.5		
599								63.0
600		142.2						
602	139.4							
609				172.7				
610					144.9			
619	140.0							
622								64.8
625			152.9					
631							89.6	
645	139.8							
650					143.2			
653								65.2
655				167.3			90.8	
665								64.4
690			149.7		142.4			
694	138.8							
705		139.6						
706				165.2				
753	138.0							
765			149.7					

Table LX .

Literature Data on Resistivity of Cadmium-Tin Alloys

Temp	*76 10.0Cd	*76 30.0Cd	*76 50.0Cd	*76 70.0Cd	*76 90.0Cd
185		52.7			
215		53.8			
228			54.9		
235	52.2				
250		54.2			
255	52.3				
258			55.6		
276				53.4	
280			56.2		
284	53.0				
289		55.6			
295				53.6	
300					41.0
305			56.7		
320	54.3				
330		56.4			
336			57.6		
345					41.4
356				54.8	
366	55.6				
367		56.8			
375					41.9
384				55.6	
392			59.0		
400					42.2
407				56.5	
440				57.1	42.5
475					43.0

Table LXI .

Literature Data on Resistivity of Cadmium-Zinc Alloys

Temp	*76 10.0Cd	*76 30.0Cd	*76 50.0Cd	*76 70.0Cd	*76 90.0Cd
308					36.1
320				38.1	
357			38.5		
359				38.0	
361					35.7
380			37.9		
393		39.4			
406				37.9	
420	36.4				35.6
443			37.5		
449		38.4			
463				37.8	
466	36.2				35.0
480		37.6	37.1		
490					36.1
502	37.4				
509					35.3
511			36.8		
516				37.8	
538		37.6			
555			36.8		
568				37.8	
576	37.1				
588		36.6			
593			36.8		
608		36.3			
618	37.4				
627	37.6				

Table LXIII .

Literature Data on Resistivity of Copper-Nickel Alloys

Temp	*15 13.8Cu	*15 35.0Cu	*15 50.1Cu	*15 81.1Cu
1187				53.7
1200				53.8
1250				54.4
1300				55.5
1326			93.0	
1350			93.6	57.2
1358		136.7		
1400		138.5	94.7	59.2
1419	120.0			
1450	120.6	140.6	95.9	62.6
1500	121.7	142.7	97.1	66.5
1550	122.7	145.0	98.2	70.0
1600	123.8	147.2	99.5	
1650	125.0		100.6	

Table LXIV . Literature Data on Resistivity of Copper-Lead Alloys

Temp	*16 2.0Cu	*16 9.1Cu	*16 11.1Cu	*16 60.6Cu	*16 63.7Cu	*16 64.0Cu	*16 83.1Cu	*16 97.1Cu	*16 98.0Cu
657	111.4								
700	113.2								
800	117.4								
900	121.6								
1000	125.8								
1010							41.26		
1021						60.02			
1072								24.71	
1075									23.74
1098					63.32				
1100	130.1					60.82	42.13	25.06	24.01
1117		118.9							
1200	134.2	121.3			64.29	61.90	43.10	26.21	25.1
1300	138.5	124.1	124.2	66.69	65.31	62.98	44.04	27.37	26.?
1305				66.79					
1400	142.7	126.1	127.1	67.57	66.27	64.05	44.98	28.53	27.31
1500				68.46	67.26		45.92		

Table LXV . Literature Data on Resistivity of Copper-Antimony Alloys

Temp	*15 1.2Cu	*15 20.0Cu	*15 30.0Cu	*15 50.6Cu	*15 60.6Cu	*15 66.7Cu	*15 76.4Cu	*15 83.2Cu	*15 98.1Cu
533		116.44							
543			119.40						
600		118.10	118.40						
625	122.90								
639						140.01			
650	123.49	119.30	119.60						
655				147.00					
682					152.20				
700	124.70	120.50	120.80	146.64	151.70	139.18			
750	125.90	121.70	122.00	146.26	150.30	138.46			
800	127.10	122.92	123.20	145.90	148.97	137.79			
815							104.50		
850	128.31	124.10	124.40	145.71	147.90	137.10	104.29		
885								84.00	
900	129.60	125.39	125.59	145.64	146.90	136.40	103.99	84.09	
950	130.94	126.70	126.78	145.63	146.14	135.63	103.64	84.31	
1000	132.36	128.10	127.08	145.68	145.38	134.60	103.39	84.59	
1050	135.90	129.60	129.17	145.82	144.85	133.60	103.21	84.79	
1070									29.00
1100		131.16	130.40	146.00	144.39	132.60	103.19	85.08	29.24
1150		132.70	131/58	146.39	143.90	131.50	103.19	85.34	29.97
1200			132.78	146.80	143.40	130.50	103.19	85.59	30.18
1250								85.84	30.62
1300								86.11	31.12
1350									31.64
1400									32.16
1450									32.68
1500									33.19

	*76 10.0Cu	*76 30.0Cu	*76 40.0Cu	*76 50.0Cu	*76 60.0Cu	*76 65.0Cu	*76 70.0Cu	*76 80.0Cu
588		115.5						
589	106.5							
617		115.8						
622			126.5					
627	106.5							
640			127.2					
647				130.0				
651							123.5	
653	107.5							
658			127.5					
659		116.5						
668						136.8		
678				130.5				

Temp	*76 10.0Cu	*76 30.0Cu	*76 40.0Cu	*76 50.0Cu	*76 60.0Cu	*76 65.0Cu	*76 70.0Cu	*76 80.0Cu
682					142.6			
683	108.0							
696							124.5	
697			128.1					
698		117.5						
705					141.3			
707						135.9		
712							124.6	
718					140.9			
723				129.5				
730			128.7					
736						135.2		
741							125.2	
742	109.6							
743					140.7			
747		118.5						
766				129.8				
775		118.9				135.0		
784							125.5	
788			130.0					
797				129.4				
830				129.7		134.2		
836							126.2	
854					138.4			
856								95.2
861						134.0		
880					138.0			
886								96.0
902								96.1
924								97.2
941								96.0

Table LXVI . Literature Data on Resistivity of Copper-Tin Alloys

Temp	*16 20,0Cu	*16 40.0Cu	*16 57.5Cu	*16 61.6Cu	*16 80.0Cu	*16 95.2Cu	*16 98.0Cu
544	58.51						
600	59.80						
619		66.62					
700	61.90	67.40					
705			76.02				
721				75.00			
800	63.98	68.45	74.95	74.02			
883					58.50		
900	66.02	69.45	74.20	73.05	58.53		
1000	68.04	70.50	73.75	72.50	58.72		
1054						32.26	
1070							25.17
1100	70.08	71.75	73.40	72.22	58.92	32.71	25.51
1200	72.10	73.10	73.40	72.08	59.11	33.63	26.53
1300	74.15	74.50	73.80	72.15	59.30	34.54	27.55
1400	76.20	75.90	73.95	72.32	59.47	35.47	28.57
1500				72.60	59.63		

Temp	*76 10.0Cu	*76 20.0Cu	*76 30.0Cu	*76 40.0Cu	*76 50.0Cu	*76 60.0Cu	*76 70.0Cu	*76 80.0Cu
411	53.8							
435	55.4							
505	55.8							
545	57.0							
548		58.7						
587		59.6	63.1					
594	58.0							
602			63.3					
610		60.2						
617				68.2				
632			63.8					
637	58.9			69.3				
648		60.8						
667			64.4	69.5				
680					71.1			
705				69.7				
708		61.4						
717					70.7			
721						75.4		
728					70.9			
733				69.9				
742						75.5		
749							72.9	
753			66.4		71.1			
768						74.8		
784		63.0						
787			66.1					
790						74.3		
799					70.9			
805				70.6			72.4	
807						73.9		
822					70.0	73.6	71.6	
842							71.3	
858								60.2
866								60.1
870								60.6
871							71.1	
884								60.6
898							70.8	
908								60.6
921								60.2
938							70.5	
941								60.6

Table LXVIII .

Literature Data on Resistivity of Copper-Zinc Alloys

Temp	*76 10.0Cu	*76 30.0Cu	*76 40.0Cu	*76 50.0Cu	*76 60.0Cu	*76 79.0Cu
591	40.5					
665	39.8					
697	39.4					
750	39.3					
762	39.0					
787		48.7				
800	38.7					
818		49.9				
827			49.9			
838		49.4				
840			49.5			
868				47.6		
875		49.4				
877			49.2			
880				47.3		
893			48.5			
895					44.7	
921			48.3			
923					45.3	
927			48.0			
928				46.4		
936		48.0				
940					45.0	
951				48.5		
974			47.2	45.6		
984					45.7	
989						37.8
1016					46.0	
1021					45.8	
1024				44.6		
1038						38.7
1050					46.1	
1068						38.7
1098						39.1
1111						39.6

Temp	*16 15.0Cu	*16 34.0Cu	*16 39.3Cu	*16 46.2Cu	*16 60.4Cu	*16 80.0Cu	*16 85.0Cu	*16 96.5Cu	*16 99.1Cu
637	44.83								
700	44.04								
800	42.78								
813		48.72							
830			49.13						
850	42.17	47.87	48.59	48.10					
900	41.56	46.69	47.35	46.95	43.90				
994						33.02			
1000		44.34	45.53	44.62	42.36	33.03			
1017							29.40		
1069								22.80	
1080									21.83
1100						33.44	29.87	23.13	22.03
1200						33.83	30.43	24.23	23.03
1300								25.33	24.03

Table LXIX .

Literature Data on Resistivity of Gallium-Indium Alloys

Temp	*125 77.5Ga	*125 84.5Ga	*125 92.0Ga
20	27.2	26.7	26.3

Table LXXI .

Literature Data on Resistivity of Gallium-Tin Alloys

Temp	*125 88.1Ga	*125 91.8Ga
20	27.3	26.7

Table LXXIV . Literature Data on Resistivity of Potassium-Sodium Alloys

Temp	*127 82.1K	*83 6.7K	*83 12.9K	*83 37.4K	*83 57.5K	*83 73.3K	*83 85.8K	*83 95.3K
-13						35.65		
7					35.75			
9	40.4							
10	40.9							
12	41.4							
14	41.4							
15	41.8							
17							32.40	
18	42.0							
20	42.0							
25	42.1							
30	42.6			28.75				
35	43.2							
40	43.3							
42								20.82
50				29.73	38.18	39.00	34.38	21.48
71			17.25					
82		13.05						
100		13.80	18.46	32.22	40.97	41.90	37.40	24.33
150		15.90	20.55	34.72	43.73	44.80	40.70	27.50
200		18.02	22.65	37.20	46.51	47.65	44.40	30.95

Table LXXV .

Literature Data on Resistivity of Potassium-Lead Alloys

Temp	*15 0.4K
319	93.60
350	95.76
400	99.24
450	102.72
500	106.21
550	109.70
600	113.22

Table LXXVI .

Literature Data on Resistivity of Potassium-Rubidium Alloys

Temp	*73 10.0K	*73 14.4K	*73 26.0K	*73 45.1K	*73 60.3K	*73 73.3K
50	22.57	22.28	21.14	19.01	16.89	
75	24.57	24.15	22.28	20.75	18.42	17.45
100	26.39	26.05	24.75	22.52	19.84	18.98

Table LXXVII .

Literature Data on Resistivity of Potassium-Tin Alloys

Temp	*15 0.2K
245	49.02
250	49.10
300	50.09
350	51.08
400	52.58
450	54.18
500	56.00
550	57.90

Table LXXVIII .

Literature Data on Resistivity of Potassium-Thallium Alloys

Temp	*15 94.7K
110	21.30
150	26.40
200	30.36
250	35.36
300	40.39
350	45.40

Table LXXX .

Literature Data on Resistivity of Sodium-Lead Alloys

Temp	*15 91.8Na
185	24.00
200	24.74
250	27.10
300	29.52
350	31.91

Table LXXXI .

Literature Data on Resistivity of Sodium-Antimony Alloys

Temp	*15 99.5Na
104	10.24
150	12.04
200	14.02
250	16.00
300	18.00
350	20.10

Table LXXXII .

Literature Data on Resistivity of Sodium-Tin Alloys

Temp	*15 0.1Na
231	47.61
250	48.18
300	49.71
350	51.20
400	52.71
450	54.21
500	55.75

Table LXXXIII .

Literature Data on Resistivity of Sodium-Thallium Alloys

Temp	*15 92.4Na
93	20.40
100	20.48
150	22.32
200	24.10
250	26.00
300	28.24
350	30.58

Table LXXXV . Literature Data on Resistivity of Lead-Antimony Alloys

Temp	*76 30.0Pb	*76 40.0Pb	*76 50.0Pb	*76 60.0Pb	*76 80.0Pb	*76 90.0Pb	*83 81.6Pb	*83 98.0Pb	*83 99.2Pb
253							96.9		
300								93.0	
307						101.7			
315									94.1
333					106.7				
339						102.3			
380					108.8				
400							102.6	97.6	97.9
422						104.7			
459				116.0					
485			116.0						
489			116.4						
494				116.0					
500							106.5	102.2	102.5
509			117.0						
519						108.2			
526		114.9							
527					112.9				
531		115.1							
548				117.6					
550		115.7							
551			118.2						
566	116.7								
575	117.3				114.5				
588						109.4			
590			118.5						
600							110.3	106.8	107.1
602	117.5								
610					115.3				
617				118.6					
618		116.9							
631	116.2								
643		117.5							
647			120.7						
653						112.5			
670	118.4				118.2				
684			120.7	120.3					
690						114.5			
700							114.1	111.4	111.6
717			122.5						
742				121.5					
800							118.1	115.9	116.2
900							122.3	120.1	120.8
1000							126.3	125.1	125.3

Table LXXXVI . Literature Data on Resistivity of Lead-Tin Alloys

Temp	*15 1.7Pb	*15 3.2Pb	*76 10.0Pb	*76 30.0Pb	*76 50.0Pb	*76 80.0Pb	*76 90.0Pb
224		48.66					
228	48.38						
243			50.6				
250	46.90	49.13					
254					63.4		
263				57.1			
265			51.2				
285					64.3		
295				57.8			
300	50.00	50.48					
307			52.2				
315					65.8		
325							87.4
336				59.0			
346							89.5
350	51.14	51.69					
357			53.4				
363					66.5		
368				60.1			
375			53.8				
376					67.2		
380						80.0	
395							92.1
399				61.1			
400	52.30	52.91					
404			54.2				
415						81.1	
427							93.0
446				62.3			
450	53.45	54.20					
457							94.0
474						83.4	
495							96.2
500	54.68	55.50					
550	56.00	56.80					
600	57.50	58.13					
650	59.08	59.42					

Temp	*83 10.5Pb	*83 59.9Pb	*83 75.8Pb	*83 88.5Pb	*83 95.1Pb	*83 98.2Pb	*83 99.3Pb	*83 99.3Pb
208	48.0							
236		65.8						
264			73.2					
288				82.3				
300	50.4	67.5	74.4	82.8				
309					90.7			
321						92.5		
325							93.0	
327								93.7
400	52.8	70.3	77.8	86.8	94.6	96.0	96.4	97.1
500	55.6	73.2	81.2	90.8	98.8	100.5	100.9	101.7
600	58.4	76.1	84.5	94.8	103.1	104.9	105.4	106.2
700	61.4	78.9	87.8	98.8	107.3	109.4	109.9	110.7
800	64.4	81.9	91.2	102.7	111.5	113.8	114.4	115.2
900	67.4	84.8	94.6	106.7	115.7	118.3	118.9	119.7
1000	70.4	87.7	98.0	110.7	120.0	122.7	123.5	124.2

Table LXXXIX . Literature Data on Resistivity of Lead-Zinc Alloys

Temp	*83 79.6Pb	*83 82.3Pb	*83 88.5Pb	*83 92.6Pb	*83 93.6Pb	*83 96.6Pb	*83 97.7Pb	*83 98.6Pb	*83 99.5Pb
235									93.2
400								94.8	96.7
438							95.6		
500							98.0		101.4
515						97.5			
588					99.1				
600				96.9	99.5	101.1	102.2		106.2
602				97.0					
648			97.7						
700			99.7	100.7	103.8	105.3	106.4	108.8	110.8
728		90.2							
783	87.7								
800	88.1	92.0	103.5	104.6	108.0	109.6	110.5	113.5	115.5
900	90.6	94.55	107.4	108.5	112.2			118.1	120.2
1000								122.8	124.9

Table XCI .

Literature Data on Resistivity of Antimony-Tin Alloys

Temp	*15 1.1Sb	*76 10.0Sb	*76 20.0Sb	*76 40.0Sb	*76 60.0Sb	*76 90.0Sb
234	48.16					
250	46.10					
277		57.0				
300	49.88	57.9				
350	51.16		65.4			
360		59.4				
400	52.40					
406			66.8			
415		60.7				
430				79.1		
450	53.69					
470				80.0		
479			68.6			
500	54.95				94.8	
509					95.1	
529						
539		63.3	69.8			
550	56.28					
580					95.2	
594			71.1			
600	57.62					
601				81.9		
637						115.3
638					96.0	
640				82.5		
677						116.0
687				84.3		
692					96.2	
716						116.7
738					97.7	
773					97.8	
816						118.4
855						118.4

Table XCII . Literature Data on Resistivity of Anitmony-Zinc Alloys

Temp	*76 10.0Sb	*76 20.0Sb	*76 30.0Sb	*76 40.0Sb	*76 .55.0Sb	*76 60.0Sb	*76 65.0Sb	*76 80.0Sb	*76 90.0Sb
447	48.8								
478	48.5								
508	48.3								
521			107.5						
527				134.0					
530								154.7	
540				133.2					
550	48.3								
556							191.7		
560			105.6						
570		68.3		129.9					
571							186.2		
579						163.1			
580					151.9				
584								152.9	
590			104.8						
599		68.3							
600	48.7								
605						157.4			
610			104.8						
611				127.2					
612									132.6
622		68.3							
627							169.5		
630	49.2								
647						153.9			
648								149.1	
651									131.8
653			123.6				163.6		
658					145.9				
661		68.3							
678							159.7		
679								147.4	
690			101.7						133.4
691				121.5					
695		68.3							
702					142.8				
708						148.9			
713				121.0					
715								146.9	
720							154.6		
731						145.7			
734								146.3	
742							152.0		
766									136.0
769									136.1
770					138.9				
774						142.5			

Table XCV .

Literature Data on Resistivity of Tin-Zinc Alloys

Temp	*76 10.0Sn	*76 30.0Sn	*76 60.0Sn	*76 90.0Sn	*15 98.9Sn	*15 99.5Sn
232						47.58
250						48.02
260				49.5		
293				50.4		
300						49.36
328				51.7		
350						50.71
369				52.2		
378			49.1			
390		43.5				
397				52.9		
400						52.02
403			49.9			
423	38.6					
430		43.8				
436				53.7		
441			50.3			
443	38.6					
450						53.35
480		44.0				
490			51.0			
496	38.3					
500					54.15	54.64
511		44.5				
532			52.4			
545	38.1					
549		44.3				
550					55.29	56.00
569		44.6				
588	37.8					
599		44.8				
600					56.42	57.30
619	38.0					
650					57.60	58.61

LIQUID AMALGAMS

Table XCVII .

Literature Data on Resistivity of Aluminum Amalgams

Temp	*30 0.01Al	*30 0.02Al
300	127.405	126.992

Table XCVIII . Literature Data on Resistivity of Gold Amalgams

Temp	*148 0.04Au	*148 0.06Au	*148 0.08Au	*148 0.12Au	*148 0.16Au	*148 0.20Au	*148 0.24Au	*148 0.28Au	*148 0.32Au
12	94.90	94.81	94.75	94.56	94.40	94.27	94.07	93.94	93.81
100	103.13	103.01	102.87	102.64	102.43	102.17	101.97	101.79	101.63
217				115.77			114.95		
258				120.87			120.07		
300	127.43	127.22	127.04	126.66	126.34	126.02	125.80	125.57	125.39

Table CII .

Literature Data on Resistivity of Calcium Amalgams

Temp	*15 0.12Ca
50	97.02
100	101.78
150	106.80
200	112.50
250	118.43
300	126.00

Table CIII .

Literature Data on Resistivity of Cadmium Amalgams

Temp	*15 0.56Cd	*15 1.72Cd
50	94.62	87.70
100	99.30	91.76
150	104.38	96.10
200	109.84	100.98
250	116.22	107.00
300	123.00	113.70

Table CIV .

Literature Data on Resistivity of Cerium Amalgams

Temp	*30 0.01Ce	*30 0.02Ce	*30 0.03Ce
300	127.720	127.655	127.611

Table CVII .

Literature Data on Resistivity of Copper Amalgams

Temp	*148 0.01Cu	*148 0.02Cu	*148 0.02Cu	*148 0.03Cu	*148 0.03Cu	*148 0.04Cu
12	94.93					
100	103.18	103.08				
300	127.53	127.36	127.21	127.08	126.91	126.80

Temp	*148 0.04Cu
300	126.61

Table CIX .

Literature Data on Resistivity of Germanium Amalgams

Temp	*30 0.01Ge	*30 0.02Ge	*30 0.02Ge	*30 0.03Ge
302	127.933	127.838	127.762	127.691
250		120.729		

Table CX .

Literature Data on Resistivity of Indium Amalgams

Temp	*125 2.9In	*125 6.0In	*125 9.2In	*125 12.5In	*125 16.0In	*125 19.7In
20	79.3	68.6	61.4	55.9	51.8	48.7

Temp	*125 23.6In	*125 27.6In	*125 31.9In	*125 36.4In	*125 41.2In	*125 46.2In
20	46.2	44.0	42.2	40.5	39.0	37.6

Temp	*125 51.5In	*125 57.2In
20	36.3	35.0

Table CXI .

Literature Data on Resistivity of Potassium Amalgams

Temp	*13 0.01K	*13 0.02K	*13 0.04K	*13 0.04K	*13 0.04K	*13 0.05K
30	97.18	97.77	98.63	98.79	98.33	98.49

Temp	*13 0.06K	*13 0.06K	*13 0.07K	*13 0.09K	*13 0.09K	*13 0.10K
30	98.79	99.31	99.59	100.40	99.10	99.49

Temp	*13 0.11K	*13 0.11K	*13 0.12K	*13 0.14K	*13 0.16K	*13 0.17K
30	99.59	100.10	100.20	100.80	101.20	101.70

Temp	*13 0.18K	*13 0.20K	*13 0.21K	*13 0.21K	*13 0.21K	*13 0.23K
30	100.20	101.00	100.90	101.40	101.60	102.00

Temp	*13 0.25K	*13 0.27K
30	102.77	103.57

Temp	*83 1.65K	*83 3.52K	*83 6.56K	*83 8.56K	*83 9.62K	*83 11.92K	*83 21.34K	*83 39.45K	*83 79.35K
57									37.10
63	128.80								
88								130.20	
100	133.95							132.80	41.30
150	140.80							142.50	46.12
162		165.76					240.25		
200	147.80	170.18					241.50	152.75	51.00
250	155.18	176.38					243.20	163.18	55.85
256						232.60			
262			197.80						
283					208.50				
287				199.90					
300	162.75	183.95	203.90	202.25		237.00	244.70	173.60	60.70
350	170.60	192.18	213.45	211.95	222.00	242.00	246.18	184.05	65.58
400			223.40	221.50	232.00				
450			233.00						

Table CXII

Literature Data on Resistivity of Lithium Amalgams

Temp	*13 0.00Li	*13 0.00Li	*13 0.01Li	*13 0.01Li	*13 0.01Li	*13 0.01Li
30	100.60	100.90	100.70	98.79	97.81	98.68

Temp	*13 0.01Li	*13 0.01Li	*13 0.01Li	*13 0.02Li	*13 0.02Li	*13 0.02Li
30	98.04	97.77	103.00	102.80	101.50	101.40

Temp	*13 0.02Li	*13 0.03Li
30	99.20	97.77

Temp	*15 0.00Li	*15 0.02Li	*15 0.04Li
50	98.82	98.32	97.50
100	103.80	103.10	101.50
150	109.21	108.32	107.00
200	115.40	114.18	112.70
250	122.18	120.70	119.20
300	129.54	127.70	125.90

Table CXV

Literature Data on Resistivity of Sodium Amalgams

Temp	*15 0.11Na	*83 0.11Na	*83 0.39Na	*83 0.95Na	*83 3.03Na	*83 4.85Na
50	99.76		100.30			
56				98.10		
100	102.74	103.75	105.95	102.90		
150	110.20	109.25	111.65	108.40		
200	116.56	115.00	117.50	113.80		
250	123.60	121.50	123.90	119.10	110.70	
300	131.40	128.50	120.90	124.30	115.00	
350		135.90	138.60	129.75	119.25	110.15
353						110.15
400					123.60	112.60
450						115.05

Temp	*83 5.70Na	*83 7.44Na	*83 17.35Na	*83 32.00Na	*83 58.70Na
48				105.60	
65					50.40
100				107.40	51.60
113			122.90		
150				109.10	53.25
200			127.00	118.00	54.95
250			129.65	112.55	56.60
300			132.35	114.30	58.25
321		126.40			
350		128.05	135.00	116.00	59.95
360	122.00				
400	123.80	130.95		117.80	61.62
450	126.20	133.80			
500		136.60			

Temp	*26 0.04Na	*26 0.05Na	*26 0.08Na	*26 0.11Na	*26 0.14Na	*26 0.21Na
0	94.29	94.38	94.48	94.57	94.71	94.80
20	96.01	96.14	96.22	96.33	96.48	96.67
78	101.55	101.66	101.81	101.97	102.12	102.36
100	103.73	103.87	104.05	104.21	104.40	104.61
185	113.23	113.40	113.61	113.88	114/17	114.34
226	118.41	118.57	118.75			
255	122.40	122.65	122.93			

Temp	*26 0.26Na	*26 0.30Na	*26 0.35Na	*26 0.46Na	*26 0.60Na
0	94.81	94.78	94.84	94.66	93.75
20	96.64	96.59	96.68	96.50	96.22
78	102.34	102.35	102.43	102.22	101.85
100	104.56	104.61	104.68	104.48	104.10
185	114.41	114.36	114.37	113.95	113.39
226					118.19
255					122.59
302				130.21	130.29

Table CXVIII .

Literature Data on Resistivity of Antimony Amalgams

Temp	*30 0.01Sb	*30 0.02Sb	*30 0.02Sb	*30 0.03Sb
302	127.984	127.915	127.838	127.761

Table CXXIII . Literature Data on Resistivity of Thallium Amalgams

Temp	*30 0.06Th	*30 0.13Th	*30 0.23Th	*30 0.38Th	*30 0.50Th	*30 0.75Th	*30 1.00Th	*15 1.03Th	*15 2.91Th
13	95.083	94.963	94.727	94.492	94.278	93.820	93.375		
50								96.58	93.20
100	103.216	103.076	102.800	102.517	102.249	101.698	101.159	101.12	97.41
150								106.22	102.10
183					110.910				
200								111.79	107.00
250								118.20	112.08
256					119.788				
295					124.448				
300								125.14	118.20

Temp	*125 5.10Th	*125 10.20Th	*125 15.20Th	*125 20.30Th	*125 25.40Th	*125 30.40Th	*125 35.40Th	*125 40.50Th
20	87.0	80.3	75.5	72.4	70.2	69.0	67.9	67.3

Table CXXIV .

Literature Data on Resistivity of Yttrium Amalgams

Temp	*30 0.01Y	*30 0.02Y	*30 0.03Y	*30 0.04Y
302	127.943	127.849	127.701	127.494

X. Bibliography

This section presents an extensive bibliography on the resistivity of molten metals, molten binary alloys, and liquid amalgams. It is believed that the bibliography is complete over the years 1900 to the present (February 1961).

The writer has thoroughly searched the various abstract services (Chemical Abstracts, Metallurgical Abstracts) and has furthermore investigated all cross-references within each reference source consulted. All pertinent references are found below.

Form of Bibliographic Entries

The individual entries are arranged numerically by author surname; for multiple authorship, surname arrangement is according to article by-line. All entries available from the University of Michigan Libraries are indicated by the appearance of an asterisk preceeding the reference number. A standard form of entry is used. Following this, all non-English articles consulted are indicated by language of origon. With available references from the Libraries, the particular Library and call number are next indicated according to the code:

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GL: General Library

Phy: Physics Library

T: Transporation Library

The call number proper is given in parentheses, preceeded by

the code letter. For all entries located through one of the abstract services, this is noted next, by the codes:

CA: Chemical Abstracts

MA: Metallurgical Abstracts

The proper code is followed by the abstract volume number and, separated by a colon, the column (or page) number.

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