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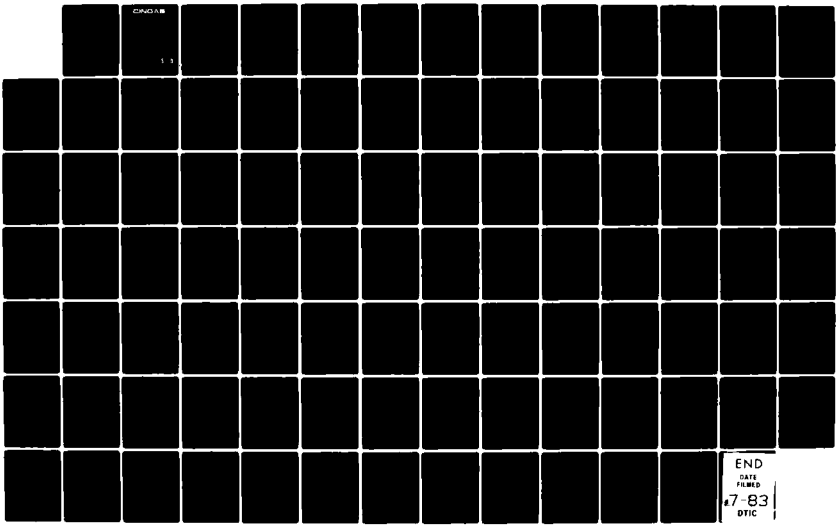

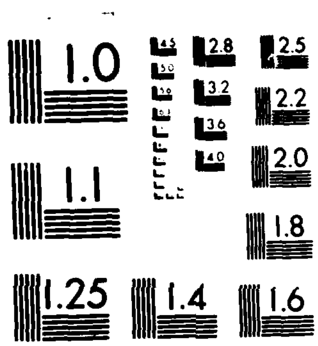

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ELECTRICAL RESISTIVITY OF ALUMINUM AND MANGANESE

By

P. D. Desai, H. M. James, and C. Y. Ho

CINDAS Report 65

March 1983

Prepared for

OFFICE OF STANDARD REFERENCE DATA
National Bureau of Standards
U.S. Department of Commerce
Washington, D.C. 20234

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PREFACE

This technical report was prepared by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under the auspices of the Office of Standard Reference Data of the National Bureau of Standards (NBS), Department of Commerce, Washington, D.C.

This report represents the most exhaustive compilation and critical evaluation of the recorded world knowledge on the electrical resistivity of aluminum and manganese and is one of a series of technical reports on the electrical resistivity of selected elements. The literature search and data compilation have been done in a most extensive and detailed manner, making it possible for all users of the subject to have access to the original data without having to duplicate the laborious and costly process of literature search and data extraction. Also, for the active researchers in the field, a detailed discussion is presented for each material, reviewing the available data and information, giving details of data analysis and synthesis, and discussing the considerations involved in arriving at the final recommended values.

It is hoped that this work will prove useful not only to the engineers and scientists in the field but also to other engineering research and development programs and for industrial applications, as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is thought that the critical evaluation, analysis and synthesis, and reference data generation constitute a unique aspect of this work.

Although this report is primarily the result of financial support and interest of the NBS Office of Standard Reference Data, the extensive documentary activity essential to this work was supported by the Defense Logistics Agency of the Department of Defense. Thanks are due Dr. H. J. White, Jr., of the NBS Office of Standard Reference Data for his guidance, cooperation, and sympathetic understanding during the course of this work.

ABSTRACT

This work compiles, reviews, and discusses the available data and information on the electrical resistivity of aluminum and manganese and presents the recommended values resulting from critical evaluation, correlation, analysis, and synthesis of the available data and information. The recommended values presented are uncorrected and also corrected for the thermal expansion of the material and cover the temperature range from 1 K to above the melting point into the molten state for aluminum and to 700 K for manganese. The estimated uncertainties in most of the recommended values are about ±2% to ±5%.

Key Words: aluminum; manganese; conductivity; critical evaluation; data analysis; data compilation; data synthesis; electrical conductivity; electrical resistivity; elements; metals; recommended values; resistivity.

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*Figures include the recommended values.

NOMENCLATURE

A	Constant in Eqs. (3b) and (8)
c	Impurity concentration
C	Constant in Eq. (3a)
e	Base of natural logarithm
h	Planck constant divided by 2π
k	Boltzmann constant
L	Length of specimen at T
L_0	Length of specimen at T_0
ΔL	$\Delta L = L - L_0$
M	Atomic weight
RRR	Residual resistivity ratio
T	Temperature
T_0	Reference temperature
x	$x = h\omega/kT$
α	Constant in Eqs. (7) and (8)
Δ	Deviation from the Matthiessen's rule
θ_D	Debye temperature
θ_R	Characteristic temperature for intrinsic electrical resistivity
ρ	Electrical resistivity
ρ_0	Residual electrical resistivity
ρ_e	Electrical resistivity due to electron-electron scattering
ρ_i	Intrinsic electrical resistivity
ω	Phonon angular frequency

1. INTRODUCTION

The principal objective of this project was to exhaustively compile, critically evaluate, analyze, and synthesize all the available data and information on the electrical resistivity of a large number of selected elements and to generate recommended values over a full range of temperature from 1 K to the melting point and beyond. The results on the electrical resistivity of aluminum and manganese are presented in this work (for manganese the recommended values cover the temperatures up to 700 K only), which is one in a series of similar works on the electrical resistivity of selected elements, some published[1-3]. The comprehensive study of the electrical resistivity of the elements at the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) has been a continuation of a similar extensive work on the thermal conductivity of the elements[4].

The general background information on this work is given in Section 2, which includes a brief introduction to the theory of the electrical resistivity of metals and a detailed explanation of the specifics and conventions used in the presentation of the data and information.

The experimental data and information and the recommended values for the electrical resistivity of the two elements are presented in Section 3. In the discussion of the electrical resistivity of each element, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties in the recommended values are stated. The recommended values uncorrected and corrected for the thermal expansion of the material are both presented in this section. The values cover the temperature range from 1 K to above the melting point for aluminum and to 700 K for manganese.

The last three sections are for acknowledgments, appendices, and references. There are two appendices given. The first appendix presents a logical organization of the methods for the measurement of electrical resistivity. The methods are designated with respective code letters and the same code letters are used in the 'Method Used' column of the Table of Measurement Information for indicating the experimental methods used by the various authors. The second appendix presents conversion factors for the units of electrical resistivity, which may be used to convert easily the electrical resistivity values in the SI units given in this work to values in any of the several other units listed.

2. GENERAL BACKGROUND

2.1. Theoretical Background

It was found experimentally by Matthiessen[5,6] that the increase in the electrical resistivity of a metal due to the presence of a small amount of another metal in solid solution is independent of the temperature. According to this Matthiessen's rule, the total electrical resistivity of an impure metal may therefore be separated into two additive contributions and written in the form

$$\rho(c,T) = \rho_0(c) + \rho_i(T) \tag{1}$$

where ρ_0 is the residual resistivity caused by the scattering of electrons by impurity atoms and lattice defects and is temperature-independent but dependent on the impurity concentration, c, and ρ_i is the temperature-dependent intrinsic resistivity arising from the scattering of electrons by lattice waves or phonons.

In reality, however, deviations from Matthiessen's rule do occur. Thus, in general the electrical resistivity of an impure metal is given by

$$\rho(c,T) = \rho_0(c) + \rho_i(T) + \Delta(c,T), \tag{2}$$

where Δ is the deviation from the Matthiessen's rule.

The intrinsic electrical resistivity which is due to scattering of electrons by phonons may be approximated by the Bloch-Grüneisen formula[7,8]:

$$\rho_i = \frac{C}{M\theta_R}\left(\frac{T}{\theta_R}\right)^5 \int_0^{\theta_R/T} \frac{x^5 e^x\, dx}{(e^x-1)^2} \tag{3a}$$

$$= A\left(\frac{T}{\theta_R}\right)^5 \int_0^{\theta_R/T} \frac{x^5 e^x\, dx}{(e^x-1)^2}, \tag{3b}$$

where C is a constant characteristic of the metal and proportional to the square of the electron-phonon interaction constant, M is the atomic weight, θ_R is a characteristic temperature of the metal which characterizes its intrinsic electrical resistivity in the same way as the Debye temperature, θ_D, characterizes its lattice specific heat, and $A \equiv C/M\theta_R$. The dimensionless variable of integration $x = \hbar\omega/kT$, where $\hbar$ is the Planck constant divided by 2π, ω is the phonon angular frequency, and k is the Boltzmann constant. The derivation of Eq. (3) is based on the simplifying assumptions that the Fermi surface is spherical, that the conduction electrons can be treated as free in the first approximation, that the spectrum of lattice vibrations is that of the Debye model, that the phonon distribution is essentially undisturbed by the scattering processes, and that electron-phonon Umklapp processes can be ignored. Consequently, it is perhaps most reasonable to expect the Bloch-Grüneisen formula to agree with experiment in the case of monovalent metals. Nevertheless, the intrinsic resistivity of many metals can be well represented by Eq. (3) over a wide temperature range by a suitable choice of θ_R and C, though no single values of θ_R can fit the data at all temperatures.

At low temperatures ($T \leq \theta_R/20$), Eq. (3a) reduces to

$$\rho_i = \frac{124.4C}{M\theta_R}\left(\frac{T}{\theta_R}\right)^5, \tag{4}$$

while at high temperatures ($T > \theta_R$), to a good approximation, it reduces to

$$\rho_i \approx \frac{C}{4M\theta_R}\left(\frac{T}{\theta_R}\right) . \tag{5}$$

Thus it agrees with the experimental facts that at very low temperatures the intrinsic or ideal electrical resistivity (after subtracting ρ_0 from ρ) of most metallic elements is proportional to T^5 which is attributed to electron-phonon intraband scattering, and at high temperatures the resistivity of most metals increases approximately linearly with temperature.

In separating the electrical resistivity into its components, the temperature dependent part sometimes includes the electrical resistivity due to electron-electron scattering, ρ_e; indeed, this is thought to be the dominant temperature-dependent term in transition metals at low temperatures. That is,

$$\rho = \rho_0 + \rho_e + \rho_i(T). \tag{6}$$

As in the case of the scattering of electrons by phonons, electron-electron collisions are of two types: normal processes in which the total wave vector is conserved, and Umklapp processes in which the total wave vectors before and after the collision differ by a reciprocal lattice vector. On the other hand, unlike electron-phonon Umklapp processes which are frozen out at low temperatures if the Fermi surface is everywhere clear of the zone boundary, electron-electron Umklapp processes are not frozen out at low temperatures. Normal processes, involving the collision between two s-band conduction electrons, do not contribute directly to the electrical resistivity because they do not change the total momentum and thus have no effect on the current. Normal processes involving the scattering of an s-band conduction electron by a non-conducting d-band electron do contribute to the electrical resistivity, and are thought to be the dominant temperature-dependent resistive processes in transition elements and their alloys at very low temperatures, since their resistivities show the T^2 temperature dependence expected for electron-electron scattering rather than the T^5 temperature dependence expected for the intrinsic resistivity. This temperature dependence of the electrical resistivity due to electron-electron scattering:

$$\rho_e = \alpha T^2 \tag{7}$$

comes about through the double application of the exclusion principle in the scattering processes; it applies to both the initial states and final states. In Eq. (7), α is a constant.

Umklapp processes between two conduction electrons do contribute to the electrical resistivity. Because these processes involve a reciprocal lattice vector, the wave functions of the electrons involved cannot be regarded as simple plane waves, but must be treated as true Bloch functions having the periodicity of the lattice. The results of this are to introduce into the expression for the resistivity the square of an interference factor. Apparently this factor is quite small, as the low temperature electrical resistivity of most ordinary metals does not show the T^2 temperature dependence expected for such a resistive mechanism.

Substituting Eqs. (7) and (3b) into Eq. (6) yields

$$\rho = \rho_0 + \alpha T^2 + A\left(\frac{T}{\theta_R}\right)^5 \int_0^{\theta_R/T} \frac{x^5 e^x dx}{(e^x-1)^2} \quad . \tag{8}$$

Equation (8) has been used frequently in analyzing the experimental data and in generating the recommended values for the electrical resistivity at low temperatures.

2.2. Presentation of Data and Information

In each of the subsections in Section 3, electrical resistivity data and information for each element are presented in the following order:

(1) A discussion text,

(2) A table of recommended values,

(3) A figure presenting experimental data as a function of temperature in a log-log scale (for manganese, due to the relatively small number of data sets, this figure is not given),

(4) A figure presenting recommended values and selected experimental data (on which the recommendations were based) as a function of temperature in a log-log scale,

(5) A figure presenting recommended values and selected experimental data (on which the recommendations were based) as a function of temperature in a linear scale,

(6) A table giving measurement information on the experimental data presented in the figures, and

(7) A table of experimental data for all the data sets listed in item 6 above.

In the discussion text on the electrical resistivity of each element, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties of the recommended values are stated.

The recommended values are for well-annealed high-purity and unoxidized specimens of the respective elements; however, those values for low temperatures are applicable only to the particular specimens having residual electrical resistivities as given at 1 K in the tables.

The recommended values uncorrected and corrected for the thermal expansion of the element are both given in the table. The uncorrected and corrected values are related by the following equation:

$$\rho_{\text{corrected}}(T) = \left[1 + \frac{\Delta L(T)}{L_0}\right] \rho_{\text{uncorrected}}(T), \tag{9}$$

where $\Delta L = L - L_0$ and L and L_0 are the lengths of the specimen at any temperature T and at a reference temperature T_0, respectively. The thermal expansion correction for aluminum amounts roughly to about -0.5% to -0.9% at very low temperatures, zero at room temperature, about 0.5% at 500 K, and about 1.6% near the melting point of the element. For manganese, the correction is about -0.3% at low temperature, zero at room temperature, and 0.8% at 500 K.

The recommended values in some cases are given with more significant figures than warranted, which is merely for tabular smoothness or for the convenience of internal comparison. Hence, the number of significant figures given in the table has no bearing on the degree of accuracy or uncertainty in the values; the uncertainty in the values is always explicitly stated.

In the figures, a data set consisting of a single data point is denoted by a number enclosed by a square, and a curve that connects a set of two or more data points is denoted by a ringed number. These data set numbers correspond to those listed in the accompanying tables providing measurement information and tabulating numerical data for each of the data sets. When several sets of data are too close together to be distinguishable, some of the data sets, though listed and tabulated in the tables, are omitted from the figure for the sake of clarity. The data set numbers of those data sets omitted from the figure are asterisked in both tables providing the measurement information and tabulating the experimental data.

The tables providing the measurement information contain for each set of experimental data the following information: data set number, reference number, author(s), year of publication, experimental method used for the measurement, temperature range covered by the data, name and specimen designation, specimen composition, specification and characterization, and information on measurement conditions, which are contained in the original paper. The experimental methods used for the measurement of the electrical resistivity are indicated in the column headed 'Method Used' in the table by the following code letters:

A Direct-current potentiometer method
B Direct-current bridge method
C Alternating-current potentiometer method
D AC bridge method
K Direct heating method
P Van der Paw method
R Rotating magnetic field method

→ This symbol means either that the method described by the author is not sufficient for assigning a specific code letter or that the use of a code letter would not convey enough of the information reported in the research document, and therefore the method used is described briefly in the last column of the table.

Details of these and other methods for the measurement of electrical resistivity may be found in the literature references given in Appendix 5.1, which presents a complete scheme for the classification and organization of the methods.

In the tables tabulating the experimental data, all the original data reported in different units have been converted to have the same units: the SI units 10^{-8} Ω m. The recommended values generated are also given in the same units. Conversion factors for the units of electrical resistivity, which may be used to convert the electrical resistivity values in the SI units given in this work to values in other units, are given in Appendix 5.2.

3. ELECTRICAL RESISTIVITY DATA AND INFORMATION

3.1. Aluminum

There is a large body of data and information available on the electrical resistivity of aluminum. This includes data not only on very pure bulk material (indicated by a 5N purity, very large RRR of up to 46000, and very low residual resistivity, ρ_0, of the order of 10^{-12} Ω m) but also on thin films as well as on effects such as those of cold-work, quenching, annealing, deformation, irradiation, and pressure. Over 190 data sets, mostly on the bulk material as a function of temperature, are presented in this work.

The information on specimen characterization and on the measurement condition for each of the data sets is given in Table 2. The data sets are tabulated in Table 3 and shown partially in Fig. 1. Only those data sets used in the recommendation procedure are shown in Figs. 2 and 3.

The work reported in the last several years (data sets 1-67) is concentrated on the study of the low-temperature behavior of the electrical resistivity and the origin of the so-called DMR (deviation from Matthiessen's rule). It has been reported that various scatterers such as impurities, dislocations, and surfaces (as in the size effect) can change the temperature-dependent resistivity substantially and can produce large DMR. Many of the data sets reported in Tables 2 and 3 can be rejected as the basis for estimation of the electrical resistivity of pure aluminum because of the impurity content, cold work, or inadequate annealing of the samples. Other data sets are for specimens subjected to procedure intended to produce oxidized surface layers. Most of the available data appears to be uncorrected for thermal expansion of the samples, although this correction amounts to 1.6% near the melting point. Among the data sets reported in Table 2, only the data of Cook et al.[22] (data set 69), Radenac et al.[44] (data set 104), Wilkes[53] (data set 115) and of Simmons and Bailuffi[74] (data set 150) are explicitly stated to have been corrected for thermal expansion, and the opposite has been assumed in all other cases.

Deviations from Matthiessen's rule are quite significant in aluminum and have been carefully studied. Ribot et al.[9] (data sets 1-21) concluded that Matthiessen's rule is obeyed below 4.2 K. However, their studies do not extend above this temperature. Another complicating factor is the importance of surface scattering for the resistance at low temperatures of pure samples in the form of foils or wires of diameter much less than 1 mm. This size-dependent contribution to the measured resistance, which is about proportional to T^2, is comparable to the temperature-dependent resistance at 2 K. Its role in the reported low-temperature behavior of electrical resistivity for aluminum has been the subject of study and disagreement. It is attributed to a change in the electron distribution near the surface and is reported by van der Mass et al.[97] to depend only on the surface resistivity. Sample-dependent anomalies complicate the study of the temperature dependence of the size effect below 4 K.

There has been an active interest in measuring and analyzing the bulk resistivity of aluminum in the low-temperature range. Sambles et al.[98] have given an extensive list of effective single-power laws that have been used in representing this resistivity over various temperature ranges below 60 K. Generally speaking, the temperature dependent part of the resistivity drops from T^5 dependence above 20 K to a T^2 dependence around 2 K. The careful studies of Ribot et al.[9] (data sets 1-21), based on their measurements of aluminum samples with RRR up to 40600, yield a temperature dependent resistivity that can be represented by $AT^2 + BT^5$ below 2.2 K, with the T^2 term dominant. This form has been found to be useful by others over a considerably wider temperature range. The T^2-dependence around 2 K has been confirmed by Garland and Van Harlingen[13] (data sets 48-54), van Kempen et al.[99], and Boysel et al.[100]. According to the elementary theory of electron-electron scattering in metals, it would give rise to a T^2 term in the resistivity, and the observed T^2-dependence of the electrical resistivity in aluminum around 2 K is commonly attributed to this scattering. The observed T^2 term is, however, much larger than that given by the simple theory of electron-electron scattering. A promising elaboration of the theory has been suggested by MacDonald[101]. Other researchers who deal with this subject are Nakamichi and Kino[10] (data sets 22-28), Babic et al.[18] (data sets 60,61), Aleksandrov and D'yakov[68] (data sets 139-141), Senoussi and Campbell[32] (data sets 85,86), and Refs. 104-108.

The recommended values for the electrical resistivity at low temperatures are based on the data of Nakamichi and Kino[10] (data sets 22-28) who studied samples of such high purity that surface scattering of the carriers became a significant factor in small wires or thin foils. Specifically, their values for the resistivity of bulk aluminum (data set 28), derived by extrapolating their results for thicker and thicker samples, were used as the basis for the recommended values below 40 K. These are the representative values to be expected for bulk samples with ρ_0 of the order 10^{-12} Ω m, or RRR approaching 27000. From 40 to 400 K, the recommended values follow closely the data of Cook et al.[22] (data set 69), Seth and Woods[45] (data set 105), Wilkes[53] (data set 115) Moore et al.[60] (data set 125), and of Simmons and Balluffi[74] (data set 150). From 400 K to the melting point, the recommended values are based on the reasonably concordant (allowing for the different treatments of thermal expansion) results of Kedves et al.[28] (data set 79), Redenac et al.[44] (data set 104), and of Logunov and Zverev[48] (data set 109). It is worth noting that their data show a progressive increase in the electrical resistivity values above the expected linearly extrapolated values above 700 K. This was attributed by Simmons and Balluffi[74] to scattering by thermally generated point defects of the type which add atomic sites (vacancy-type defects).

There are about 15 data sets available for the electrical resistivity of aluminum in the liquid region. The temperature range covered by these data sets is from 933 to 1973 K. There is a general agreement (±5%) between most of the data sets. The recommended values in the liquid region are based on these data sets, giving weight to the data of Romanova and Persion[35] (data set 89), Levin et al.[40] (data set 95), Powell et al.[63] (data set 130), Roll et al.[78] (data set 157), and of Matuyama[88] (data set 181).

The recommended values for the electrical resistivity given in Table 1 and shown in Figs. 2 and 3 are for well-annealed unoxidized aluminum of purity 99.99% or higher, but those below 40 K apply specifically to samples with ρ_0 = 1.00×10^{-12} Ω m. The table gives both values uncorrected and corrected for thermal expansion, while Figs. 2 and 3 show only the uncorrected recommended values along with the experimental data which were used to generate these values. Thermal expansion values needed to carry out thermal expansion correction were taken from ref. 109. The uncertainty in the recommended values is estimated to be within ±1% below 400 K, ±2% from 400 K up to the melting point, and about ±3% for the liquid.

As mentioned earlier, electrical resistivity measurements for aluminum reported in the literature are not only for bulk material but also for aluminum under various physical as well as thermal conditions. Additional information is available in refs. 110-188. In the following paragraphs, an attempt is made to sort the source documents to highlight important effects.

The electrical resistivity studies at low temperature of thin films is of great interest to many researchers. The main purpose of the study appears to study so-called 'size effect.' Some of the works are cited above. The effect of grain boundary scattering on the electrical resistivity was reported by Bandyopadhyay and Pal[189] and by Andrews et al.[190]. Additional information on the thin films in general is reported in refs. 191-211.

Properties such as specific heat as well as electrical resistivity show a progressive increase above the linearly extrapolated values at high temperatures. As mentioned earlier, this increase is ascribed to scattering by thermally generated point defects. Several semiempirical approaches to calculate contribution to vacancy-type defects have been proposed by various investigators. In addition to the study of Simmons and Balluffi[74] reported here, the readers are directed to refs. 212-230.

The lattice defects of solids induced at low temperature by irradiation have received considerable attention in the recent years. These studies are reported in refs. 231-250. The effect of deformation on the electrical resistivity is also an equally well investigated area. Interested readers may refer to refs. 251-269 for information on the electrical resistivity of deformed aluminum. Last but not least, magnetic field effects are reported in refs. 270-277, effects of heat treatment, quenching, and cold-working are given in refs. 278-290, and effects of high pressure are discussed in refs. 291-296.

TABLE 1. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF ALUMINUM[a]

[Temperature, T, K; Electrical Resistivity, ρ, 10^{-8} Ω m]

T	ρ		T	ρ	
	uncorrected	corrected		uncorrected	corrected
1	0.000100	0.000100	700	7.350	7.322
2	0.000102	0.000102	800	8.700	8.614
4	0.000109	0.000109	900	10.18	10.005
7	0.000139	0.000140	933.52	10.74(s)	10.565(s)
10	0.000193	0.000192	933.52		24.77(ℓ)
15	0.000346	0.000345	1000		25.88
20	0.000755	0.000748	1100		27.46
25	0.00187	0.00186	1200		28.95
30	0.00453	0.00451	1300		30.38
40	0.0181	0.0180	1400		31.77
50	0.0478	0.0476	1500		33.11
60	0.0959	0.0955	1600		34.40
70	0.1624	0.1618	1700		35.69
80	0.245	0.2439	1800		36.93
90	0.339	0.338	1900		38.18
100	0.442	0.440	2000		39.34
150	1.006	1.003			
200	1.587	1.584			
250	2.157	2.155			
273	2.417	2.417			
293	2.650	2.650			
300	2.733	2.733			
400	3.866	3.875			
500	4.995	5.020			
600	6.130	6.122			

[a]The values are for well-annealed aluminum of purity 99.99% or higher, but those below 40 K apply specifically to samples with $\rho_0 = 1.00 \times 10^{-12}$ Ω m. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. Solid line separating tabular values indicates solid to liquid state transformation.

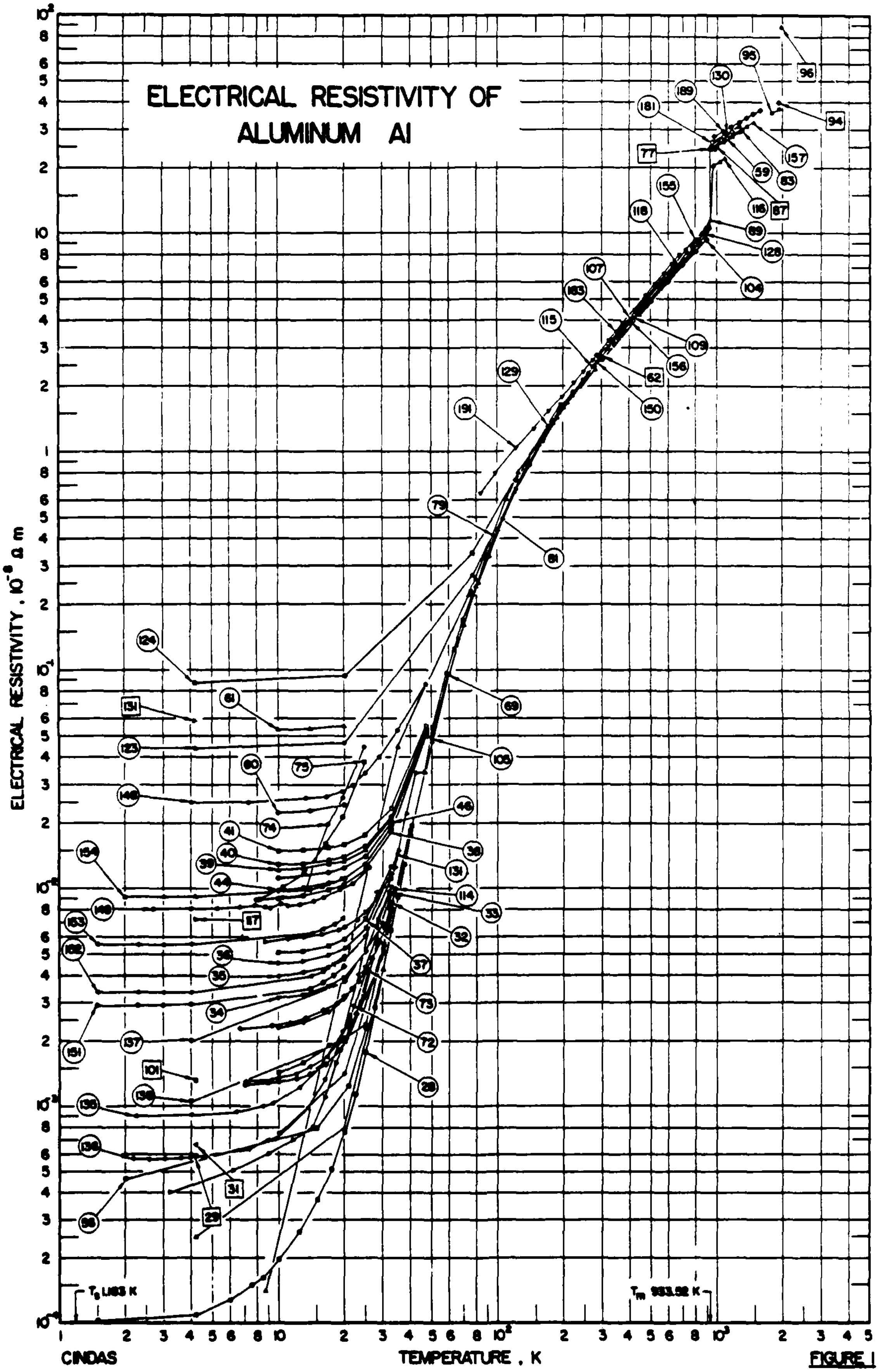

ELECTRICAL RESISTIVITY OF ALUMINUM Al
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
T_s 1.163 K
T_m 933.52 K
CINDAS

FIGURE 1

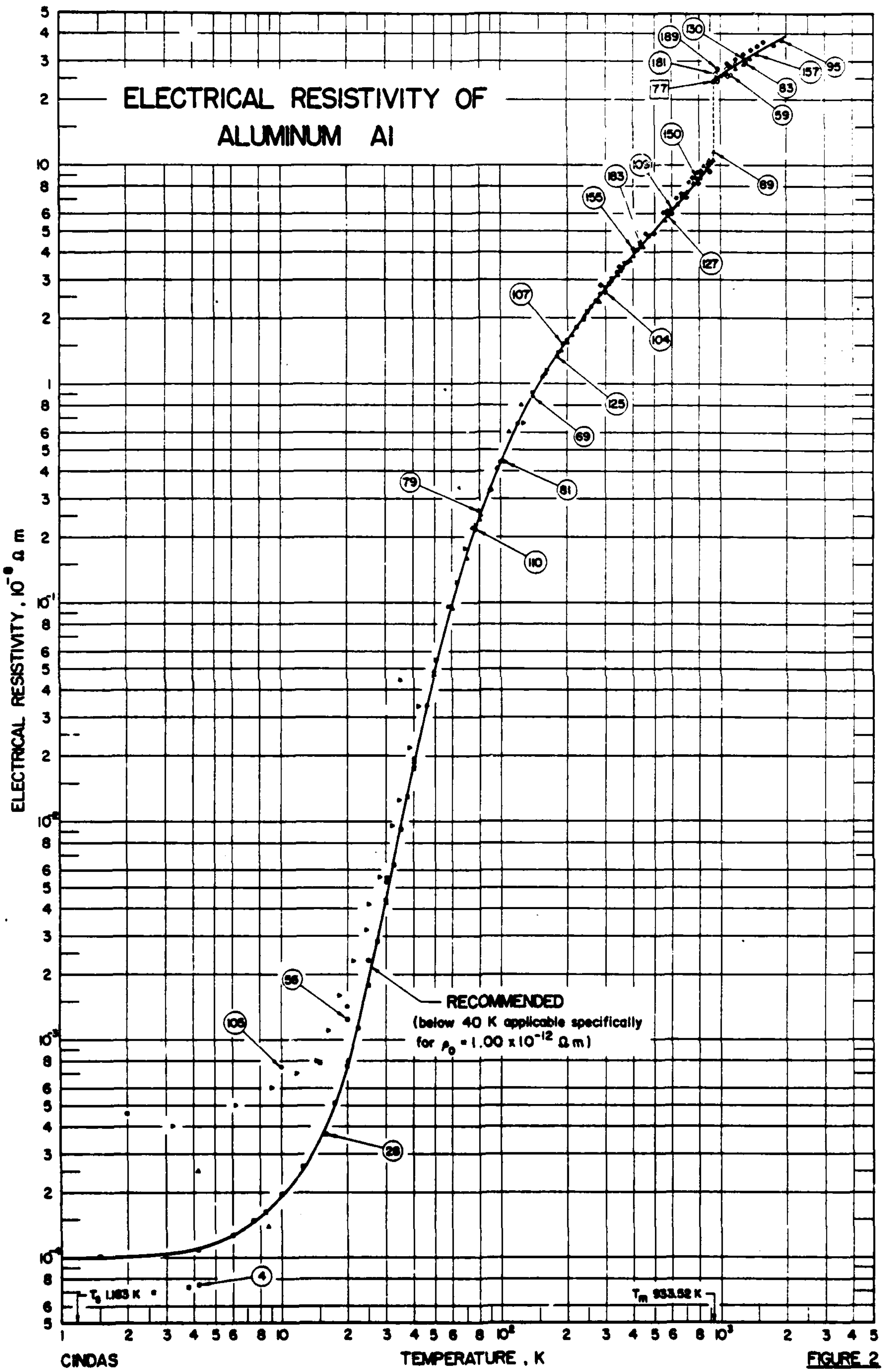
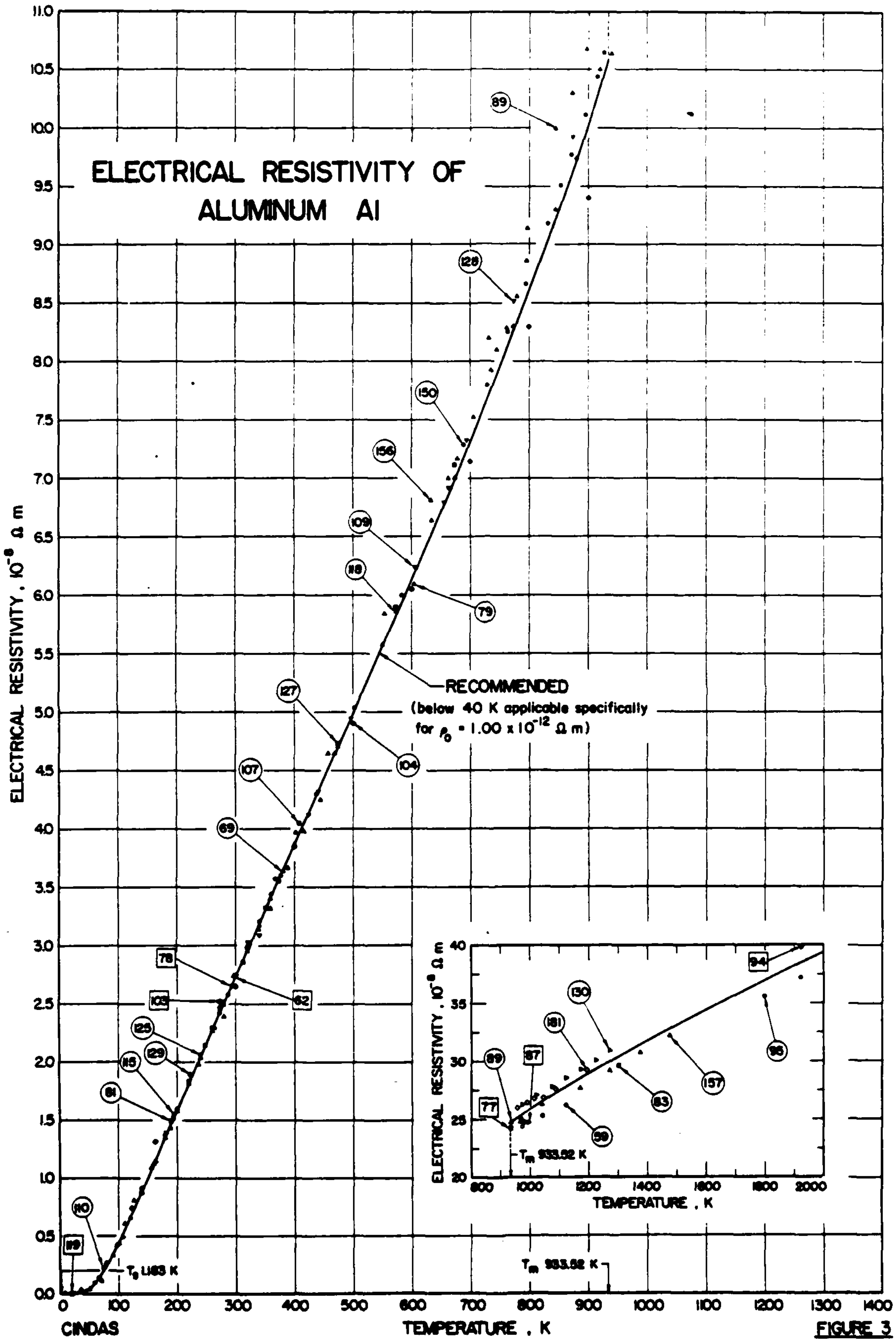

ELECTRICAL RESISTIVITY OF ALUMINUM Al
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 40 K applicable specifically for $\rho_0 = 1.00 \times 10^{-12}$ Ω m)
T_s 1.183 K
T_m 933.52 K
CINDAS

FIGURE 2



CINDAS

FIGURE 3

TABLE 2. MEASUREMENT INFORMATION OF THE ELECTRICAL RESISTIVITY OF ALUMINUM Al

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1*	9	Ribot, J.H.J.M., Bass, J., van Kempen, H., van Vucht, R.J.M., and Wyder, P.	1981	+	1.600-2.171	Sample 1	High purity specimen; nominal impurity <0.5 ppm; ρ_o = 0.0000928 x 10^{-8} Ωm; RRR = 29000; 1.4 mm diam. and about 1.5 m long cylindrical wire wound in double helix around quartz cylinder; before mounting, samples were cleaned in 40% NaOH solution to facilitate spot welding to 1 mm diam. ultrapure aluminum potential leads; welds were made with minimum electrical energy needed to achieve mechanical stability and showed no extra oxide formation; after annealing, test weld had resistance <5 x 10^{-8} Ω at 4.2 K; samples were annealed in dry hydrogen (≤10 ppm water) at 1 atm for 1 h at 773 K and 1 h at 673 K and cooled slowly to room temperature; lead wires were superconducting, attached using superconducting solder, T_c = 1.18 K; measurement utilized superconducting flux gated galvonometer and current comparator with optimal precision of 0.1 ppm; series "a" data.
2*	9	Ribot, J.H.J.M., et al.	1981	+	1.298-3.842		Same as above except measurements designated as series "b".
3*	9	Ribot, J.H.J.M., et al.	1981	+	1.600,2.171		Same as above except measurements designated as series "c".
4	9	Ribot, J.H.J.M., et al.	1981	+	2.631-4.221	Sample 2	Same as in data set 1 except sample diam. 3.0 mm; ρ_o = 0.0000667 x 10^{-8} Ωm; RRR = 40,600; measurements designated as series "a".
5*	9	Ribot, J.H.J.M., et al.	1981	+	2.362-3.997		Same as above except measurements designated as series "b".
6*	9	Ribot, J.H.J.M., et al.	1981	+	4.134,4.224		Same as above except measurements designated as series "c".
7*	9	Ribot, J.H.J.M., et al.	1981	+	1.180-2.172		Same as above except measurements designated as series "d".
8*	9	Ribot, J.H.J.M., et al.	1981	+	2.578-4.220	Sample 3	Same as in data set 1 except sample diam. 3.0 mm; ρ_o = 0.0013 x 10^{-8} Ωm; RRR = 21000; nominal impurity <5 ppm; measurements designated as series "a".
9*	9	Ribot, J.H.J.M., et al.	1981	+	1.950-2.80		Same as above except measurements designated as series "b".
10*	9	Ribot, J.H.J.M., et al.	1981	+	1.292-1.900		Same as above except measurements designated as series "c".
11*	9	Ribot, J.H.J.M., et al.	1981	+	1.253-1.451		Same as above except measurements designated as series "d".
12*	9	Ribot, J.H.J.M., et al.	1981	+	2.049,2.100	Sample 4	Same as in data set 1 except nominal impurity <8 ppm; sample diam. 3.0 mm; ρ_o = 0.000292 x 10^{-9} Ωm; RRR = 9300; measurements designated as series "d".

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
13*	9	Ribot, J.H.J.M., et al.	1981	→	3.183–4.133		Same as above except measurements designated as series "b".
14*	9	Ribot, J.H.J.M., et al.	1981	→	1.501–4.221		Same as above except measurements designated as series "c".
15*	9	Ribot, J.H.J.M., et al.	1981	→	4.209		Same as above except measurements designated as series "d".
16*	9	Ribot, J.H.J.M., et al.	1981	→	1.254–1.601		Same as above except measurements designated as series "e".
17*	9	Ribot, J.H.J.M., et al.	1981	→	1.522–4.218	Sample 5	Nominal impurity <100 ppm; ρ_o = 0.01068 x 10^{-8} Ωm; RRR = 255; cylindrical wire 2.0 mm diam. and 10 cm long; cleaned in NaOH solution, annealed in hydrogen as described in data set 1 and then recleaned in solution; ultrapure, 3 cm long aluminum potential leads were then spot-welded to sample 2 cm in from each end; mounting of sample was achieved as described in data set 1.
18*	9	Ribot, J.H.J.M., et al.	1981	→	1.294–4.200	Sample 6	Same as above (data set 17) except impurity unknown; ρ_o = 0.01106 x 10^{-8} Ωm; RRR = 245; specimen diam. 1.0 mm.
19*	9	Ribot, J.H.J.M., et al.	1981	→	1.224–4.206	Sample 7	Intermediate purity sample, impurity <10 ppm; ρ_o = 0.000663 x 10^{-8} Ωm; RRR = 4100; samples were spark-cut from aluminum sheet 1 mm thick, 10 cm long, and 1 mm wide contained four tabs 1 mm wide and 2 mm long located approximately symmetrically on the sample about 1 cm in from each end; cleaned in NaOH solution; annealed in air; potential contacts were soldered to ends of two tabs on the same side of the sample.
20*	9	Ribot, J.H.J.M., et al.	1981	→	1.371–4.229	Sample 8	Same as above (data set 19) except ρ_o = 0.000601 x 10^{-8} Ωm; RRR = 4500; sample annealed in hydrogen for 22 h.
21*	9	Ribot, J.H.J.M., et al.	1981	→	1.241–4.211	Sample 9	Same as above (data set 19) except ρ_o = 0.002245 x 10^{-8} Ωm; RRR = 1100; sample left unannealed.
22*	10	Nakamichi, I. and Kino, T.	1980	A	1–42		Specimen made from block (10 x 20 x 90 mm^3) cut from zone refined polycrystalline Al bar (RRR = 26000); thickness 0.0195 mm x 5 mm (reduced thickness 0.019 mm based on 2 x cross section divided by perimeter); specimen annealed for 3 h at 600°C in air and then cooled down in furnace; RRR = 1692; data taken from figure.
23*	10	Nakamichi, I. and Kino, T.	1980	A	1–43		Similar to the above except thickness 1.484 mm and width 2.94 mm (reduced thickness 0.986 mm); RRR = 17310; values are fairly close to the bulk values calculated from data for strips using Fuchs-Sondheimer relation; data taken from figure.
24*	10	Nakamichi, I. and Kino, T.	1980	A	1–35		Similar to the above except thickness 0.1955 mm and width 3.17 mm (reduced thickness 0.184 mm); RRR = 7523; data taken from figure.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
25*	10	Nakamichi, I. and Kino, T.	1980	A	1–41		Similar to the above except thickness 0.101 mm and width 4.66 mm (reduced thickness 0.099 mm); RRR = 4697; data taken from figure.
26*	10	Nakamichi, I. and Kino, T.	1980	A	1–42		Similar to the above except thickness 0.039 mm and width 5 mm (reduced thickness 0.039 mm); RRR = 2717; data taken from figure.
27*	10	Nakamichi, I. and Kino, T.	1980	A	1–42		Similar to the above except thickness 0.030 mm and width 5 mm (reduced thickness 0.030 mm); RRR = 2041; data taken from figure.
28	10	Nakamichi, I. and Kino, T.	1980	A	1–40		Values for bulk material based on their measurements for 0.0195–1.484 mm thick strips of zone refined aluminum bar of bulk RRR = 26000 and Fuchs-Sondheimer relation; the values are fairly close to the values for 1.484 mm thick strip.
29	11	Kim, S.H. and Wang, S.T.	1978	A	4.2	Aluminum #1	99.999 Al; polycrystalline supplied by D. Koop of Alcoa; 0.7 cm diam. x 3.5 cm long; soft shouldered on both ends with copper bars 1.8 cm diam. x 7.5 cm long; resistivity obtained from following relationship: $\rho(\epsilon,B) = \rho_o + \rho_d(\epsilon) + \rho_m(\epsilon,B)$ (ϵ & B have no significance since ϵ was considered at zero strain (ϵ) and zero magnetic field (B)); data taken from figure; reported error 10%.
30*	11	Kim, S.H. and Wang, S.T.	1978	A	4.2	Aluminum #3	Similar to above specimen.
31	11	Kim, S.H. and Wang, S.T.	1978	A	4.2	Aluminum #4	Similar to above specimen.
32	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	99.999 Al; obtained from Koch-Light (type 8013 h, batch 1); 0.508 mm diam.; reduced by rolling and drawing through diamond dies to various diameters, and through a varying number of dies which accounts for reducing specimen diam. by 11% and changes in ρ_o; number of dies zero for this specimen; annealed at 340°C for 3 h; $\rho_o = 0.001306 \times 10^{-8}\ \Omega m$; values calculated from graphically extracted values for ρ_T, temperature dependent resistivity.
33	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	Same as above except $\rho_o = 0.00222 \times 10^{-8}\ \Omega m$; number of dies is 1.
34	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	Same as above except $\rho_o = 0.00309 \times 10^{-8}\ \Omega m$; number of dies are 2.
35	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	Same as above except $\rho_o = 0.00391 \times 10^{-8}\ \Omega m$; number of dies are 3.
36	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	Same as above except $\rho_o = 0.00447 \times 10^{-8}\ \Omega m$; number of dies are 4.
37	12	Rowlands, J.A. and Woods, S.B.	1978	B	10–33	Al(1)	Same as above except $\rho_o = 0.00499 \times 10^{-8}\ \Omega m$; number of dies are 5.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
38	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Similar to above specimen; ρ_o = 0.00874 x 10^{-8} Ωm; number of dies are zero; run I.
39	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except ρ_o = 0.0121 x 10^{-8} Ωm; number of dies is 1.
40	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except ρ_o = 0.0127 x 10^{-8} Ωm; number of dies are 2.
41	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except ρ_o = 0.0147 x 10^{-8} Ωm; number of dies are 4.
42*	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except ρ_o = 0.0148 x 10^{-8} Ωm; number of dies are 6.
43*	12	Rowlands, J.A. and Woods, S.B.	1978	B	13,20	Al(2)	Similar to above specimen; ρ_o = 0.00877 x 10^{-8} Ωm; number of dies are zero; run II.
44	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(2)	Same as above except diam. = 0.494 mm; ρ_o = 0.00963 x 10^{-8} Ωm; number of dies are 1.4.
45*	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(2)	Same as above except diam. = 0.482 mm; ρ_o = 0.0102 x 10^{-8} Ωm; number of dies are 1.2.
46	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(2)	Same as above except diam. = 0.469 mm; ρ_o = 0.0111 x 10^{-8} Ωm; number of dies are 1.4.
47*	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(2)	Same as above except diam. = 0.458 mm; ρ_o = 0.01174 x 10^{-8} Ωm; number of dies is 1.
48*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.35-6.46	Al-1	Pure, polycrystalline 30 mm diam. rods; ρ_o = 0.0002057 x 10^{-8} Ωm; normal resistance ratio = 12000; annealed in air at 550°C for several hours; RRR = 12327; values calculated from graphically reported $\rho_T-\rho_o$ vs T values; voltage measured using SQUID detector.
49*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-2	Similar to above specimen; values are calculated from $\rho = \rho_o + AT^2$ using ρ_o = 0.0002341 x 10^{-8} Ωm, and A = 5.4 ± 0.4 x 10^{-4} nΩ cm K^{-2}.
50*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-3	Similar to above specimen; ρ_o = 0.0002012 x 10^{-8} Ωm; RRR = 12588, A = 5.7 ± 0.4 x 10^{-4} nΩ cm K^{-2}.
51*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-4	Similar to above specimen but cold-worked after annealing; ρ_o = 0.0006195 x 10^{-8} Ωm; RRR = 4201, A = 6.7 x 10^{-4} nΩ cm K^{-2}.
52*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-5	Similar to above specimen; ρ_o = 0.0000519 x 10^{-8} Ωm; RRR = 5030, A = 5.2 x 10^{-4} nΩ cm K^{-2}.
53*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-6a	Similar to Al-1; ρ_o = 0.0000944 x 10^{-8} Ωm; RRR = 25999, A = 4.3 x 10^{-4} nΩ cm K^{-2}.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
54*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5–4.0	Al-6b	Similar to above specimen but cold-worked after annealing; ρ_o = 0.00004638 x 10^{-8} Ωm; RRR = 5625, A = 4.6 x 10^{-4} nΩ cm K^{-2}.
55*	14	Masovic, D.R. and Zekovic, S.	1978	A	933		No details given.
56	15	Klopkin, M.N., Panova, G.Kh., and Samoilov, B.N.	1977	A	2–295		99.999 Al; RRR = 5900; ρ_o = 0.00046 x 10^{-8} Ωm; values calculated from graphically reported ρ_T–ρ_o values which are temperature dependent resistivity.
57*	16	Fujita, T. and Ohtsuka, T.	1977	A	1.51–9.72	Al-4	99.999 Al; zone refined specimen wires 0.6 mm in diam.; annealed in vacuum at 600°C for 2 days; all specimens chemically etched and rinsed with distilled water; ρ_o = 0.000448 x 10^{-8} Ωm; measurement done with SQUID galvonometer with voltage sensitivity ±10^{-13} V; heating effects negligible; data extracted from figure; a main source of error was the specimen size; SQUID detector used; uncertainty about 1%.
58*	16	Fujita, T. and Ohtsuka, T.	1977	A	1.50–9.09	Al-1a	Similar to the above specimen except it was cold-worked; sandwiched between clean Al sheets and rolled to 0.3 mm thick plate form; ρ_o = 0.001355 x 10^{-8} Ωm.
59	17	Kéita, M., Steinemann, S., Künzer, H.U., and Güntherodt, H.J.	1977	C	933–1122		No details given; liquid state specimen; data extracted from figure.
60	18	Babic, E., Krsnik, R., and Ocko, M.	1976	A	10–20		99.999 Al from Koch Light; temperature controlled by helium exchange gas and by resistance heater; ρ_o = 0.022 x 10^{-8} Ωm.
61	18	Babic, E., et al.	1976	A	10–20		Similar to above except ρ_o = 0.053 x 10^{-8} Ωm.
62	19	Kawata, S.	1976	A	300	VIII-1	99.999 Al; zone refined; ρ_o = 0.000193 x 10^{-8} Ωm.
63*	20	Krevet, B. and Schauer, W.	1976	A	4.2–32	Sample I	Pure; polycrystalline; from Vereinigte Aluminumwerke, AG, Bonn; Al tape samples 0.3 x 6 mm^2 cross-section; liquid hydrogen cryostat used; RRR = 2200; data extracted from figure.
64*	20	Krevet, B. and Schauer, W.	1976	A	4.2–32	Sample II	Similar to above specimen; RRR = 3800.
65*	20	Krevet, B. and Schauer, W.	1976	A	4.2–32	Sample III	Similar to above specimen; RRR = 5600.
66*	20	Krevet, B. and Schauer, W.	1976	A	5.5–32	Sample IV	Similar to above specimen; RRR = 8900.
67*	20	Krevet, B. and Schauer, W.	1976	A	4.2–32	Sample VI	Similar to above specimen; RRR = 13900.
68*	20	Hartwig, K.T. and Worzala, F.J.	1976	A	273		Pure; melted in induction furnace in high purity graphite crucibles under argon; ingots from the melt (1 in. diam.) were extruded to 1/4 in. diam.; specimens were then cut to 2 in. lengths and homogenized in air at 873 K for 12 h, then water quenched and immersed in liquid nitrogen for storage.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
69	22	Cook, J.G., Moore, J.P., Matsumura, and Van der Mur, M.P.	1975	A	4.2-400		99.9999 Al; specimens purchased from Cominco Ltd., Oakville, Ontario; three samples measured with three techniques; sample with RRR = 11,000 annealed at Cominco Ltd.; sample with RRR = 8500 annealed at NRC; sample with RRR = 950 of commercial purity; data extracted from tabulated values which were obtained by passing a smooth curve approximately midway between the high and low results for the pure specimens; data reported were corrected for thermal expansion; author's estimated uncertainty 0.8%.
70*	23	Rapp, O. and Fogelholm, R.	1975	A	318	Sample 1	Pure; <4 ppm of transition metal impurities and <36 ppm total impurities; rolled and drawn into wire 0.25 mm diam.; annealed at 450°C for 6 h.
71*	23	Rapp, O. and Fogelholm, R.	1975	A	318	Sample 2	Similar to above specimen.
72	24	Rowlands, J.A. and Woods, S.B.	1975	B	7-26	Al 1 Type 8013h	99.999 Al from Koch-Light; 1 mm diam. wires reduced in diam. in stages by drawing through dies to final diam. of 0.02 in.; annealed at 340°C for 3 h in vacuum to remove physical defects and inhibit growth of very large crystallites which would prevent uniform drawing; ρ_0 = 0.00124 x 10^{-8} Ωm; values obtained from graphically reported temperature dependent electrical resistivity, ρ_T.
73	24	Rowlands, J.A. and Woods, S.B.	1975	B	7-26	Al 1	Same as above except plastically elongated at room temperature by amounts 5-300% by drawing them through dies, or, for small strains, stretching them.
74	24	Rowlands, J.A. and Woods, S.B.	1975	B	7-25	Al 2	Similar to the above annealed specimen except ρ_0 = 0.0088 x 10^{-8} Ωm; data extracted from figure.
75	24	Rowlands, J.A. and Woods, S.B.	1975	B	8-25	Al 2	Same as above except cold-worked to the smallest value of ρ_T; data extracted from figure.
76*	25	Kawata, S. and Kino, T.	1975	A	4.2-300		99.999 Al supplied by Sumitomo Chemical Co. Ltd.; zone-refined; polycrystalline wire of 1 mm diam.; RRR = 12200-16200.
77	26	Srivastava, S.K.	1975		938		No details given.
78	27	Bradley, J.M. and Stringer, J.	1974	A	293		99.999 Al; cold rolled to a thickness of 0.5 mm from which rectangular specimen (5 mm x 40 mm) was cut; specimen was solution treated at 500°C and water quenched immediately prior to measurement of resistivity.
79	28	Kedves, F.J., Gergely, L., and Hordos, M.	1973	A	26.4-947.9		99.999 Al; 50 mm long (at low temp.), 100-1200 mm long (at high temp.); wound to form a coil on a mica sheet; cold drawn (0.8-1.0 mm diam.); annealed and homogenized at 620-630°C for 1 h; double chamber cryostat used; data extracted from figure; reported error ±1%.
80*	29	Oeamura, K., Hiroaka, Y., and Murakami, Y	1973	A	4.2,77	5N Grade	99.9999 Al; 59 grade; supplied by Asahi Metal Co.; RRR = 9700.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
81	29	Osamura, K., Hiroaka, Y., and Murakami, Y.	1973	A	3.2-200	5N Grade	99.999 Al, 59 grade; wire specimen 0.6 mm in diam.; supplied by Asahi Metal Co.; RRR = 9700; low temperature unpublished data from Nakamura, Furukawa, and Takamura; data extracted from figure.
82*	29	Osamura, K., et al.	1973	A	4.2,77		0.175 Zn; specimen 50 mm x 4 mm with long projecting Hall probes and 70 µm thick; supplied by Sumitomo Mining Co.; cold-rolled, solution treated for 1 h at 450°C, cooled and held for 1 h at 300°C; quenched in water at 0°C, and immediately immersed in liquid nitrogen.
83	30	Stallard, J.M. and Davis, C.M., Jr.	1973		976,1302	MRC VP Grade	99.995 Al; rod 5.08 cm.
84*	31	Thompson, G.E. and Noble, B.	1973	A	74.98,266.5		High purity; cast under argon in an induction furnace; ingots were extruded, homogenized, and cold-rolled to 1.3 mm strip; data extracted from figure.
85*	32	Senoussi, S. and Campbell, I.A.	1973	A	1.32-4.21	Commercial 5N Al	Commercial 5N Al wire (RRR = 1200); ρ_0 = 0.002409 x 10^{-8} Ωm; geometrical factor of the order of 10^3; data taken from figure of $\rho-\rho_0/\rho$ vs T^3.
86*	32	Senoussi, S. and Campbell, I.A.	1973	A	2.98-4.19	Commercial 3N Al	Commercial 3N Al wire (RRR = 65); ρ_0 = 43.31 nΩ cm; geometrical factor of the order of 10^3; data taken from figure of $\rho-\rho_0/\rho$ vs T^3.
87	33	Korochkina, L.N. and Kasimirov, V.P.	1973		993		Pure; no other details are given.
88*	34	Enderby, J.E. and Howe, R.A.	1973		1120		Pure.
89	35	Romanova, O.V. and Persion, Z.V.	1973		842.5-1041.3		Pure aluminum specimen.
90*	36	Sirota, N.N., Gostishchev, V.I., and Drozd, A.A.	1972		4.2,273		Single crystal; 60 x 4 x 3 mm; specimen axis along <110> direction; ρ(273) calculated from resistance ratio of order of 6000 (assumed equal to resistivity ratio) and ρ(4.2 K).
91*	37	Horak, J.A. and Blewitt, T.H.	1972	A	4.5,295		Polycrystalline wire specimen; approximately 5 cm long with a diam. of 0.025 cm.
92*	38	Callarotti, R.C. and Alfonso, M.	1972	→	77		Bar of very common structural aluminum; 12 cm long, 9.5 mm diam; inductive method.
93*	38	Callarotti, R.C. and Alfonso, M.	1972	→	77		Similar to the above; resistive method.
94	39	Levin, E.S., Ayushina, G.D., and Gel'd, P.V.	1972	R	1923	AV-000	99.99 Al; data taken from figure; contactless method.
95	40	Levin, E.S., et al.	1972	R	1923,1798	AV-00	99.99 Al; data taken from figure; reported error 7%; contactless method.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
96	41	Levin, E.S. and Ayushina, G.D.	1972	R	1973	AV 000	99.99 Al; data taken from figure; contactless method.
97*	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 1	99.9999 Al; <0.03 at. ppm Ag, 0.1 at. ppm Cu, 0.5 at. ppm Fe, 0.1 at. ppm Mg, 0.5 at. ppm Si; from Cominco American Inc.; ribbon shaped, 18 cm long, 0.080 cm wide, and 0.017 cm thick; annealed in air at 600 ± 5°C for zero h.
98*	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 2	Same as above except annealed for 5 h.
99*	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 3	Same as above except annealed for 20 h.
100*	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 4	Same as above except annealed for 23 h.
101	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 5	Same as above except annealed for 36 h.
102*	42	DiMelfi, R.J. and Siegel, R.W.	1971	A	4.2	Specimen No. 6	Same as above except annealed for 48 h.
103	43	Alp, T., Brough, I., Sanderson, S.J., and Entwistel, K.M.	1970	A	273		99.9999 Al; zone refined; 8 ppm impurities by weight; 0.508 mm diam. wire; quenched in ice water at 0°C from 200°C.
104	44	Radenac, A., Lacoste, M., and Roux, C.	1970	R	300-900		99.995 Al; 0.0040 Mg, 0.0005 Fe, 0.0002 Cu, and 0.0002 Si; 4 mm diam. x 3 mm; expansion corrected; uncertainty ±3%; contactless method.
105	45	Seth, R.S. and Woods, S.B.	1970	A	10-295	Grade 5N	99.999 Al; polycrystalline; obtained from Consolidated Mining and Smelting Co. of Canada; 6 mm diam. rod drawn through steel dies to 1.5 mm diam., then etched, then drawn through diamond dies to 0.5 mm diam.; annealed for 12 h at 400°C in 10^{-6} Torr atmosphere; electrical resistance ratio R(293 K)/R(4 K) = 4000; resistivity deduced from $\rho = \rho_i + \rho_o$, ρ_o = 0.0007 μΩ cm, ρ_i(273.2 K) = 2.429 μΩ cm, and smoothed values of $\rho_i(T)/\rho_i(273.2\ K)$ extracted from table.
106*	45	Seth, R.S. and Woods, S.B.	1970	A	273.2		0.12 Mg; 6 mm diam. rods made by melting freshly cleaned pellets in evacuated sealed quartz tubes, then drawn through steel dies to 1.5 mm diam.; etched and drawn through diamond dies to 0.5 mm diam.; annealed at 400°C for 12 h in 10 Torr H_2 atmosphere in close-fitting Pyrex container; residual resistivity 0.0487 μΩ cm.
107	46	Böhm, R. and Wachtel, E.	1969		194-408		99.997% Al; impurities 0.001 Cu, 0.001 Fe, 0.001 Si; cylindrical specimen 10 mm in diam.
108*	47	Rubanenko, I.R. and Grossman, M.I.	1969		293		7 x 7 x 28 mm; measuring temperature assumed 20°C.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
109	48	Logunov, A.V. and Zverev, A.F.	1968	A	321-693		99.946 Al; 4 mm diam. x 100 mm; data taken from figure; not corrected for expansion of sample; reported error <0.5%.
110	49	Wilkes, K.E. and Powell, R.W.	1968	A	77,273		99.99989 Al; polycrystalline; 0.5 ppm Cu, 0.5 ppm Si, 0.1 ppm Mg; obtained from Advanced Research Materials; 1.225 cm diam. x 10.16 cm.
111*	50	Von Bassewitz, A. and Mitchell, E.N.	1968	A	4.6-90.3		99.999 Al.
112*	51	Sharma, J.K.N.	1967	D	1.5,293		99.999 Al; polycrystalline wire specimen obtained from Aluminum Laboratories; RRR = 664; 1 mm diam. x 70 cm long.
113*	52	Stevenson, R.	1967		9-35	5N	99.999 Al; wire obtained from Consolidated Mining and Smelting Co.; received extensive deformation in the wire-drawing process and further deformation when wound on mandrels of 0.5 in. diam. in making the samples for the experiment; mounted samples annealed at 150°C for 4 h; resistivity ratio = 476; residual electrical resistivity = 5.74 x 10^{-11} Ω m; data extracted from smooth curve.
114	52	Stevenson, R.	1967		9-35	6N	Similar to the above except resistivity ratio = 1173; ρ_0 = 2.27 x 10^{-11} Ω m; data extracted from smooth curve.
115	53	Wilkes, K.E.	1967	A	78-298		99.99989 Al, 0.00005 Cu, 0.00005 Si, and 0.00001 Mg; 1.226 cm diam. x 10.16 cm long; obtained from Aremco Products Inc.; density 2.700 g cm^{-3} at 23°C; results corrected for thermal expansion by multiplying the room temperature dimensions by $(1 + \bar{\alpha}_0 T)$ where $\bar{\alpha}_0$ is average coefficient of linear thermal expansion and T is the change from room temperature.
116	54	Busch, G. and Güntherodt, H.J.	1967	C	883-1080		No details given.
117	55	Boato, G., Bugo, M., and Rizzuto, C.	1966	A	4.2		99.995 Al; the specimen was annealed in air for one day at 610°C, then quenched in iced salt water for less than a second; the measurement was taken using a Keitly nanovoltmeter, whose calibration was better than 3%.
118	56	Nobili, D. and DeBacci, M.A.	1966	A	298-773		99.99 Al, <0.005 S, 0.003 Cu, 0.003 Fe, <0.001 Mg, and <0.001 Zn; cylindrical specimen; annealed at 550°C for 2 h; reported error <1%.
119	57	Mealy, H.H. and Sosin, A.	1966		20.4		99.9999 Al; specimen supplied by United Minerals Corp.; wire drawn to diam. of 0.0053 cm.
120*	57	Mealy, H.H. and Sosin, A.	1966		20.4		99.995 Al; wire supplied by Aluminum Corporation of America; was drawn to 0.0053 cm diam.
121*	58, 59	Pawlek, F. and Rogalla, D.	1966	B	4-273	Extra pure Al; 99.999	99.999 Al, 0.00024 Fe, 0.00019 Cu, 0.00015 Si, and 0.0003 remaining impurities; 2 mm diam. wire received, with works analysis, from Aluminium-Hütte Rheinfelden GmbH, Rheinfelden; electrical resistivity ratio ρ(273 K)/ρ(4.2 K) = 2210, ρ(293 K)/ρ(20.4 K) = 1130.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
122*	58 59	Pawlek, F. and Rogalla, D.	1966	B	4-273	Very pure Al	99.994 Al, 0.0024 Cu, 0.0020 Si, and 0.0012 Fe; 2 mm diam. wire supplied by Vereinigte Aluminiumwerke AG, Bonn; annealed 1 h in argon at 300°C (authors report annealing temperature as 300°C in Fig. 5, but 400°C on p. 17 of their paper); cooling rate <50°C/h; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 400$, $\rho(293\ K)/\rho(20.4\ K) = 328$.
123	58 59	Pawlek, F. and Rogalla, D.	1966	B	4-273	Pure Al, Al 99.9	99.8673 Al, 0.0730 Fe, 0.0420 Si, 0.0140 Zn, 0.0020 Mn, and 0.0017 Cu; similar to the above except electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 55.2$, $\rho(293\ K)/\rho(20.4\ K) = 57.1$.
124	58 59	Pawlek, F. and Rogalla, D.	1966	B	4-273	Al 99.7	99.814 Al, 0.1100 Fe, 0.0580 Si, 0.0100 Zn, 0.0040 Ti, 0.0020 Cu, and 0.0020 Mn; similar to the above except electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 28.3$, $\rho(293\ K)/\rho(20.4\ K) = 28.6$.
125	60	Moore, J.P., McElroy, D.L., and Barisoni, M.	1966	A	100-360		99.999 Al; RRR = 520; cylindrical specimen machined from a stock obtained from Reynolds Aluminum Co.; estimated uncertainty ±0.6%.
126*	61	Wiser, N.	1966		973		No details given.
127	62	Powell, R.W., Tye, R.P., and Woodman, M.J.	1965	A	313-673		99.993 Al; rod obtained from British Aluminum Co.; specimen 2.53 cm in diam. and 20.4 cm long.
128	62	Powell, R.W., et al.	1965	A	323-873		99.993 Al; from British Aluminum Co.; specimen 2.81 cm in diam. and 28.0 cm long; smoothed values from table; longitudinal heat flow apparatus used.
129	62	Powell, R.W., et al.	1965	A	123-323		99.993 Al; from British Aluminum Co.; specimen 8.0 x 0.44 x 0.44 cm; smoothed values from table.
130	63	Powell, R.W., Tye, R.P., and Metcalf, S.C.	1965	A	973-1273		99.993 Al; from British Aluminum Co.; in molten state; smoothed values from table.
131	64	Forsvoll, K. and Holwech, I.	1964		4.2	Specimen 1	99.99 Al; containing 0.004 Zn; zone refined; bulk resistance ratio $R_{293}/R_{4.2} = 26500$.
132*	64	Forsvoll, K. and Holwech, I.	1964		4.2	Specimen 2	99.999 Al; containing 0.001 Zn; zone refined; bulk resistance ratio $R_{293}/R_{4.2} = 26500$.
133*	65	Frois, C. and Dimitrov, O.	1964		20.4		99.95 Al, 0.05 total impurities; aluminum purified by 15 passages in zone refinement; values measured immediately after deformation in liquid hydrogen; data extracted from figure.
134*	65	Frois, C. and Dimitrov, O.	1964		20.4		Similar to above specimen.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
135	66	Fenton, E.W., Rogers, J.S., and Woods, S.B.	1963		2-28	Al 3	99.9999 Al; zone refined sheet 0.010 in. thick x 0.125 in. diam. rods; supplied by Research Labs. of Consolidated Mining and Smelting Co. of Canada, Trail, British Columbia; acid-etched to remove surface contamination before annealing; rods passed through rollers producing a square cross section that degenerated to rhomboid after several passes; specimen drawn once through steel die to restore cross section to nearly round shape about half way through reduction; further etched to remove surface contamination; annealed in air at 550°C for 10 minutes; ρ_0 = 0.00903 x 10^{-8} Ω m.
136	66	Fenton, E.W., et al.	1963		2-21	Al 6	Same as the above except ρ_0 = 0.000568 x 10^{-8} Ω m.
137	67	Purcell, J.R. and Jacobs, R.B.	1963	A	4-30	99.9983 pure	99.9983 Al; specimen (approx.) 0.004 in. x 0.25 in. x 40 in.; supplied by Consolidated Aluminum Co., Jackson, Tennessee; annealed at 350°C for 2 h; R(300)/R(4) = 1,370; sample completely immersed in bath of either liquid helium or liquid hydrogen during measurements; resistivities computed from resistance ratios, value used for room temperature resistivity 2.7 x 10^{-6} Ω cm (Rutter, J.W. and Reekie, J. [81]; reported error 10%.
138	67	Purcell, J.R. and Jacobs, R.B.	1963	A	4-30	99.999 pure	99.999 Al; approximate specimen dimensions 0.030 in. x 0.125 in. x 40 in.; supplied by A.I.A.G. Metals Inc., New York, New York; annealed at 350°C for 2 h; R(300)/R(4) = 2,600; sample completely immersed in bath of either liquid helium or liquid hydrogen during measurements; resistivities computed from resistance ratios, value used for room temperature resistivity 2.7 x 10^{-6} Ω cm (Rutter, J.W. and Reekie, J. [81]; reported error 10%.
139*	68	Aleksandrov, B.N. and D'yakov, I.G.	1963	A	273-650		99.9 Al, 0.05 Si, 0.03 B; $\rho_{273\ K}$ = 2.417 x 10^{-8} Ω m assumed; data of Pochapsky [96]; error in resistance ±1%.
140*	68	Aleksandrov, B.N. and D'yakov, I.G.	1963	A	14-290		Single crystal with wire axis coincident with either principal axis or [110] direction; wire diam. 10-15 mm; data taken from figure.
141*	68	Aleksandrov, B.N. and D'yakov, I.G.	1963	A	14-261		Polycrystalline Al wire with axis coincident either with the principal axis or with [110] direction; purified by zone melting; $\rho_{4.2}/\rho_{293}$ = 3.4 x 10^{-5}; below <14 K, $\rho \sim T^5$; data extracted from figure.
142*	69	Swanson, M.L., Piercy, G.R., and MacKinnon, D.J.	1962	A	1.8	1	99.99 Al; strip specimen 0.003 in. thick; annealed 0.010 in. wires rolled at room temperature; annealed.
143*	69	Swanson, M.L., et al.	1962	A	1.8	2	Similar to the above specimen.
144*	69	Swanson, M.L., et al.	1962	A	1.8	3	Same as above specimen.
145*	69	Swanson, M.L., et al.	1962	A	1.8	4	99.999 Al; strip specimen 0.008 in. thick; annealed 0.010 in. wires rolled at room temperature; annealed.
146*	70	Korol'kov, A.M. and Shashkov, D.P.	1962		294-1073		No details given.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
147*	71	Sirota, N.N.	1962		20-372		No details given; data taken from figure.
148	72	Powell, R.L., Hall, W.J., and Roder, H.M.	1960	A	4-76	Single crystal High purity	99.995 Al, originally; single crystal; the JM 340 rod made from Johnson-Matthey stock by Horizons, Inc., Cleveland, Ohio; ground to 3.66 mm diam.; chemical etching after the reduction in diameter indicated the material was still a single crystal; after the last fabrication the rod was annealed in vacuum at about 400°C for 2 h; data extracted from smooth curve; reported error 2%.
149	73	Hedgcock, F.T., Muir, W.B., and Wallingford, E.	1960	A	2.7-26	GKP	<0.002 Cu, <0.002 Fe, <0.002 Mg, <0.001 Mn, <0.001 Si; prepared by the Aluminum Co. of Canada; cold-rolled; annealed in helium at 300°C for 24 h; values calculated from graphically reported ρ/ρ_{300} values using ρ_{300} = 2.77 x 10^{-8} Ω m; reported error 0.5%.
150	74	Simmons, R.O. and Balluffi, R.W.	1960		287-928	High purity Al	99.995 Al, 0.003 Cu, 0.001 Fe, and 0.001 Si; material donated by Aluminum Co. of America; annealed a few degrees below 933 K for several days; swaged and drawn into 0.43 mm diam. wire; R(273 K)/R(4.2 K) = 414 after annealing and essentially the same value for the starting material; resistance ratios corrected for thermal expansion from crude dimensional measurements on specimen ρ(20°C) = 2.70 ± 0.12 μΩ cm; therefore, standard value of ρ(20°C) = 2.6548 μΩ cm.
151	75	DeSorbo, W.	1958	A	1-20	Zone refined	Spectroscopic composition: "trace" of Cu, specimen 0.020 in. diam. x 7-9 ft. long; obtained from W. E. Trogert; single crystal obtained after 6 passes of zone-refining, machined, swaged, and then drawn; between each swaging and each drawing, metal pickled in warm 15% NaOH solution; drawing done with diamond die; heat treatment: annealed for several hours at 550°C and cooled 2-3°C/min.
152	75	DeSorbo, W.	1958	A	1-20	Zone refined	Same sample as above except heat treatment air quenched from 350°C.
153	75	DeSorbo, W.	1958	A	1-20	Zone refined	Same sample as above except heat treatment air quenched from 550°C.
154	75	DeSorbo, W.	1958	A	1-20	Zone refined	Same sample as above except heat treatment fast quenched from 510°C.
155	76	Mikryokov, V.E.	1958	K	339-795		Pure; polycrystal; data from figure; error 1-1.5%; Kohlrausch method.
156	77	Mikryokov, V.E.	1957	K	338-797		99.99 Al; polycrystalline.
157	78	Roll, A., Motz, H., and Felger, H.	1957	R	933-1473		Pure liquid Al; data is represented by linear equation ρ (in μΩ cm) = 0.0146·T(K) + 10.56.
158*	79	Broom, T.	1952	B	90-373		99.996+ Al; impurities 0.002 Mg, <0.001 Si, <0.0005 Cu, Fe; wire drawn from 0.183 cm to 0.056 cm diam. then annealed at 500°C for 2 h and furnace cooled; Kelvin double bridge method.
159*	80	Andrews, F.A., Webber, R.T., and Spohr, D.A.	1951	A	4.2,273	Al I	99.996+ Al, 0.001 Mg, 0.001 Si, 0.0006 Fe, 0.0004 Cu, and 0.0004 Na; single crystal rods, 0.15 in. diam. x 4 in. long; from Alcoa; ρ_0 = 0.00304 x 10^{-8} Ω m; Wenner potentiometer; reported error <2%.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
160*	80	Andrews, F.A., et al.	1951	A	4.2,273	Al II	Similar to the above specimen; $\rho_0 = 0.00385 \times 10^{-8}\ \Omega$ m.
161*	80	Andrews, F.A., et al.	1951	A	4.2,273	Al III	99.995+ Al, 0.002 Mg, 0.001 Si, and trace Cu, Fe, and Na; polycrystalline; from Johnson and Matthey; rods 0.15 in. diam. x 4 in. long; $\rho_0 = 0.00551 \times 10^{-8}\ \Omega$ m.
162*	81	Rutter, J.W. and Reekie, J.	1950		20-297	H-S brand	99.999 Al; polycrystalline; rod specimen; from Johnson, Matthey Ltd.; H-S brand; not cold worked.
163*	81	Rutter, J.W. and Reekie, J.	1950		20-297	H-S	Same as the above specimen except percent reduction of area was 17.9%, i.e., cold worked from annealed state by drawing through diamond dies at uniform speed.
164*	81	Rutter, J.W. and Reekie, J.	1950		20-297	H-S	Same as the above specimen except percent reduction of area was 40.4%.
165*	81	Rutter, J.W. and Reekie, J.	1950		20-297	H-S	Same as the above specimen except percent reduction of area was 60.2%.
166*	81	Rutter, J.W. and Reekie, J.	1950		20-297	H-S	Same as the above specimen except percent reduction of area was 83.1%.
167*	82	Powell, H. and Evans, E.J.	1942		273		99.99 Al; 0.4 cm x 2.5 cm x 12 cm; electrically refined aluminum from Aluminum Industries, A. G. Nenhansen, Switzerland; specimen heated up to the annealing temperature and maintained at that temperature from 2-3 weeks, specimen then allowed to cool slowly to room temperature; resistivity was measured at 273 K, specimen was then heated in furnace and previous annealing temperature was continued for about 3 weeks; after cooling the resistivity of each specimen at 273 K was again determined, this process was continued until no change in resistivity at 273 K was found upon further annealing; density 2.71 g cm^{-3}.
168*	82	Powell, H. and Evans, E.J.	1942		273		Same as the above specimen before annealing.
169*	83	Taylor, C.S., Willey, L.A., Smith, D.W., and Edwards, J.D.	1938		293	High purity	99.9960 Al (by difference), 0.0020 Si, 0.0010 Cu, 0.0003 Ca, 0.0003 Mg, 0.0003 Na, and 0.0001 Fe; specimen 14 gage sheet, 1 in. wide, 24 in. long; produced by Compagnie des Produits Chimiques et Electrometallurgiques d'Alais Froges et Camargue; electrolytically refined notch-bar ingot remelted in graphite crucible, cast in sheet ingot 1.5 in. thick, cold-rolled to 1 in. thick, surface of slab removed by machining, and further cold-rolled.
170*	84	Eucken, A. and Warrertrup, H.	1935		273.2		99.7 Al.
171*	85	Kapitza, P.	1929	A	88	Al_I	99.951 Al, 0.021 Cu, 0.013 Si, 0.012 Fe, 0.002 Ti, 0.001 Vn; wire specimen 0.17 mm in diam. from American Aluminum Co.; resistance ratio R(290 K)/R(91 K) = 8.77; units not explicitly given, presume they are in Ω cm.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
172*	85	Kapitza, P.	1929	A	88	Al_{II}	Spectroscopic comparison with Al_I showed Al_{II} somewhat more impure than Al_I, chief impurity copper; strip specimen 0.1 mm thick and about 0.5 mm wide; from Aluminum Co. of America, gift of Dr. Chadwick; resistance ratio R(290 K)/R(91 K) = 7.09; units not explicitly given, presume they are in Ω cm.
173*	85	Kapitza, P.	1929	A	88	Al_{III}	Spectroscopic comparison showed Al_{III} somewhat more impure than Al_{II}, copper chief impurity; wire specimen 0.15 in diam.; from Hartmann and Braun; resistance ratio R(290 K)/R(91 K) = 7.14; units not explicitly given, presume they are in Ω cm.
174*	85	Kapitza, P.	1929	A	88	Al_{III}	The above specimen after magnetoresistivity measurements performed with magnetic field perpendicular to current; resistance ratio R(290 K)/R(88 K) = 8.26; units not explicitly given, presume they are in Ω cm.
175*	86	Staebler, T.	1929		89-476		Pure.
176*	87	Grüneisen, E. and Goens, E.	1927	A	21.2-273.2	Aluminum 1	Rather pure; source Aluminum Co. of America; turned into small rod from coarse-grained casting; annealed in vacuum at 300°C for 2.5 h; thermal resistivity 0.0500 and 0.289 $W\,cm^{-1}K^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 1.77 and 1.27 x 10^{-8} $\Omega\,W\,K^{-2}$ at 21.2 and 83.2 K, respectively.
177*	87	Grüneisen, E. and Goens, E.	1927	A	21.2-273.2	Al 3	Same as above; grain size 5-15 mm long; drawn and annealed, then stretched 2.5%, and recrystallized by annealing thermal resistivity 0.0840 and 0.290 $W\,cm^{-1}K^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 1.97 and 1.32 x 10^{-8} $W\,K^{-2}$ at 21.2 and 83.2 K, respectively.
178*	87	Grüneisen, E. and Goens, E.	1927	A	21.2-273.2	Al 100	Technically pure; source unknown, commercial conductor; annealed in vacuum at 250°C; thermal resistivity 0.341 and 0.374 $W\,cm^{-1}K^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.18 and 1.47 x 10^{-8} $\Omega\,W\,K^{-2}$ at 21.2 and 83.2 K, respectively.
179*	87	Grüneisen, E. and Goens, E.	1927	A	21.2-273.2	Al 101	Same as above; after annealing stretched 3% and recrystallized by annealing; thermal resistivity 0.470 and 0.408 $W\,cm^{-1}K^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.20 and 1.55 x 10^{-8} $\Omega\,W\,T^{-2}$ at 21.2 and 83.2 K, respectively; measuring length = 2 crystal grains.
180*	87	Grüneisen, E. and Goens, E.	1927	A	21.2-273.2	Al 21	Moderately pure; single crystal; grown by recrystallization; thermal resistivity 0.730 and 0.481 $W\,cm^{-1}K^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.20 and 1.66 x 10^{-8} $\Omega\,W\,K^{-2}$ at 21.2 and 83.2 K, respectively.
181	88	Matuyama, Y.	1927	-	959-1198		Chemically pure; melting point 931.65 K, r = 2.58 mm, ℓ = 62.? mm, σ_{em} = 25.5 x 10^{-8}.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
182*	89	Smith, A.W.	1925	B	296.2		99.97+ Al; 1.9 cm diam. x 10 cm long; specimen from Aluminum Co. of America.
183	90	Schofield, F.H.	1925	A	289-814		99.7 Al; free from discontinuities between core and surrounding layers, inclusion of dross, oxidized skin, and unsoundness; supplied by British Aluminium Co., Ltd.; 6.75 in. diam. billets cast from a maximum temperature of 973 K, annealed at 773 K for 2.5 h, extruded at 693 K to 0.75 in. diam.; annealed at 723 K for 2.5 h; density 2.70 g cm^{-3} at 294 K; reported error 1%.
184*	91	Holborn, L.	1921		273,293	Al IV	99.59 Al; 0.22 Si, 0.18 Fe, and 0.01 C.
185*	91	Holborn, L.	1921		273,293	Al IV	Same as the above except specimen was annealed.
186*	91	Holborn, L.	1921		273,293	Al VI	99.9 Al, 0.06 Cu, 0.02 Si, and trace of Fe; wire specimen 1 mm in diam. and 7.3 m wound on porcelain tube; material from specimen Al IV above purified, drawn by Heraeus.
187*	91	Holborn, L.	1921		273,293	Al VI	Above specimen annealed for a long time at 250°C.
188*	92	Holborn, L.	1919		20-195		99.6 Al, 0.4% impurities; polycrystalline.
189	93	Bornemann, K. and Wagenmann, K.	1914		973-1573		Pure aluminum specimen was obtained from Neubausen
190*	94	Wolff, F.A. and Dellinger, J.H.	1911		293		99.52-99.60 Al, 0.26-0.34 Si, and 0.14-0.15 Fe; commercial hard-drawn aluminum wire; density 2.70 g cm^{-3}.
191	95	Niccolai, G.	1908		84-673		Wire specimen obtained from Firma C.A.F. Kahlbaum; 0.5 mm diam. x 8 m long.

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al

[Temperature, T, K; Electrical Resistivity, ρ, 10^{-8} Ω m]

DATA SET 1*

T	ρ
1.600	0.93577 x 10^{-4}
1.650	0.93631
1.700	0.93686
1.755	0.93750
1.800	0.93804
1.850	0.93867
1.904	0.93937
1.950	0.94001
2.000	0.94073
2.050	0.94148
2.100	0.94226
2.145	0.94299
2.156	0.94318
2.167	0.94336
2.170	0.94341
2.171	0.94343 x 10^{-4}

DATA SET 2*

T	ρ
1.298	0.93306 x 10^{-4}
1.302	0.93308
1.322	0.93324
1.355	0.93351
1.362	0.93356
1.363	0.93358
1.402	0.93390
1.453	0.93436
1.500	0.93479
1.550	0.93526
2.171	0.94341
2.647	0.95304
2.647	0.95297
2.905	0.95982
3.149	0.96749
3.401	0.97660
3.646	0.98661
3.842	0.99557
4.042	1.0056
4.106	1.0092 x 10^{-4}

DATA SET 3*

T	ρ
1.600	0.93577 x 10^{-4}
2.171	0.94341 x 10^{-4}

DATA SET 4

T	ρ
2.631	0.69215 x 10^{-4}
3.796	0.73259
4.221	0.75419 x 10^{-4}

DATA SET 5*

T	ρ
2.362	0.68624 x 10^{-4}
2.582	0.69098
2.728	0.69456
2.989	0.70186
3.1875	0.70819
3.378	0.71501
3.596	0.72343
3.797	0.73302
3.997	0.74195 x 10^{-4}

DATA SET 6*

T	ρ
4.134	0.74837 x 10^{-4}
4.224	0.753804 x 10^{-4}

DATA SET 7*

T	ρ
1.180	0.67147 x 10^{-4}
1.191	0.67154
1.225	0.67176
1.298	0.67231
1.401	0.67316
1.500	0.67406
1.601	0.67506
1.701	0.67616
1.801	0.67737
1.901	0.67868
2.001	0.68014
2.101	0.68168
2.172	0.68286 x 10^{-4}

DATA SET 8*

T	ρ
2.578	1.3260 x 10^{-4}
2.725	1.3300
2.986	1.3382
3.186	1.3454
3.378	1.3532
3.596	1.3632

DATA SET 8 (cont.)*

T	ρ
3.770	1.3720
3.978	1.3836
4.132	1.3929
4.220	1.3985 x 10^{-4}

DATA SET 9*

T	ρ
1.950	1.3135 x 10^{-4}
2.000	1.3143
2.050	1.3151
2.101	1.3160
2.171	1.3172
2.329	1.3200
2.468	1.3232
2.80	1.3323 x 10^{-4}

DATA SET 10*

T	ρ
1.292	1.3060 x 10^{-4}
1.402	1.3069
1.501	1.3079
1.541	1.3083
1.601	1.3090
1.650	1.3095
1.701	1.3101
1.750	1.3107
1.800	1.3114
1.850	1.3121
1.900	1.3128 x 10^{-4}

DATA SET 11*

T	ρ
1.253	1.3056 x 10^{-4}
1.289	1.3059
1.352	1.3065
1.451	1.3074 x 10^{-4}

DATA SET 12*

T	ρ
2.049	2.9341 x 10^{-4}
2.100	2.9349 x 10^{-4}

DATA SET 13*

T	ρ
3.183	2.9662 x 10^{-4}

DATA SET 13 (cont.)*

T	ρ
3.593	2.9857
3.785	2.9967
3.978	3.0090
4.133	3.0198 x 10^{-4}

DATA SET 14*

T	ρ
1.501	2.9268 x 10^{-4}
1.700	2.9290
1.800	2.9303
1.900	2.9317
2.000	2.9332
2.171	2.9362
2.360	2.9402
2.578	2.9452
2.726	2.9497
2.988	2.9584
3.380	2.9749
4.221	3.0264 x 10^{-4}

DATA SET 15*

T	ρ
4.209	3.0254 x 10^{-4}

DATA SET 16*

T	ρ
1.254	2.9246 x 10^{-4}
1.302	2.9250
1.353	2.9254
1.402	2.9259
1.541	2.9272
1.601	2.9279 x 10^{-4}

DATA SET 17*

T	ρ
1.522	106.801 x 10^{-4}
1.763	106.804
1.986	106.681
2.162	106.811
2.610	106.821
2.994	106.834
3.389	106.853
3.389	106.852
3.80	106.879
4.218	106.916 x 10^{-4}

DATA SET 18*

T	ρ
1.294	110.640 x 10^{-4}
1.535	110.642
1.774	110.645
1.990	110.648
2.167	110.651
2.611	110.661
3.011	110.675
3.400	110.694
3.800	110.721
4.200	110.755 x 10^{-4}

DATA SET 19*

T	ρ
1.224	6.6282 x 10^{-4}
1.443	6.6298
1.600	6.6314
1.773	6.6332
1.989	6.6361
2.167	6.6388
2.628	6.6481
3.019	6.6594
3.407	6.6742
3.793	6.6935
4.101	6.7066
4.206	6.7198 x 10^{-4}

DATA SET 20*

T	ρ
1.371	6.0091 x 10^{-4}
1.663	6.0118
1.931	6.0151
2.102	6.0176
2.613	6.0277
3.022	6.0392
3.395	6.0534
3.803	6.0737
4.193	6.0981
4.229	6.0995 x 10^{-4}

DATA SET 21*

T	ρ
1.241	22.449 x 10^{-4}
1.521	22.452
1.762	22.454
1.982	22.458

DATA SET 21 (cont.)*

T	ρ
2.166	22.461
2.620	22.470
3.016	22.481
3.402	22.496
3.699	22.509
3.945	22.523
4.211	22.540 x 10^{-4}

DATA SET 22*

T	ρ
1.5	15.4 x 10^{-4}
4.1	15.4
6.2	15.9
8.0	17.0
9.7	18.1
11.6	19.2
13.3	20.8
15.5	23.5
17.4	25.6
19.0	28.8
21.4	33.1
23.9	40.0
25.7	46.4
27.8	55.4
29.5	65.5
31.4	79.9
32.2	86.8
34.4	109.0
36.0	129.0
36.5	135.0
37.6	153.0
39.5	184.0
41.6	222.0 x 10^{-4}

DATA SET 23*

T	ρ
1.5	1.60 x 10^{-4}
4.3	1.63
5.9	1.12
8.2	1.68
10.1	1.70
11.8	2.25
13.6	3.33
15.6	3.88
18.8	6.57

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

DATA SET 23 (cont.)*

T	ρ
20.7	9.24
23.1	12.9
25.0	18.3
26.7	24.1
28.1	30.5
29.2	37.4
31.1	50.2
32.2	61.3
33.6	75.7
34.7	86.8
35.6	98.0
37.1	121.0
39.3	155.0
41.1	195.0
42.0	217.0×10^{-4}

DATA SET 24*

T	ρ
1.5	3.73×10^{-4}
4.4	3.23
5.5	3.77
7.3	4.32
10.0	4.35
12.2	4.90
13.9	5.45
15.8	6.53
17.9	8.68
19.6	10.2
21.5	13.5
23.5	16.1
25.4	21.5
27.1	27.3
29.3	39.0
30.6	48.0
32.8	65.6
33.1	68.2
34.2	79.9×10^{-4}

DATA SET 25*

T	ρ
1.5	5.32×10^{-4}
4.3	5.35
5.1	5.36
6.8	6.44
7.5	6.44
8.9	6.46
10.5	7.54

DATA SET 25 (cont.)*

T	ρ
12.1	7.55
14.2	9.17
16.3	10.2
17.9	12.4
20.7	14.5
21.8	17.2
23.9	20.4
26.0	28.4
27.7	34.7
29.7	47.0
31.7	60.8
33.1	74.1
34.9	91.6
36.7	116.0
39.0	151.0
40.4	182.0×10^{-4}

DATA SET 26*

T	ρ
1.5	9.56×10^{-4}
4.3	9.59
5.7	10.6
6.6	10.6
8.0	10.7
9.0	11.2
10.3	11.7
13.0	13.4
14.6	15.0
17.6	17.7
19.5	20.9
21.3	23.5
22.8	27.3
24.7	31.5
26.5	38.4
27.7	43.2
29.2	51.2
30.3	57.0
31.7	66.6
33.9	87.3
36.1	113.0
37.8	137.0
39.8	173.0
41.5	210.0×10^{-4}

DATA SET 27*

T	ρ
1.5	12.7×10^{-4}

DATA SET 27 (cont.)*

T	ρ
4.1	12.7
5.7	12.7
8.0	13.8
9.7	14.9
11.2	15.5
13.0	17.1
15.4	19.2
17.6	21.0
19.3	24.0
21.7	28.8
23.9	34.7
25.7	40.0
27.5	48.5
29.9	60.2
31.7	73.5
32.6	82.0
34.7	102.0
36.0	119.0
37.5	139.0
39.5	176.0
41.5	218.0×10^{-4}

DATA SET 28

T	ρ
1.5	1.02×10^{-4}
4.2	1.08
6.0	1.27
7.5	1.49
8.5	1.63
10.0	1.96
12.5	2.64
15.0	3.70
17.5	5.14
20.0	7.62
22.5	11.4
25.0	17.8
27.5	28.5
30.0	43.4
32.5	64.6
35.0	92.1
37.5	130.0
40.0	175.4×10^{-4}

DATA SET 29

T	ρ
4.2	5.80×10^{-4}

DATA SET 30*

T	ρ
4.2	5.517×10^{-4}

DATA SET 31

T	ρ
4.2	6.706×10^{-4}

DATA SET 32

T	ρ
10	14.3×10^{-4}
13	15.9
17	19.1
20	20.6
25	23.7
32.8	85.9×10^{-4}

DATA SET 33

T	ρ
10	22.9×10^{-4}
13	24.1
17	27.2
20	31.0
25	43.6
32.8	95.4×10^{-4}

DATA SET 34

T	ρ
10	31.5×10^{-4}
13	32.6
17	35.6
20	39.3
25	51.7
32.8	102.0×10^{-4}

DATA SET 35

T	ρ
10	39.7×10^{-4}
13	40.7
17	43.6
20	47.6
25	60.4
32.8	112.0×10^{-4}

DATA SET 36

T	ρ
10	45.4×10^{-4}
13	46.5
17	49.4

DATA SET 36 (cont.)

T	ρ
20	53.5
25	66.0
32.8	118.0×10^{-4}

DATA SET 37

T	ρ
10	50.7×10^{-4}
13	51.9
17	54.9
20	58.9
25	72.5
32.8	126.0×10^{-4}

DATA SET 38

T	ρ
10	89.4×10^{-4}
13	92.5
17	98.2
20	105.0
25	123.0
32.8	182.0
47.9	500.0×10^{-4}

DATA SET 39

T	ρ
10	122.0×10^{-4}
13	124.0
17	129.0
20	134.0
25	151.0
32.8	208.0
47.9	528.0×10^{-4}

DATA SET 40

T	ρ
10	128.0×10^{-4}
13	130.0
17	135.0
20	140.0
25	157.0
32.8	214.0
47.9	534.0×10^{-4}

DATA SET 41

T	ρ
10	148.0×10^{-4}
13	150.0

DATA SET 41 (cont.)

T	ρ
17	154.0
20	160.0
25	176.0
32.8	234.0
47.9	555.0×10^{-4}

DATA SET 42

T	ρ
10	149.0×10^{-4}
13	151.0
17	156.0
20	161.0
25	179.0
32.8	241.0
47.9	570.0×10^{-4}

DATA SET 43

T	ρ
13	92.1×10^{-4}
20	107.0×10^{-4}

DATA SET 44

T	ρ
10	98.0×10^{-4}
13	100.0
17	106.0
20	112.0
25	129.0
32.8	187.0×10^{-4}

DATA SET 45*

T	ρ
10	103.0×10^{-4}
13	106.0
17	111.0
20	112.0
25	133.0
32.8	189.0×10^{-4}

DATA SET 46

T	ρ
10	112.0×10^{-4}
17	119.0
20	125.0
25	141.0
32.8	200.0

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

T	ρ
DATA SET 47*	
10	119.0 x 10^{-6}
13	121.0
17	125.0
25	148.0
32.8	205.0 x 10^{-6}
DATA SET 48*	
1.35	2.068 x 10^{-6}
1.46	2.069
1.55	2.071
1.66	2.073
1.78	2.077
1.86	2.079
1.95	2.080
2.07	2.081
2.18	2.083
2.29	2.085
2.41	2.089
2.50	2.091
2.58	2.094
2.69	2.097
2.81	2.099
2.92	2.102
2.98	2.104
3.10	2.108
3.21	2.112
3.32	2.116
3.38	2.122
3.50	2.124
3.61	2.130
3.72	2.134
3.84	2.137
3.95	2.139
4.04	2.143
4.13	2.152
4.24	2.159
4.35	2.167
4.47	2.171
4.55	2.177
4.70	2.182
4.75	2.188
4.87	2.198
4.98	2.204
5.10	2.208
5.18	2.215
5.30	2.223

T	ρ
DATA SET 48 (cont.)*	
5.41	2.238
5.52	2.244
5.61	2.255
5.72	2.267
5.81	2.275
5.92	2.284
6.01	2.294
6.12	2.301
6.23	2.316
6.35	2.323
6.46	2.339 x 10^{-6}
DATA SET 49*	
1.5	2.35 x 10^{-6}
2.0	2.36
3.0	2.39
4.0	2.43 x 10^{-6}
DATA SET 50*	
1.5	2.03 x 10^{-6}
2.0	2.04
3.0	2.06
4.0	2.10 x 10^{-6}
DATA SET 51*	
1.5	6.21 x 10^{-6}
2.0	6.22
3.0	6.26
4.0	6.30 x 10^{-6}
DATA SET 52*	
1.5	5.20 x 10^{-6}
2.0	5.21
3.0	5.24
4.0	5.27 x 10^{-6}
DATA SET 53*	
1.5	0.95 x 10^{-6}
2.0	0.95
3.0	0.98
4.0	1.01 x 10^{-6}

T	ρ
DATA SET 54*	
1.5	4.65 x 10^{-6}
2.0	4.66
3.0	4.68
4.0	4.71 x 10^{-6}
DATA SET 55*	
933	24.2
DATA SET 56	
2	4.6 x 10^{-6}
15.05	7.9
20.08	12.5
25.00	23.2
30.45	55.7
40.42	195.2 x 10^{-6}
295	2.66
DATA SET 57*	
1.51	4.49 x 10^{-6}
2.51	4.51
3.32	4.53
3.72	4.55
4.05	4.57
4.41	4.59
4.94	4.64
5.85	4.72
6.36	4.80
6.93	4.88
7.33	4.98
7.76	5.08
8.21	5.23
8.68	5.35
9.19	5.48
9.72	5.54 x 10^{-6}
DATA SET 58*	
0	13.55 x 10^{-6}
1.50	13.55
1.89	13.56
2.06	13.56
2.38	13.57
2.76	13.57
3.28	13.59

T	ρ
DATA SET 58 (cont.)*	
3.69	13.61
4.02	13.63
4.26	13.64
4.65	13.66
5.38	13.75
6.23	13.77
6.41	13.85
7.20	13.92
7.63	14.03
8.33	14.09
8.83	14.19
9.09	14.28 x 10^{-6}
DATA SET 59	
973.6	24.4
997.7	24.8
1023.6	25.1
1040.7	25.3
1074.2	25.8
1091.3	25.7
1109.7	26.2
1122.3	26.2
DATA SET 60	
10	222.0 x 10^{-6}
14	227.0
20	242.0 x 10^{-6}
DATA SET 61	
10	532.0 x 10^{-6}
14	537.0
20	552.0 x 10^{-6}
DATA SET 62	
300	2.733
DATA SET 63*	
4.09	11.7 x 10^{-6}
7.92	12.6
9.90	13.5
11.8	14.8
13.8	16.3

T	ρ
DATA SET 63 (cont.)*	
15.8	18.2
17.8	20.7
19.8	23.9
21.6	28.6
23.6	35.9
25.5	42.3
27.6	51.8
29.6	65.4
31.2	79.0 x 10^{-6}
DATA SET 64*	
4.21	6.62 x 10^{-6}
7.05	6.92
9.77	7.84
11.8	8.78
13.8	10.0
15.8	11.2
17.8	13.4
19.7	16.0
21.6	20.1
25.7	31.5
27.6	43.2
29.4	57.5
31.4	79.0 x 10^{-6}
DATA SET 65*	
4.20	3.77 x 10^{-6}
5.93	4.07
8.03	4.68
10.0	5.30
11.9	6.24
13.9	7.17
16.0	8.10
17.8	10.3
19.7	12.8
21.7	16.3
23.7	21.6
25.7	29.2
27.7	38.4
29.6	52.7
31.3	66.7 x 10^{-6}
DATA SET 66*	
5.56	2.80 x 10^{-6}

T	ρ
DATA SET 66 (cont.)*	
7.66	3.10
10.0	3.71
12.1	4.01
13.8	4.95
17.8	8.09
19.6	10.6
21.6	13.7
23.7	19.1
25.7	25.4
27.6	34.6
29.5	47.6
31.3	61.3 x 10^{-6}
DATA SET 67*	
4.20	1.86 x 10^{-6}
6.05	1.85
8.03	2.46
10.0	2.76
11.9	3.38
13.9	3.68
15.9	4.93
17.9	6.18
19.7	8.39
21.6	11.8
23.7	17.2
25.8	25.1
29.7	52.1
31.4	65.4 x 10^{-6}
DATA SET 68*	
273	2.46
DATA SET 69	
4.2	0.00025
20	0.0008
30	0.0043
40	0.0179
50	0.0472
60	0.0953
70	0.1618
80	0.2439
90	0.3377
100	0.4401
120	0.6601

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM ' Al (continued)

DATA SET 69 (cont.)

T	ρ
140	0.8899
160	1.123
180	1.356
200	1.589
220	1.820
240	2.049
260	2.278
280	2.506
300	2.733
320	2.961
340	3.189
360	3.416
380	3.645
400	3.875

DATA SET 70*

T	ρ
318	2.943

DATA SET 71*

T	ρ
318	2.945

DATA SET 72

T	ρ
7.09	13.0×10^{-4}
9.27	13.2
10.0	13.6
12.2	14.3
14.0	15.3
16.9	17.0
18.7	19.9
21.3	25.3
22.0	29.0
25.3	43.9×10^{-4}

DATA SET 73

T	ρ
7.09	12.6×10^{-4}
8.91	12.8
10.0	13.0
12.2	13.5
14.0	14.1
16.5	15.6
19.1	18.1
21.3	23.5
22.7	26.7
25.6	42.4×10^{-4}

DATA SET 74

T	ρ
7.99	89.0×10^{-4}
10.5	91.0
13.2	93.0
16.9	196.0
19.6	260.0
24.6	448.0×10^{-4}

DATA SET 75

T	ρ
8.19	89.0×10^{-4}
10.5	102.0
13.2	118.0
16.5	160.0
19.6	214.0
24.6	382.0×10^{-4}

DATA SET 76*

T	ρ
4.2	0.000182
273.15	2.429
300	2.733

DATA SET 77

T	ρ
938	24.20

DATA SET 78*

T	ρ
293	2.65

DATA SET 79

T	ρ
8.77	0.00014
35.0	0.044
74.5	0.222
79.24	0.261
96.7	0.419
110.4	0.611
125.4	0.802
155.3	1.089
189.7	1.439
210.5	1.694
237.8	1.980
264.4	2.299
280.3	2.394
297.8	2.660
359.1	3.324
389.8	3.679

DATA SET 79 (cont.)

T	ρ
416.0	3.989
442.3	4.255
468.6	4.653
499.2	4.964
551.8	5.584
573.6	5.894
604.3	6.249
634.9	6.647
661.2	7.002
678.7	7.179
705.0	7.533
735.6	7.932
744.3	8.109
761.9	8.286
788.1	8.552
814.4	8.863
845.0	9.306
880.1	9.749
893.2	10.10
919.4	10.50
928.2	10.63

DATA SET 80

T	ρ
4.2	0.00231
77	0.237

DATA SET 81

T	ρ
3.2	0.0004
6.2	0.0005
9.0	0.0006
11.7	0.0007
14.4	0.0008
16.3	0.0011
18.4	0.0016
21.3	0.0023
24.1	0.0032
25.2	0.0042
28.2	0.0056
28.5	0.0072
32.0	0.0096
34.6	0.0126
35.3	0.015
38.4	0.022
42.5	0.034
46.3	0.034
50.8	0.055

DATA SET 81 (cont.)

T	ρ
58.9	0.097
63.8	0.125
66.4	0.14
69.8	0.17
77.2	0.22
81.6	0.25
88.6	0.31
91.1	0.33
100.5	0.44
106.6	0.49
122.8	0.67
140.6	0.87
145.5	0.94
162.1	0.14
165.8	1.19
169.5	1.23
179.5	1.36
181.6	1.39
189.5	1.49
200.0	1.59

DATA SET 82*

T	ρ
4.2	0.018
77	0.265

DATA SET 83

T	ρ
976	24.8
1302	29.6

DATA SET 84*

T	ρ
74.98	0.4318
266.5	2.713

DATA SET 85*

T	ρ
1.30	24.093×10^{-4}
1.50	24.095
2.27	24.106
2.45	24.110
2.56	24.113
2.71	24.117
3.00	24.127
3.12	24.132
3.59	24.152
4.01	24.178

DATA SET 85 (cont.)*

T	ρ
4.13	24.186
4.21	24.192×10^{-4}

DATA SET 86*

T	ρ
2.98	433.15×10^{-4}
3.20	433.16
3.57	433.18
3.74	433.19
3.91	433.21
3.97	433.21
4.12	433.22
4.19	433.23×10^{-4}

DATA SET 87

T	ρ
993	24.7

DATA SET 88*

T	ρ
1120	27.0

DATA SET 89

T	ρ
842.5	9.96
872.0	10.30
897.8	10.68
930.2	11.19
932.5	11.60
933.9	24.81
943.4	24.98
949.3	25.15
957.4	25.14
967.0	25.13
986.8	25.47
1007.4	25.81
1014.0	25.80
1030.2	25.97
1041.3	26.35

DATA SET 90*

T	ρ
4.2	0.00012
273.2	0.72

DATA SET 91*

T	ρ
4.5	0.00102
295	2.33

DATA SET 92*

T	ρ
77	0.748

DATA SET 93*

T	ρ
77	0.705

DATA SET 94

T	ρ
1923	39.89

DATA SET 95

T	ρ
1798	35.56
1923	37.23

DATA SET 96

T	ρ
1973	88.615

DATA SET 97*

T	ρ
4.2	12.43×10^{-4}

DATA SET 98*

T	ρ
4.2	14.35×10^{-4}

DATA SET 99*

T	ρ
4.2	13.22×10^{-4}

DATA SET 100*

T	ρ
4.2	13.95×10^{-4}

DATA SET 101

T	ρ
4.2	13.29×10^{-4}

DATA SET 102*

T	ρ
4.2	13.47×10^{-4}

DATA SET 103

T	ρ
273	2.521

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

DATA SET 104

T	ρ
300	2.65
400	3.85
500	4.90
600	6.05
700	7.15
800	8.30
900	9.40

DATA SET 105

T	ρ
10	0.00075
20	0.00143
30	0.00532
40	0.01867
50	0.04807
60	0.09640
70	0.1632
80	0.2455
90	0.3400
100	0.4425
120	0.6631
140	0.8934
160	1.127
180	1.361
200	1.593
220	1.824
240	2.053
260	2.280
273.2	2.430
295	2.678

DATA SET 106*

T	ρ
273.2	2.485

DATA SET 107

T	ρ
193.7	1.52
248.2	2.14
298.2	2.72
351.2	3.33
408.4	4.05

DATA SET 108*

T	ρ
293	2.9

DATA SET 109

T	ρ
321	3.03
340	3.09
367	3.57
397	3.85
424	4.12
441	4.32
496	4.94
605	6.24
655	6.79
662	6.92
693	7.33

DATA SET 110

T	ρ
77	0.221
273	2.425

DATA SET 111*

T	ρ
4.6	0.00261
15.1	0.00383
17.7	0.00380
21.0	0.00109
24.9	0.00505
27.8	0.00768
30.1	0.0103
35.4	0.0156
41.9	0.0302
48.1	0.0461
54.0	0.0647
61.3	0.103
69.8	0.169
80.0	0.260
90.3	0.375

DATA SET 112*

T	ρ
1.5	0.00428
293	2.84

DATA SET 113*

T	ρ
8.7	57.7×10^{-6}
11.2	58.6
13.2	59.7
15.8	61.7
18.9	65.0

DATA SET 113 (cont.)*

T	ρ
20.4	67.1×10^{-6}
21.8	69.5
23.0	72.1
24.4	75.1
25.4	78.3
26.4	82.3
27.8	88.7
28.9	95.0
30.2	102.6
31.4	110.8
32.3	118.1
33.2	126.8
34.1	136.8
34.7	144.2×10^{-6}

DATA SET 114

T	ρ
6.7	22.7×10^{-6}
9.4	23.5
11.4	24.5
13.3	25.6
16.1	27.7
18.5	30.2
20.1	32.2
21.8	34.7
23.3	37.8
24.7	41.1
25.8	43.9
26.9	48.1
27.9	52.4
29.0	57.2
29.9	61.9
30.6	66.4
31.6	73.4
32.6	81.6
33.4	88.6
34.0	95.3
34.3	100.6×10^{-6}

DATA SET 115

T	ρ
77.78	0.2257
194.6	1.554
273.2	2.450
298.5	2.724

DATA SET 116

T	ρ
883	10.3
922	10.8
933	20.1
936	20.2
939	20.6
943	20.7
944	20.4
947	20.5
960	20.6
963	20.7
974	20.7
998	21.0
1001	21.0
1004	21.1
1006	21.1
1008	21.2
1014	21.2
1025	21.4
1034	21.3
1044	21.7
1050	21.6
1078	22.1
1080	22.2

DATA SET 117

T	ρ
4.2	0.00725

DATA SET 118

T	ρ
298	2.74
373	3.57
473	4.71
573	5.86
673	7.06
773	8.30

DATA SET 119

T	ρ
20.4	40.9×10^{-6}

DATA SET 120*

T	ρ
20.4	69.7×10^{-6}

DATA SET 121*

T	ρ
4.2	0.00111
20.4	0.00238
77	0.221
195	1.44
273	2.46

DATA SET 122*

T	ρ
4.2	0.00575
20.4	0.00766
77	0.224
195	1.50
273	2.30

DATA SET 123

T	ρ
4.2	0.0439
20.4	0.0463
77	0.270
195	1.62
273	2.42

DATA SET 124

T	ρ
4.2	0.087
20.4	0.0942
77	0.341
195	1.63
273	2.46

DATA SET 125

T	ρ
100	0.441
120	0.668
140	0.901
160	1.133
180	1.367
200	1.599
220	1.830
240	2.062
260	2.292
280	2.522
300	2.751
320	2.982
340	3.211
360	3.443

DATA SET 126*

T	ρ
973	25

DATA SET 127

T	ρ
313	2.86
373	3.56
473	4.73
573	5.90
673	7.12

DATA SET 128

T	ρ
323	2.98
373	3.56
473	4.73
573	5.90
673	7.12
773	8.51
873	9.92

DATA SET 129

T	ρ
123	0.74
173	1.31
223	1.89
273	2.46
323	3.02

DATA SET 130

T	ρ
973	26.3
1023	27.1
1073	27.8
1123	28.6
1173	29.3
1223	30.1
1273	30.9

DATA SET 131

T	ρ
4.2	0.0586

DATA SET 132*

T	ρ
4.2	0.0166

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

DATA SET 133*

T	ρ
20.4	0.698

DATA SET 134*

T	ρ
20.4	0.624

DATA SET 135

T	ρ
2.24	9.0×10^{-4}
4.00	9.1
6.40	9.4
6.40	9.5
8.55	10.0
9.35	10.2
10.2	10.4
12.51	12.3
15.3	15.0
19.6	22.2
23.4	40.4
28.0	96.3×10^{-4}

DATA SET 136

T	ρ
2.19	5.70×10^{-4}
2.56	5.70
3.06	5.70
3.58	5.72
3.91	5.77
7.31	6.31
8.94	6.98
9.56	7.07
13.68	9.82
16.38	13.3
17.10	14.4
21.39	26.5×10^{-4}

DATA SET 137

T	ρ
4	20.0×10^{-4}
20	28.2
30	69.9×10^{-4}

DATA SET 138

T	ρ
4	0.00106
20	0.00201
30	0.00514

DATA SET 139*

T	ρ
273	2.417
373	2.500
473	4.619
573	5.801
673	7.046
773	8.346
823	9.170
873	9.755
898	10.139
923	10.540

DATA SET 140*

T	ρ
14.2	0.000153
15.5	0.000211
16.2	0.000266
17.0	0.000334
18.6	0.000383
20.3	0.000482
21.2	0.000607
59.5	0.0825
68.1	0.119
85.3	0.227
97.7	0.328
128.3	0.569
290.4	2.16

DATA SET 141*

T	ρ
14.2	0.000158
14.8	0.000218
16.3	0.000286
17.8	0.000343
17.8	0.000376
19.5	0.000494
20.4	0.000649
58.0	0.000809
60.7	0.116
79.8	0.230
87.4	0.347
115	0.627
261	2.25

DATA SET 142*

T	ρ
1.8	37.6×10^{-4}

DATA SET 143*

T	ρ
1.8	20.0×10^{-4}

DATA SET 144*

T	ρ
1.8	17.5×10^{-4}

DATA SET 145*

T	ρ
1.8	14.9×10^{-4}

DATA SET 146*

T	ρ
294	2.8
372	3.8
492	5.4
618	6.7
721	7.5
822	9.5
914	9.7
942	25.5
976	25.9
1024	26.1
1073	27.7

DATA SET 147*

T	ρ
20.08	0.070
80.13	0.422
186.6	1.252
272.6	2.362
372.0	3.445

DATA SET 148

T	ρ
4.00	0.02488
7.33	0.02489
13.40	0.02606
16.60	0.02642
19.77	0.02805
21.98	0.02992
25.01	0.03404
28.91	0.04018
35.08	0.05346

DATA SET 148 (cont.)

T	ρ
47.00	0.08630
76.04	0.2301

DATA SET 149

T	ρ
2.7	80.6×10^{-4}
4.1	80.6
5.3	80.9
5.7	80.9
6.3	82.0
6.7	82.0
7.2	82.8
7.8	83.9
8.7	82.3
9.2	81.7
10.3	85.6
11.0	83.7
11.7	83.9
12.6	84.5
13.4	87.5
14.5	87.5
16.1	91.4
19.1	99.4
21.9	106.0
26.1	126.0×10^{-4}

DATA SET 150

T	ρ
287.4	2.586
289.4	2.609
293.0	2.653
296.1	2.687
377.4	3.605
387.8	3.726
438.4	4.304
502.0	5.041
583.6	6.006
688.3	7.286
728.8	7.802
764.4	8.264
770.9	8.355
794.1	8.663
831.3	9.185
843.3	9.345
854.3	9.516
872.5	9.774
878.1	9.868

DATA SET 150 (cont.)

T	ρ
895.0	10.117
905.6	10.292
915.9	10.449
927.8	10.644

DATA SET 151

T	ρ
1.5	29.2×10^{-4}
2.3	29.2
3.0	29.2
4.0	29.4
14.1	34.9
16.0	37.3
18.0	40.2
20.0	44.1×10^{-4}

DATA SET 152

T	ρ
1.5	33.6×10^{-4}
2.3	33.6
3.0	33.7
4.0	33.7
14.2	39.8
16.0	41.9
18.0	45.2
20.0	49.1×10^{-4}

DATA SET 153

T	ρ
1.5	55.4×10^{-4}
2.3	55.4
3.0	55.4
4.0	55.5
14.3	62.5
16.0	65.0
18.0	68.7
19.9	73.5×10^{-4}

DATA SET 154

T	ρ
2.0	91.6×10^{-4}
3.0	91.7
4.2	91.9
13.9	98.6
14.9	100.0
15.9	102.0
16.9	103.9

DATA SET 154 (cont.)

T	ρ
17.9	106.3
18.8	108.8
19.7	111.4×10^{-4}

DATA SET 155

T	ρ
339	3.26
404	4.11
459	4.82
552	6.04
634	7.01
728	8.36
795	9.34

DATA SET 156

T	ρ
338.0	3.15
401.6	3.97
457.2	4.65
553.0	5.85
631.0	6.82
730.2	8.20
796.6	9.14

DATA SET 157

T	ρ
933.4	24.25
973	24.83
1073	26.30
1173	27.77
1273	29.24
1373	30.71
1473	32.17

DATA SET 158*

T	ρ
90.2	0.352
194.7	1.55
273.2	2.44
373.2	3.59

DATA SET 159*

T	ρ
4.2	0.00304
273.2	2.554

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ALUMINUM Al (continued)

T	ρ
DATA SET 160*	
4.2	0.00385
273.2	2.603
DATA SET 161*	
4.2	0.00551
273.2	2.573
DATA SET 162*	
20	0.0241
90	0.371
297	2.7414
DATA SET 163*	
20	0.0293
90	0.381
297	2.7330
DATA SET 164*	
20	0.0321
90	0.381
297	2.740
DATA SET 165*	
20	0.0281
90	0.377
297	2.7359
DATA SET 166*	
20	0.0261
90	0.406
297	2.750
DATA SET 167*	
273	2.50
DATA SET 168*	
273	2.52
DATA SET 169*	
293	2.65

T	ρ
DATA SET 170*	
273.2	2.695
DATA SET 171*	
88	0.318
DATA SET 172*	
88	0.394
DATA SET 173*	
88	0.382
DATA SET 174*	
88	0.342
DATA SET 175*	
89	0.725
273	2.70
374	3.92
476	5.16
DATA SET 176*	
21.2	0.0188
83.2	0.3065
273.2	2.50
DATA SET 177*	
21.2	0.0351
83.2	0.319
273.2	2.52
DATA SET 178*	
21.2	0.0157
83.2	0.458
273.2	2.65
DATA SET 179*	
21.2	0.219
83.2	0.525
273.2	2.72

T	ρ
DATA SET 180*	
21.2	0.340
83.2	0.663
273.2	2.84
DATA SET 181	
959.15	26.0
988.15	26.4
1018.15	26.8
1047.15	26.8
1089.15	27.6
1198.15	29.2
DATA SET 182*	
296.2	2.96
DATA SET 183	
289.4	2.83
290.0	2.79
290.0	2.81
346.2	3.45
350.2	3.53
352.2	3.53
433.2	4.47
434.2	4.48
575.9	6.15
577.6	6.23
579.4	6.24
672.2	7.39
773.2	8.77
775.6	8.79
813.9	9.31
DATA SET 184*	
273	2.74
293	2.99
DATA SET 185*	
273	2.64
293	2.87
DATA SET 186*	
273	2.61
293	2.84

T	ρ
DATA SET 187*	
273	2.53
293	2.75
DATA SET 188*	
20	0.108
80.1	0.367
81.1	0.380
194.7	1.64
DATA SET 189	
973	27.80
1073	29.28
1173	30.75
1273	32.22
1373	33.68
1473	35.17
1573	36.60
DATA SET 190*	
293	2.828
DATA SET 191	
84	0.641
98	0.795
123	1.038
148	1.282
173	1.535
198	1.782
223	2.067
248	2.321
273	2.618
298	2.928
323	3.237
348	3.562
373	3.858
398	4.192
423	4.498
448	4.827
473	5.172
498	5.518
523	5.850
548	6.204
573	6.559
598	6.917
623	7.274

T	ρ
DATA SET 191 (cont.)	
648	7.638
673	7.991

*Not shown in figure.

3.2. Manganese

There are 16 references available reporting temperature dependence of the electrical resistivity from 1 to 1873 K. However, the data are highly contradictory, and in several cases disagree both qualitatively and quantitatively. Further careful measurements on purer samples covering the entire temperature range, especially above 300 K and below 20 K, are required and strongly recommended. The information on specimen characterization and on measurement condition for each of the data sets is given in Table 5. The data sets are tabulated in Table 6 and partially shown in Figs. 4 and 5.

Electrical resistivity data on polycrystalline manganese reported earlier are much higher than those reported recently. These differences may be possibly due to the low purity and insufficient heat treatment of the manganese samples studied earlier. Meaden and Pelloux-Gervais[302] demonstrated that the room-temperature electrical resistivity dropped from 205 x 10^{-8} Ω m to 144.2 x 10^{-8} Ω m after annealing the specimen at 898 K.

Meaden[303] (data set 10), Bellou and Coles[306] (data set 14), and White and Woods[307] (data set 15), have reported T^2 dependence of the temperature-dependent resistivity (ρ_i) below 17 K. This was confirmed by Nagasawa and Senba[300] (data set 4) and by Murayama and Nagasawa[310] (data set 19). The recommended values from 20-325 K are based on the generally agreed upon data of Nagasawa and Senba[300] (data set 4), Meaden and Pelloux-Gervais[302], (data set 12), Bellou and Coles[306] (data set 14), and of White and Woods[307] (data set 16). The recommended values below 20 K for ρ_0 = 6.9 x 10^{-8} Ω m are based on the data of Meaden[303] (data set 10) and Meaden and Pelloux-Gervais[304] (data set 12).

An appreciable spin-disorder contribution is indicated by large resistivity values. It appears that the spin-disorder contribution generally present at higher temperatures still remains at liquid helium temperatures. The temperature dependent resistivity (ρ_i) falls linearly and slowly with temperature below 325 K. It goes through a minimum at about 94 K, and then remains practically constant for 4 to 5 degrees before increasing to a weak maximum at 70 K. Below this temperature, ρ_i drops very rapidly, finally becoming proportional to T^2 below 17 K.

Alpha-Mn is a stable phase below 980 K and has a complex cubic (A12) crystal structure with 58 atoms in the unit cell. At 980 K, α-Mn transforms to β-Mn which has a complex cubic structure (A13) with 20 atoms in the unit cell. It is possible to retain the β phase at room temperature by rapid quenching from 980-1300 K. Brunke[311] obtained a value of 91 x 10^{-8} Ω m for the electrical resistivity of β-Mn. Potter et al.[312] and Erfling[313] have reported about 40 x 10^{-8} Ω m for the room-temperature electrical resistivity of fct γ-Mn. High-temperature δ-Mn with a bcc structure is stable between 1411 and 1519 K.

There are only two data sources available in the temperature range 325-1519 K. Grube and Speidel[308] (data set 17) reported that the resistivity of manganese increases slowly with increasing temperature from 325 to 980 K and then decreases sharply from 980 to 1519 K. However, Akshentsev et al.[301] (data sets 5,6) reported that the electrical resistivity rises sharply between 800-980 K, then slowly from 980 to 1300 K followed by a slow decrease from 1300 to 1400 K and then further increases. The reliability of these results is questionable. Room-temperature electrical resistivity of Grube and Speidel[308] (data set 17) is twice as much as the recommended value, and indicates a high impurity in their sample. The value of 38 x 10^{-8} Ω m at 800 K for the electrical resistivity reported by Akshentsev et al.[301] (data set 5) is far lower than the recommended room-temperature value of 144 x 10^{-8} Ω m. Therefore, these data are rejected. The recommended values from 325 to 700 K are obtained by extrapolating the low-temperature data.

The published work on the electrical resistivity of molten manganese is equally contradictory. For instance, Akshentsev et al.[301] (data set 6) reported an increase in the resistivity with temperature, contrary to the results of Levin et al.[298] (data set 2) and of Vostryakov et al.[305] (data set 13) who reported a decrease in the resistivity with temperature. On the other hand, Grube and Speidel[308] (data set 17) reported a constant value of 40 x 10^{-8} Ω m from 1523 to 1543 K. Summarizing this, the electrical resistivity at the melting point varies from 40 to 190 x 10^{-8} Ω m. Therefore, the available data and information at and above melting point cannot be used for meaningful data analysis. Consequently, no recommendations were made for the electrical resistivity of manganese in the melting region.

The recommended values of the electrical resistivity given in Table 3 and shown in Figs. 4 and 5 along with the experimental data are for manganese of purity 99.99% or higher, but those below room temperature are applicable specifically to manganese with $\rho_0 = 6.90 \times 10^{-8}$ Ω m. The table gives both values uncorrected and corrected for thermal expansion, while the figure shows only the uncorrected values. The thermal expansion values needed for such correction are taken from ref. 314. The uncertainty in the recommended values is estimated to be within $\pm$10% from 7 to 100 K and above 300 K, and $\pm$5% below 7 K and from 100 to 300 K.

The effect of a magnetic field on the resistivity of manganese at low temperature is relatively small compared with that for pure copper. Meaden[303] found that a magnetic field of 18.5 kOe increases the resistivity by 10.5% at 4.2 K, 9% at 5.4 K, 8% at 5.9 K, and 0.2% at 77 K. Murayama and Nagasawa[310] (data set 19) studied temperature and magnetic field dependence of the resistivity of polycrystalline α-Mn and observed that the anomalously large coefficient of T^2 term in the low temperature resistivity decreased appreciably for an increase in the applied field, suggesting the suppression of spin fluctuations in the antiferromagnetic α-Mn by the high applied field. Those readers seeking additional information on the effect of magnetic field on the electrical resistivity of manganese are directed to refs. 315-341.

Adanu and Grassie[297] (data set 1) studied the temperature dependence of the electrical resistivity of a thin manganese film. For a film of thickness 4000 A formed on a thin glass substrate, they found that the resistivity decreased linearly as the temperature was reduced from room-temperature, then passed through a minimum at ~120 K and a maximum at ~70 K, followed by a sharp drop before going through another minimum at 22 K. These features of the resistivity of thin films, with the exception of the minimum at ~22 K, are qualitatively similar to those reported for bulk specimens reported by Meaden and Pelloux-Gervais[302] (data set 12) and by White and Woods[307] (data sets 15,16). Additional information/data on films are reported in refs. 342-350. The pressure dependence of the electrical resistivity is reported in refs. 352-355.

TABLE 4. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF MANGANESE[a]

[Temperature, T, K; Electrical Resistivity, ρ, 10^{-8} Ω m]

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
0	6.90	6.88	94	131.9	131.4
1	7.02	7.00	100	132.5	132.1
4	8.82	8.79	150	136.3	135.9
7	12.78	12.74	200	139.4	139.1
10	18.90	18.84	250	142.0	141.9
15	33.9	33.8	273	143.1	143.0
20	53.8	53.6	293	144.0	144.0
25	75.8	75.6	300	144.2	144.2
30	93.7	93.4	350	145.9	146.1
40	116.0	115.6	400	147.3	147.7
50	126.5	126.1	500	149.4	150.1
60	131.2	130.7	600	150.9	152.1
70	133.0	132.5	700	151.9	153.6
80	132.5	132.0			
90	132	131.5			

[a]The values are for well-annealed manganese of purity 99.99% or higher, but those below room temperature are applicable specifically to manganese having a residual resistivity of 6.90 x 10^{-8} Ω m. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively.

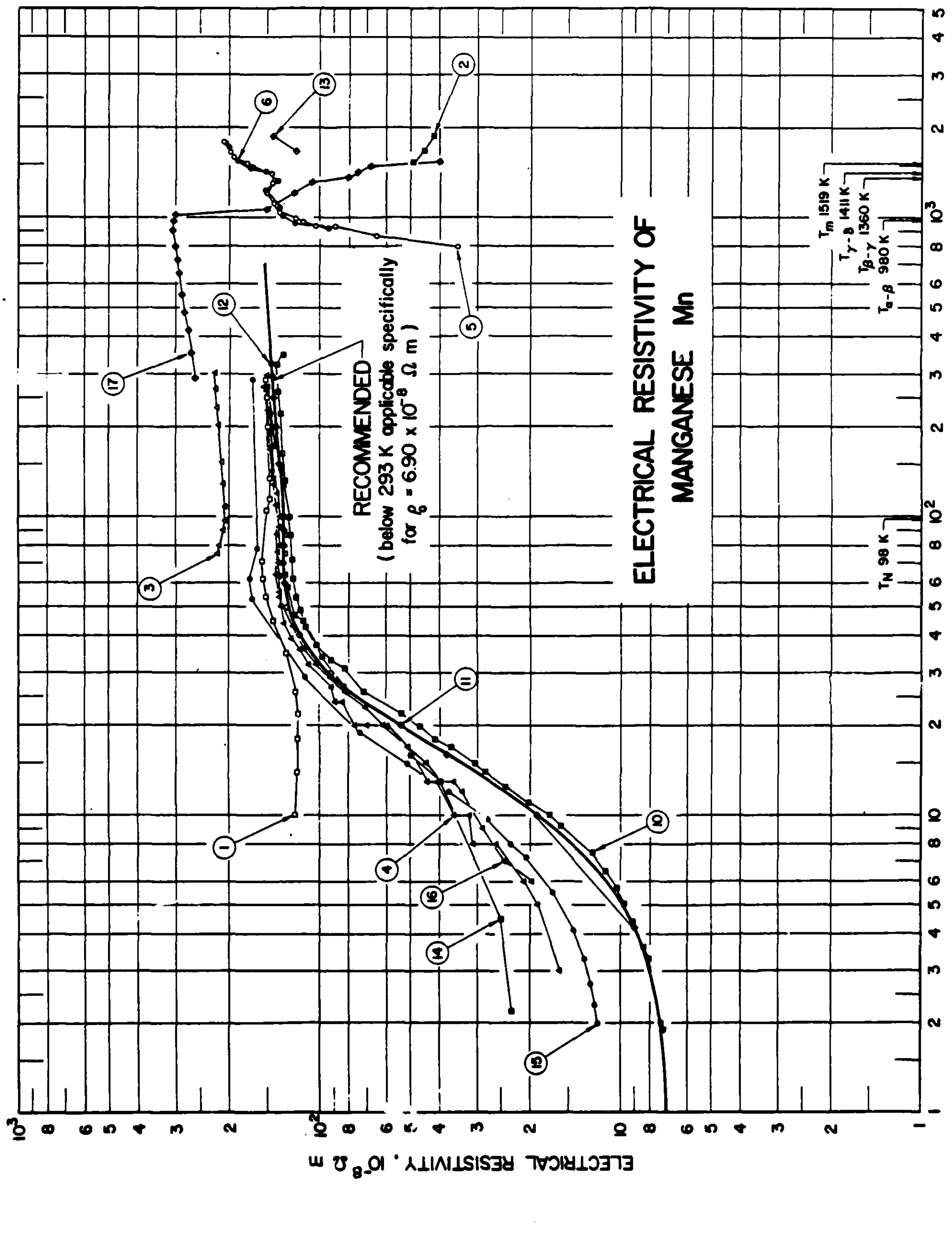

ELECTRICAL RESISTIVITY OF
MANGANESE Mn
RECOMMENDED
(below 293 K applicable specifically
for ρ = 6.90 x 10^{-8} Ω m)
T_m 1519 K
$T_{\gamma-\delta}$ 1411 K
$T_{\beta-\gamma}$ 1360 K
$T_{\alpha-\beta}$ 980 K
T_N 98 K
TEMPERATURE, K
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
CINDAS

FIGURE 4

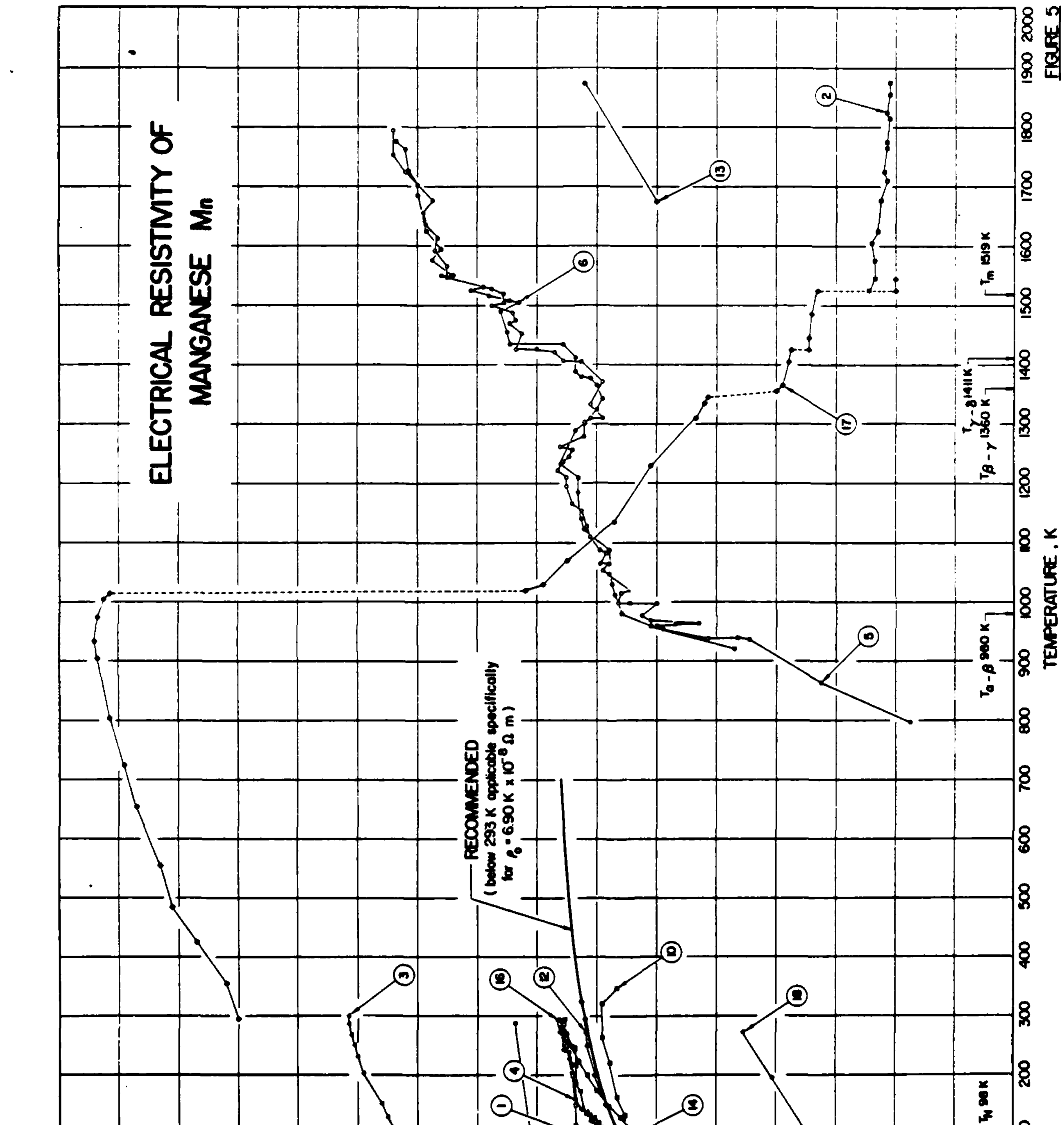

ELECTRICAL RESISTIVITY OF MANGANESE Mn
RECOMMENDED
(below 293 K applicable specifically for ρ_0 = 6.90 K x 10^{-8} Ω m)
T_N 98 K
$T_{\alpha-\beta}$ 980 K
$T_{\beta-\gamma}$ 1360 K
$T_{\gamma-\delta}$ 1411 K
T_m 1519 K
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS

FIGURE 5

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	297	Adanu, K.G. and Grassie, A.D.C.	1978	P	10-287	Sxxii(a)	99.98 Mn; electrolytic flakes from Koch Light Laboratories; cleaned in 5% HCl in methanol to remove surface oxidation and contamination; dried and ground immediately before being loaded into a previously cleaned molybdenum boat; films were prepared by thermal evaporation of Mn powder onto thin glass substrates, cut to size and cleaned; substrates heated to 473 K during evacuation of chamber then cooled to 383 K, temperature at which evaporation was carried out; coating pressure was about 10^{-6} torr; films were allowed to cool to room temperature before removing from vacuum chamber; thickness of film is 4000 Å; data read from figure; very large value of about 120 x 10^{-8} Ω m is attributed to several atoms driven into spin fluctuations.
2	298	Levin, E.S., Zamarayev, V.N., and Gel'd, P.V.	1976	+	1523-1873		Liquid manganese; remelted electrolytic distilled in a vacuum; average of heating and cooling experiments; measurements with contact-less method in a revolving magnetic field; torsional oscillating method; measurements error did not exceed 7%.
3	299	Butylenko, A.K. and Kobzenko, N.S.	1976	A	75-301	α-Mn	99.9 Mn; data extracted from figure; two coordinate potentiometer.
4	300	Nagasawa, H. and Senba, M.	1975	V	3-282	α-Mn	99.99 Mn; flakes were etched in HNO_3 to remove surface oxidation; accuracy of resistance measurements is about 0.05%; uncertainty of about 10% assigned to resistivity values because of the uncertainty in determining cross-sectional area of sample; current reversed to eliminate thermal emf; data extracted from graph.
5	301	Akshentsev, Yu.N., Baum, B.A., and Gel'd, P.V.	1969	R	797-1793		99.99 Mn; triple vacuum melted; measurements in helium using aluminum oxide crucibles with closely fitted lids of the same material; resistivity of Mn increased by 5% during melting; data extracted from figure for heating experiment.
6	301	Akshentsev, Yu.N., et al.	1969	R	921-1775		Same as above except data for cooling experiment.
7*	302	Meaden, G.T. and Pelloux-Gervais, P.	1967	A	1.87-300		99.995 Mn; electrolytic Mn from Koch Light Laboratories; 20 ppm Mg, 2 ppm Si, <1 ppm Cu; irregularly shaped flakes of uniform thickness of about 1 mm; platelet samples were shaped by spark erosion into rectangular parallelopipeds 5-6 mm x 20-30 mm; the values in the parenthesis are for specimen after being etched in dilute HCl and annealed in vacuum 1-8 x 10^{-6} torr for 7 hr at 898 K.
8*	302	Meaden, G.T. and Pelloux-Gervais, P.	1967	A	300		Similar to the above except electrolytic manganese supplied by Pechinery of unknown purity; the values given in parenthesis are for specimens after being etched in dilute HCl and annealed in vacuum 1-8 x 10^{-6} torr for 7 hr at 898 K.
9*	302	Meaden, G.T. and Pelloux-Gervais, P.	1967	A	4.2,300		Similar to the above except electrolytic manganese supplied by Johnson-Matthey of unknown purity; the values given in parenthesis are for specimen after being etched in dilute HCl and annealed in vacuum 1-8 x 10^{-6} torr for 7 hr at 898 K.

*Not shown in figure.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
10	303	Meaden, G.T.	1966	A	1.9–348		99.995 Mn supplied by Koch Light Laboratories Ltd.; impurities such as 20 ppm Mg, 2 ppm Si, 1 ppm Cu; surface contamination was removed by reduction in dilute HCl; annealed in 10^{-8} torr vacuum for 7 hr at 898 K; extrapolated ρ_0 from 2 K is 6.87 x 10^{-8} Ω m; values read from figure which do not agree with some values given in text.
11	303	Meaden, G.T.	1966	A	16–70		Same as above except data extracted from table (text).
12	304	Meaden, G.T. and Pelloux-Gervais, P.	1965	A	0–325		99.995 Mn; 20 ppm Mg, 2 ppm Si, <1 ppm Cu; the electrolytically made specimen was supplied by Koch Light Laboratories Ltd.; the specimen dimension 0.965 x 4.92 x 24.95 mm; the specimens were annealed under a vacuum of 10^{-8} to 8 x 10^{-8} torr for 7 hr at 898 K; the resistivity at 0 K was obtained by extrapolating from 2 K; error associated with resistivity data did not exceed 1%; above 80 K average of heating and cooling experiments.
13	305	Vostryakov, A.A., Vatolin, N.A., and Esin, O.A.	1964	-	1673–1873		Electrolytic manganese.
14	306	Bellau, R.V. and Coles, B.R.	1963	A	2–293		Two specimens 99.95 Mn taken from different batches of Johnson Matthey electrolytic manganese; vacuum annealed near 873 K after cutting into suitable shapes (~4 cm x 1 mm x 1 mm) with an ultrasonic cutter; measured resistance was converted to resistivity by assuming $\rho_{300}-\rho_{4.2}$=130 x 10^{-8} Ω m for pure manganese; observed Néel temperature is 95 ± 2 K· data extracted from the graphically smooth values of the authors.
15	307	White, G.K. and Woods, S.B.	1957	A	2–288	Mn3	Specimen from Ms. Johnson Matthey and Mallory Ltd. (JM 19792); high purity specimen with 10 ppm of Mg as major solid impurity; annealed specimen; data calculated from ρ_i values represented graphically using ρ_0=11.3 x 10^{-8} Ω m reported by authors.
16	307	White, G.K. and Woods, S.B.	1957	A	6–295	Mn	Specimen cut from material supplied by A. D. MacKay Inc.; annealed in vacuum at 873 K for some hours to remove adsorbed hydrogen; spectrographic analysis showed that this material was of comparable high purity to that of Mn3; data extracted from figure; data exhibits a shallow minimum near 100 K and falls rapidly below 50 K; residual resistivity ρ_0=16.8 x 10^{-8} Ω m.
17	308	Grube, G. and Speidel, H.	1940	R	293–1543		Vacuum distilled Mn; 0.01–0.001% Fe and Si, <0.001% of Cu, Ca, and Al; cylindrical specimen 9 mm diam. and 15 mm length.
18	309	Reddemann, H.	1935	-	78–273	β-Mn	No details given except sample ~16 mm long and ~5 mm diameter and end surfaces were ground; values calculated from reported ρ/ρ_{273} values and 91.0 x 10^{-8} Ω m for electrical resistivity at 273 K.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
19*	310	Murayama, S. and Nagasawa, H.	1977	A	1.17-4.15	α-Mn	Pure Mn; specimen same as the one reported in data set 4; annealed at 625°C for 48 h to obtain pure α-Mn and at 600°C for 24 h to remove strain during sample; measurements in 0 kOe; longitudinal and transverse magnetoresistance.

*Not shown in figure.

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn

[Temperature, T, K; Electrical Resistivity, ρ, 10^{-8} Ω m]

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
DATA SET 1		DATA SET 3 (cont.)		DATA SET 4 (cont.)		DATA SET 5 (cont.)		DATA SET 6		DATA SET 7 (cont.)*	
10.6	122	96.7	206.1	98.9	138.0	1063	139.1	921	94	4.2	(13.7)
14.4	119	102.6	206.1	105.7	139.7	1080	137.9	958	122	4.2	(11.2)
18.2	118	108.4	207.9	109.1	140.5	1086	139.7	978	132	4.2	(9.1)
22.0	118	129.4	209.8	117.5	140.5	1109	142.1	1010	134	1.87	(7.3)
26.8	120	151.6	212.2	122.6	142.1	1127	143.3	1028	135		
35.2	130	203.0	217.7	129.3	142.1	1153	145.1	1086	136	DATA SET 8*	
44.7	143	231.0	219.5	132.7	143.0	1165	148.6	1121	144		
54.1	152	250.9	221.4	137.8	143.8	1194	150.4	1139	145	300	345(185)
61.7	155	268.4	222.0	142.8	145.5	1209	150.4	1183	146	300	320(175)
67.4	156	287.1	222.6	169.8	147.1	1220	153.9	1209	146		
71.2	156	301.1	222.6	183.3	147.1	1235	151.0	1232	152	DATA SET 9*	
76.8	156			190.0	148.0	1244	149.3	1288	147		
105.2	150	DATA SET 4		205.2	148.7	1261	152.8	1300	144	300	290(160)
114.7	147			218.7	148.7	1256	148.1	1323	140	300	253(155)
120.3	147	3.5	16.8	228.8	149.5	1279	144.6	1341	138	4.2	(15.0)
135.5	147	5.2	19.4	240.6	149.5	1291	144.7	1364	140		
150.6	147	6.9	21.0	244.0	151.2	1303	144.7	1376	142	DATA SET 10	
197.9	148	8.6	26.1	250.7	150.3	1309	142.4	1379	145		
250.8	150	8.7	31.2	257.5	150.3	1309	138.8	1388	147	1.90	7.21
286.8	151	10.4	32.8	264.2	152.0	1332	142.4	1411	147	2.01	7.32
		10.4	36.2	282.8	152.8	1370	138.9	1434	151	3.30	8.04
DATA SET 2		13.8	41.3			1405	145.3	1434	169	3.65	8.37
		13.9	44.6	DATA SET 5		1405	151.3	1454	170	4.46	9.02
1523	49	17.3	51.4			1420	154.8	1504	166	5.19	9.73
1543	47	20.7	60.6	797	35.9	1425	160.0	1507	169	5.74	10.33
1573	47	20.8	70.7	863	65.2	1425	167.0	1489	172	6.03	10.68
1603	48	20.9	77.5	935	89.9	1452	165.9	1516	176	6.50	11.22
1623	46	24.3	84.2	938	93.9	1469	169.4	1530	178	6.84	11.94
1673	45	24.4	89.3	938	103.3	1475	167.7	1524	182	7.56	12.55
1708	43	27.8	92.6	964	106.8	1487	168.3	1550	188	9.25	15.83
1723	44	33.0	109.5	961	114.4	1504	171.2	1550	192	10.2	17.31
1763	43	36.4	117.1	952	118.5	1519	171.8	1576	195	11.6	20.23
1773	43	39.8	125.5	958	120.3	1498	175.3	1594	192	12.2	22.23
1813	42	39.9	128.0	975	119.1	1527	175.9	1644	197	12.5	24.31
1823	43	44.9	132.2	967	122.0	1547	190.6	1685	200	13.8	26.79
1853	42	48.3	133.9	978	121.4	1565	190.6	1702	200	14.5	28.37
1873	42	50.0	135.6	996	120.9	1591	194.7	1726	203	15.3	30.51
		56.8	137.2	975	125.5	1612	193.6	1761	204	16.1	32.87
DATA SET 3		63.5	137.2	996	129.7	1635	197.7	1775	207	17.3	36.57
		70.3	138.0	996	133.2	1655	198.9			18.2	41.45
75.6	218.8	73.7	138.0	1019	129.7	1676	195.4	DATA SET 7*		20.2	46.38
80.3	217.0	80.4	137.2	1013	132.6	1723	204.8			22.4	53.75
83.8	214.6	83.8	137.2	1045	136.1	1752	208.4	300	210(149)	22.9	56.50
89.7	209.1	87.1	136.3	1051	138.5	1793	208.4	300	205(148)	26.6	71.64
92.0	207.3	92.2	137.2	1063	136.2			300	205(144.2)	31.9	82.29

*Not shown in figure.

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn (Continued)

DATA SET 10 (cont.)

T	ρ
33.4	91.41
36.9	103.4
45.1	113.1
47.5	121.5
58.1	128.3
64.2	130.6
74.7	130.6
86.9	130.6
98.6	130.6
109.1	130.6
133.5	130.6
163.4	133.1
221.1	135.6
263.8	138.1
322.8	138.1
348.2	133.2

DATA SET 11

T	ρ
16	38.0
20	54.0
30	92.0
40	117.0
50	128.0
63	132.5
70	133.0

DATA SET 12

T	ρ
0	6.9
4.2	9
10	19
20	54
30	92
40	118
50	128
60	132
70	133
80	132.5
90	132
94	131.9
100	132.5
150	137
200	140.5
250	143
273.15	143.5
295	144.0
325	145.2

DATA SET 13

T	ρ
1673	120
1873	144

DATA SET 14

T	ρ
2.3	23.0
4.6	24.7
13.7	40.2
16.0	50.6
27.5	83.9
34.4	97.7
43.5	111.5
49.2	116.7
55.0	120.7
63.0	123.0
72.1	124.7
87.0	125.3
100.8	127.0
128.2	132.8
148.9	136.8
174.0	140.2
200.4	143.1
224.4	146.6
248.5	148.9
271.4	150.6
293.1	152.3

DATA SET 15

T	ρ
2.0	12.0
2.3	12.2
2.7	12.6
3.3	13.2
4.1	14.4
5.5	16.9
7.2	20.6
7.7	21.6
8.0	23.4
9.7	27.7
9.7	28.4
12	37.27
15	50.71
19	73.8
29	112.5
53	168.2
62	171.6
78	161.3
288	167.4

DATA SET 16

T	ρ
0.4	19.2
5	20.3
6	22.6
7	24.9
7	27.1
8	29.4
10	32.2
11	35.0
12	37.3
13	41.2
13	45.8
16	52.6
17	62.2
19	71.8
23	83.6
26	93.8
28	105.1
32	114.2
36	122.1
39	124.3
49	136.7
53	139.0
59	140.6
69	139.4
72	141.1
75	138.3
82	139.9
85	140.5
86	138.2
91	137.6
93	135.4
94	137.6
98	138.7
103	138.1
105	139.2
114	139.8
116	142.6
118	140.9
123	142.0
129	144.8
168	147.4
182	148.5
211	148.9
239	150.4
266	155.4
286	155.8
289	153.5

DATA SET 17

T	ρ
293	260
353	266
423	274
483	282
553	286
653	294
723	298
803	303
903	307
933	308
973	307
1003	305
1013(α)	303
1018(β)	164
1028	158
1068	150
1133	134
1228	122
1308	107
1333	104
1343(β)	103
1353(γ)	80
1363	78
1403	76
1423(γ)	75
1423(δ)	69
1453	69
1483	68
1523(s)	66
1523(ℓ)	40
1543	40

DATA SET 18

T	ρ
78.1	66.5
90.1	68.3
194.7	81.1
273	91.0

DATA SET 19*

T	ρ
1.17	28.12
1.27	28.18
1.30	28.12
1.39	28.24
1.42	28.24
1.56	28.24

DATA SET 19 (cont.)*

T	ρ
1.66	28.30
1.75	28.30
1.80	28.36
1.93	28.42
1.97	28.49
2.07	28.48
2.11	28.52
2.22	28.58
2.28	28.61
2.38	28.67
2.43	28.73
2.48	28.76
2.53	28.76
2.59	28.79
2.65	28.82
2.71	28.88
2.80	28.88
2.83	28.97
2.89	29.00
2.97	29.00
3.00	29.06
3.06	29.09
3.11	29.12
3.20	29.21
3.27	29.21
3.36	29.27
3.39	29.33
3.47	29.39
3.53	29.39
3.60	29.49
3.67	29.55
3.76	29.64
3.83	29.67
3.93	29.73
4.03	29.85
4.15	29.94

*Not shown in figure.

4. ACKNOWLEDGMENTS

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5. APPENDICES

5.1. Methods for the Measurement of Electrical Resistivity

At the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) of Purdue University, the experimental methods for the measurement of electrical resistivity have been classified into various categories according to a similar scheme used by CINDAS for the classification of methods for the measurement of thermal conductivity [356, pp. 13a-25a]. This classification scheme of CINDAS is presented below. Note that the letters in parentheses following the respective methods are the code letter used in the 'Method Used' column of the Table of Measurement Information for indicating the experimental methods used by the various authors.

<u>Methods for the Measurement of Electrical Resistivity</u>

A. Steady-State Methods

1. Voltmeter and ammeter direct reading method (V) [357, p. 159; 358, pp. 244-5]
2. Direct-current potentiometer method (A) [359, pp. 151-8]
    a. 4-probe potentiometer method
3. Direct-current bridge methods (B) [359, pp. 144-51]
    a. Kelvin double bridge method
    b. Mueller bridge method
    c. Wheatstone bridge method
4. Van der Pauw method (P) [360,361]
5. Direct heating method (K) [362,363]

B. Non-Steady-State Methods

1. Periodic current method
    a. Direct connection to sample
        (1) Alternating-current potentiometer method (C) [359, pp. 161-2]
        (2) Alternating-current bridge method (D), [359, p. 162]
    b. No connection to sample
        (1) Rotating magnetic field method (R) [364]

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5.2. Conversion Factors for the Units of Electrical Resistivity

The recommended values and experimental data for the electrical resistivity tabulated in this work are in the units: 10^{-8} Ω m. Conversion factors for the units of electrical resistivity, which may be used to convert the values given in (10^{-8} Ω m) to values in other units, are given below.

Conversion Factors for the Units of Electrical Resistivity

Units to be Converted to	Multiply the Value Given in (10^{-8} Ω m) by
ohm-meter (Ω m)	1×10^{-8}
ohm-centimeter (Ω cm)	1×10^{-6}
ohm-inch (Ω in.)	3.937×10^{-7}
ohm-foot (Ω ft)	3.281×10^{-8}
microohm-centimeter (μΩ cm)	1
abohm-centimeter (abΩ cm)	1×10^{3}
statohm-centimeter (statΩ cm)	1.113×10^{-18}
emu (= abΩ cm)	1×10^{3}
esu (= statΩ cm)	1.113×10^{-18}
ohm-circular mil per foot (Ω cmil ft^{-1})	6.015

Example: 1.000×10^{-8} Ω m = 3.937×10^{-7} Ω in..

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