

Electrical Resistivity of Aluminum and Manganese

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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 $\pm 2\%$ to $\pm 5\%$.

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

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Nomenclature

c	Impurity concentration
e	Base of natural logarithm
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
Δ	Deviation from the Matthiessen's rule
ρ	Electrical resistivity
ρ_0	Residual electrical resistivity
ρ_e	Electrical resistivity due to electron-electron scattering
ρ_i	Intrinsic electrical resistivity

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 Sec. 2, which includes a brief introduction to the theory of the electrical resistivity of metals and a detailed

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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 Sec. 3. In the discussion of the electrical resistivity of each element, details of data analysis are discussed, and the uncertainties in the recommended values are stated. The recommended values both uncorrected and corrected for the thermal expansion of the material are 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 two sections are for acknowledgments and references. The classification and organization of methods for the measurements of electrical resistivity and the conversion factors for the units of electrical resistivity have been given in Ref. 5.

2. General Background

It was found experimentally by Matthiessen that the increase in the electrical resistivity of a metal due to the presence of a small amount of another metal in the 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 additive contributions: ρ_0 , 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 , the temperature-dependent intrinsic resistivity arising from the scattering of electrons by lattice waves or phonons. However, in reality it is observed that

$$\rho(c, T) = \rho_0(c) + \rho_i(T) + \Delta(c, T), \quad (1)$$

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

It is to be noted that for some metals, especially transition metals, an electron-electron scattering term (ρ_e) makes a significant contribution to ρ_i at low temperatures, and is generally included along with the Bloch-Grüneisen^{7,8} term in representing ρ_i . Further comments on Matthiessen's rule and the theoretical aspects of the temperature-dependent electrical resistivity are given in Refs. 5-8.

In Sec. 3, electrical resistivity data and information for aluminum and manganese 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, individual pieces of the data and information on which the recommendations are based are indicated, the considerations involved in arriving at the final assessment and recommendations are discussed, and the uncertainties of the recommended values are stated.

The recommended values are for well-annealed, high-purity specimens; however, values for low temperatures are applicable only to specimens having the residual electrical resistivity 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:

$$\rho_{\text{corrected}}(T) = \left[1 + \frac{\Delta L(T)}{L_0} \right] \rho_{\text{uncorrected}}(T), \quad (2)$$

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.

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. The data set numbers of those data sets omitted from the figure are asterisked in tables providing the measurement information and tabulating the experimental data.

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 Pauw 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. |

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 5 *N* purity, very large residual resistivity ratio (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 characterizations 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), Wilkes⁵³ (data set 115), and of Simmons and Balluffi⁷⁴ (data set 150) are explicitly stated to have been corrected for thermal expansion, and the opposite has been assumed in all other cases.

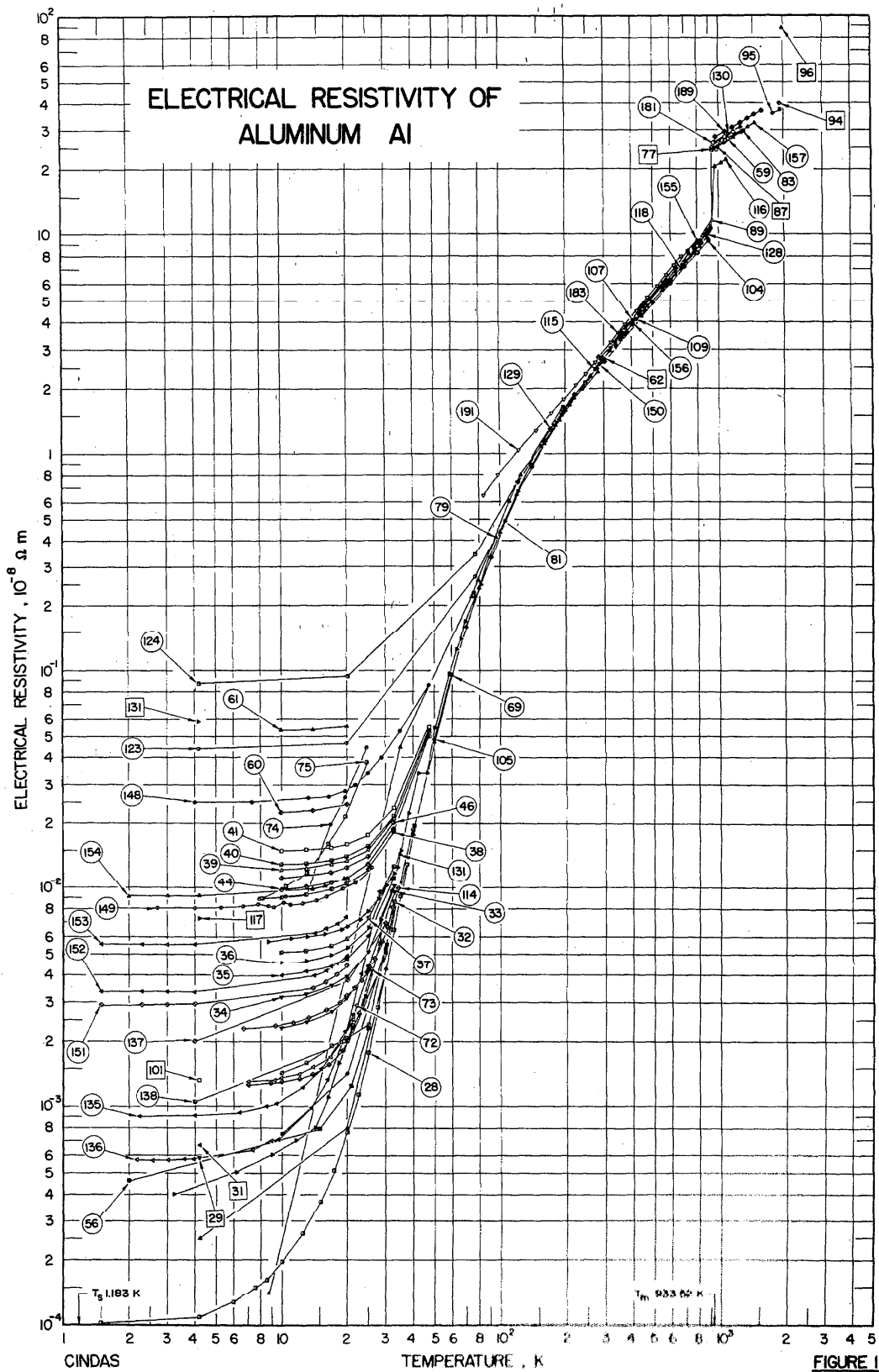
Deviations from Matthiessen's rule are quite significant in aluminum and have been carefully studied. Ribot *et al.*⁹ (data sets 1-21) concluded that Matthiessen's rule is obeyed below 4.2 K. However, their studies do not extend above this temperature. Another complicating factor is the importance of 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 as determined by van der Mass *et al.*,⁹⁷ is comparable to the temperature-dependent resistance at 2 K which has been attributed to electron-electron scattering, for instance by Ribot *et al.*⁹ 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

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			

^aThe 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.



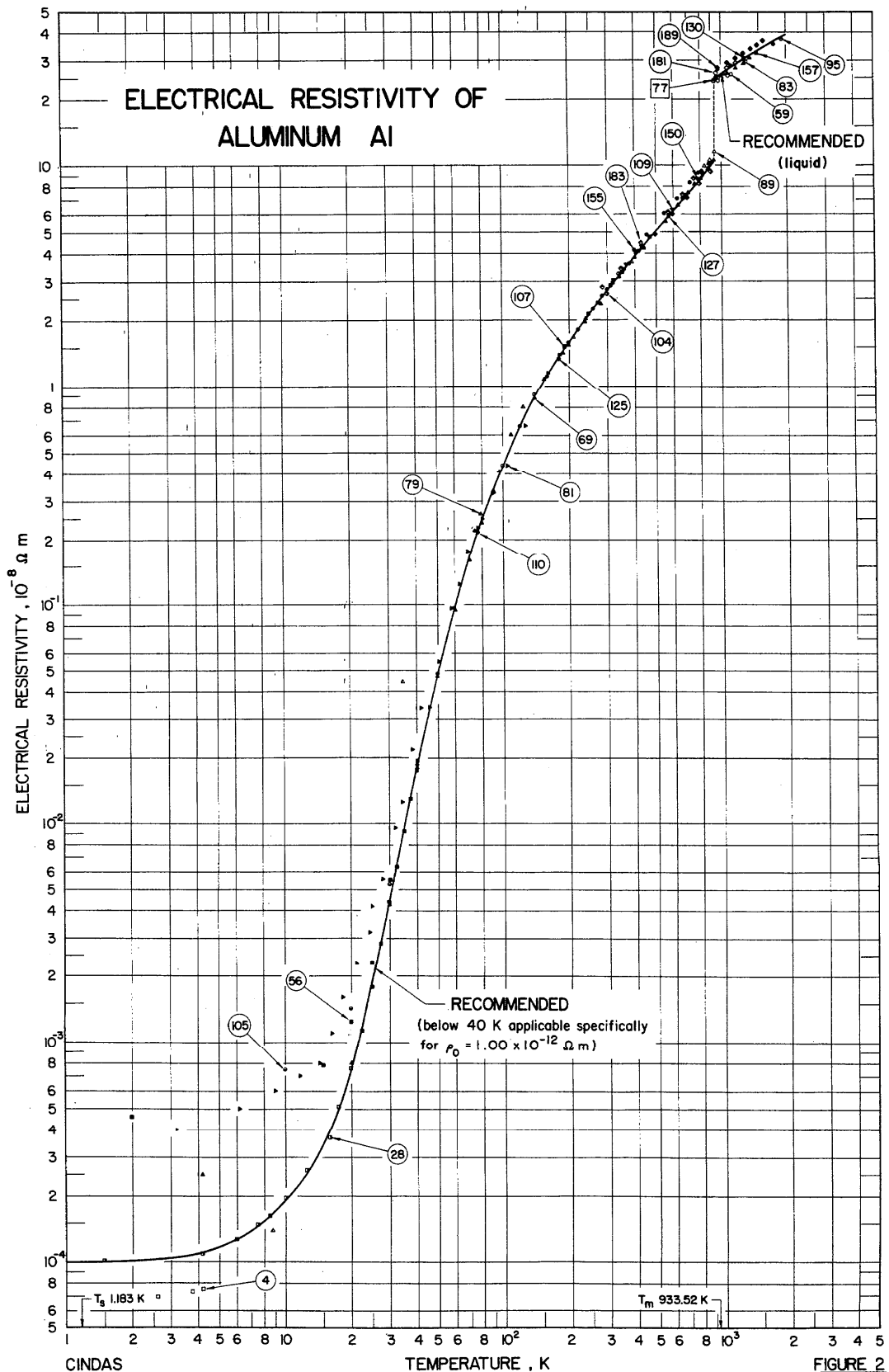
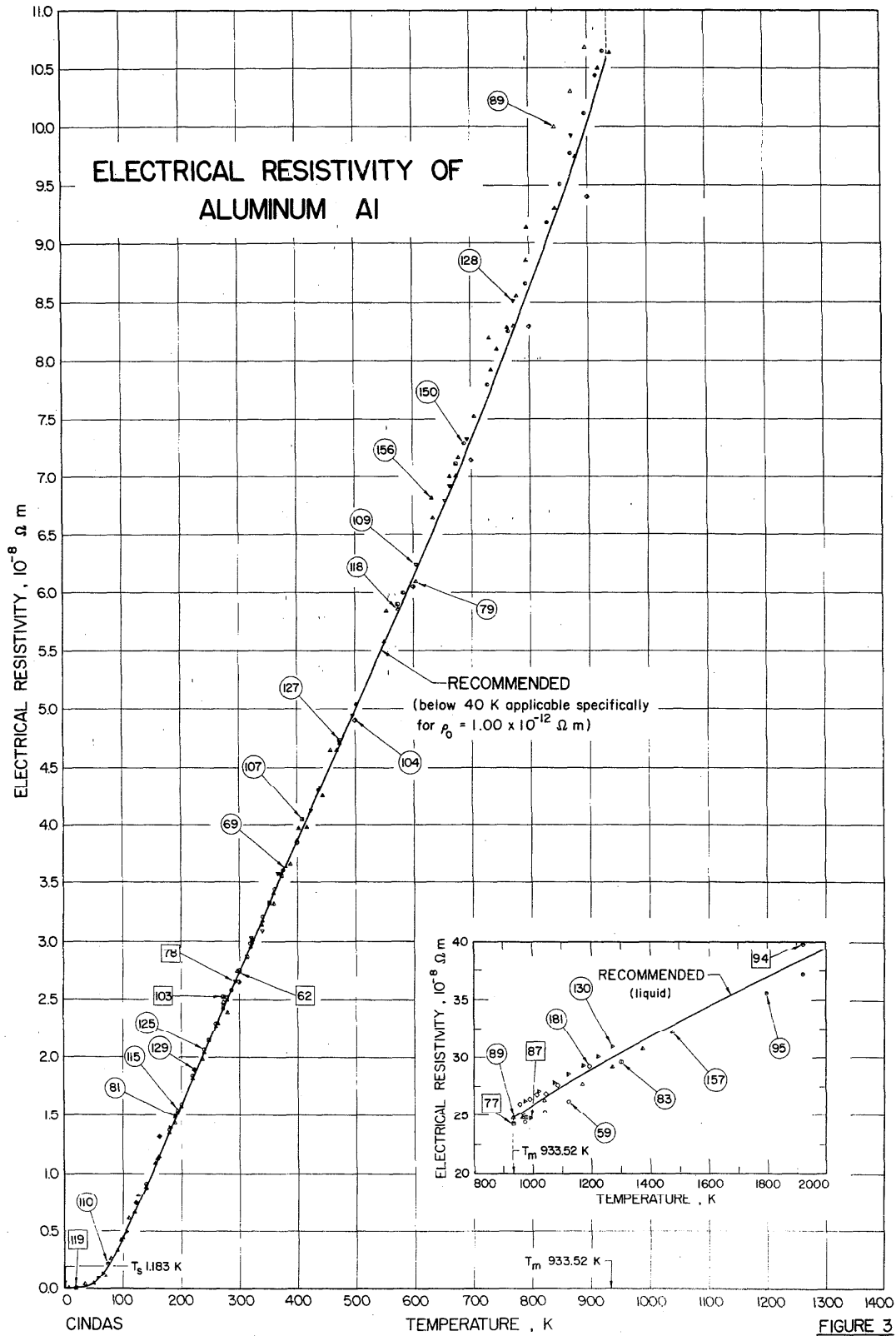


FIGURE 2



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 Harlingen¹³ (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 Kino¹⁰ (data sets 22–28), Babic *et al.*¹⁸ (data sets 60, 61), Aleksandrov and D'yakov⁶⁸ (data sets 139–141), Senoussi and Campbell³² (data sets 85, 86), and Refs. 102–108.

The recommended values for the electrical resistivity at low temperatures are based on the data of Nakamichi and Kino¹⁰ (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 $10^{-12} \Omega \text{ m}$, 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 Woods⁴⁵ (data set 105), Wilkes⁵³ (data set 115), Moore *et al.*⁶⁰ (data set 125), and of Simmons and Balluffi⁷⁴ (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 Zverev⁴⁸ (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 Balluffi⁷⁴ 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 ($\pm 5\%$) 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 Persion³⁵ (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 Matuyama⁸⁸ (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 $\rho_0 = 1.00 \times 10^{-12} \Omega \text{ m}$. 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 $\pm 1\%$ below 400 K, $\pm 2\%$ from 400 K up to the melting point, and about $\pm 3\%$ for the liquid.

Electrical resistivity of slightly less pure aluminum with different residual resistivity can be calculated from the recommended values using the Matthiessen rule. This procedure involves subtracting ρ_0 from the recommended ρ value to obtain the temperature-dependent part to which ρ_0 of the specimen in question be added to generate a set of values applicable to that specimen. However, it should be pointed out that this procedure neglects contributions due to deviations from the Matthiessen rule. It is noted that Ribot *et al.*⁹ found the deviations from Matthiessen's rule (DMR) to be insignificant below 4.2 K for $0.7 \times 10^{-12} < \rho_0 < 111 \times 10^{-12} \Omega \text{ m}$. The review by Cimberle *et al.*³⁵⁶ indicates that toward higher temperature DMR becomes significant at 20 K for $\rho_0 > 2 \times 10^{-12} \Omega \text{ m}$ and at 50 K for $\rho_0 > 1.0 \times 10^{-10} \Omega \text{ m}$.

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 Pal¹⁸⁹ 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 Balluffi⁷⁴ 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

TABLE 2. MEASUREMENT INFORMATION ON 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; $\rho_0 = 0.0000928 \times 10^{-8} \Omega\text{m}$; 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 $<5 \times 10^{-8} \Omega$ 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 galvanometer 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; $\rho_0 = 0.0000667 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.0013 \times 10^{-8} \Omega\text{m}$; 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	Same as in data set 1 except nominal impurity <8 ppm; sample diam. 3.0 mm; $\rho_0 = 0.000292 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.01068 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.01106 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.000663 \times 10^{-8} \Omega\text{m}$; 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 $\rho_0 = 0.000601 \times 10^{-8} \Omega\text{m}$; 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 $\rho_0 = 0.002245 \times 10^{-8} \Omega\text{m}$; 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: $\rho(\epsilon, B) = \rho_0 + \rho_d(\epsilon) + \rho_m(\epsilon, B)$ (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_0 ; number of dies zero for this specimen; annealed at 340°C for 3 h; $\rho_0 = 0.001306 \times 10^{-6} \Omega\text{m}$; 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 $\rho_0 = 0.00222 \times 10^{-6} \Omega\text{m}$; number of dies is 1.
34	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(1)	Same as above except $\rho_0 = 0.00309 \times 10^{-6} \Omega\text{m}$; number of dies are 2.
35	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(1)	Same as above except $\rho_0 = 0.00391 \times 10^{-6} \Omega\text{m}$; number of dies are 3.
36	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(1)	Same as above except $\rho_0 = 0.00447 \times 10^{-6} \Omega\text{m}$; number of dies are 4.
37	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-33	Al(1)	Same as above except $\rho_0 = 0.00499 \times 10^{-6} \Omega\text{m}$; number of dies arc 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; $\rho_0 = 0.00874 \times 10^{-8} \Omega\text{m}$; 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 $\rho_0 = 0.0121 \times 10^{-8} \Omega\text{m}$; number of dies is 1.
40	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except $\rho_0 = 0.0127 \times 10^{-8} \Omega\text{m}$; number of dies are 2.
41	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except $\rho_0 = 0.0147 \times 10^{-8} \Omega\text{m}$; number of dies are 4.
42*	12	Rowlands, J.A. and Woods, S.B.	1978	B	10-48	Al(2)	Same as above except $\rho_0 = 0.0148 \times 10^{-8} \Omega\text{m}$; number of dies are 6.
43*	12	Rowlands, J.A. and Woods, S.B.	1978	B	13,20	Al(2)	Similar to above specimen; $\rho_0 = 0.00877 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.00963 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.0102 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.0111 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.01174 \times 10^{-8} \Omega\text{m}$; 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; $\rho_0 = 0.0002057 \times 10^{-8} \Omega\text{m}$; normal resistance ratio = 12000; annealed in air at 550°C for several hours; RRR = 12327; values calculated from graphically reported $\rho_T - \rho_0$ 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 $\rho = \rho_0 + A T^2$ using $\rho_0 = 0.0002341 \times 10^{-8} \Omega\text{m}$, and $A = 5.4 \pm 0.4 \times 10^{-4} \text{ n}\Omega \text{ cm K}^{-2}$.
50*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-3	Similar to above specimen; $\rho_0 = 0.0002012 \times 10^{-8} \Omega\text{m}$; RRR = 12588, $A = 5.7 \pm 0.4 \times 10^{-4} \text{ n}\Omega \text{ cm K}^{-2}$.
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; $\rho_0 = 0.0006195 \times 10^{-8} \Omega\text{m}$; RRR = 4201, $A = 6.7 \times 10^{-4} \text{ n}\Omega \text{ cm K}^{-2}$.
52*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-5	Similar to above specimen; $\rho_0 = 0.0000519 \times 10^{-8} \Omega\text{m}$; RRR = 5030, $A = 5.2 \times 10^{-4} \text{ n}\Omega \text{ cm K}^{-2}$.
53*	13	Garland, J.C. and Harlingen, D.J.	1978	A	1.5-4.0	Al-6a	Similar to Al-1; $\rho_0 = 0.0000944 \times 10^{-8} \Omega\text{m}$; RRR = 25999, $A = 4.3 \times 10^{-4} \text{ n}\Omega \text{ cm K}^{-2}$.

*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; $\rho_0 = 0.0004638 \times 10^{-8} \Omega\text{m}$; RRR = 5625, $A = 4.6 \times 10^{-4} \text{ m}\Omega \text{ cm K}^{-1}$.
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; $\rho_0 = 0.00046 \times 10^{-8} \Omega\text{m}$; values calculated from graphically reported $\rho_T - \rho_0$ 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; $\rho_0 = 0.000448 \times 10^{-8} \Omega\text{m}$; measurement done with SQUID galvanometer 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; $\rho_0 = 0.001355 \times 10^{-8} \Omega\text{m}$.
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; $\rho_0 = 0.022 \times 10^{-8} \Omega\text{m}$.
61	18	Babic, E., et al.	1976	A	10-20		Similar to above except $\rho_0 = 0.053 \times 10^{-8} \Omega\text{m}$.
62	19	Kawata, S.	1976	A	300	VIII-1	99.999 Al; zone refined; $\rho_0 = 0.000193 \times 10^{-8} \Omega\text{m}$.
63*	20	Krevet, B. and Schauer, W.	1976	A	4.2-32	Sample I	Pure; polycrystalline; from Vereinigte Aluminiumwerke, AG, Bonn; Al tape samples $0.3 \times 6 \text{ mm}^2$ 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*	21	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; $\rho_0 = 0.00124 \times 10^{-8} \Omega\text{m}$; 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 $\rho_0 = 0.0088 \times 10^{-8} \Omega\text{m}$; 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 Sunitomo 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	Osamura, 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., Hircaka, Y., and Murakami, Y.	1973	A	3.1-200	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 μ m 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); $\rho_0 = 0.002409 \times 10^{-8} \Omega\text{m}$; geometrical factor of the order of 10^5 ; data taken from figure of ρ_0/ρ 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); $\rho_0 = 43.31 \text{ n}\Omega\text{cm}$; geometrical factor of the order of 10^5 ; data taken from figure of ρ_0/ρ vs T^3 .
87	33	Korochkina, L.N. and Kazimirov, 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., Gostishev, V.I., and Drozd, A.A.	1972		4.2, 273		Single crystal; 60 x 4 x 3 mm; specimen axis along <110> direction; $\rho(273)$ calculated from resistance ratio of order of 6000 (assumed equal to resistivity ratio) and $\rho(4.2 \text{ K})$.
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 Alfouzo, M.	1972	+	77		Bar of very common structural aluminum; 12 cm long, 9.5 mm diam; inductive method.
93*	38	Callarotti, R.C. and Alfouzo, 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 ₂
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 Entwistle, 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 $\rho = \rho_i + \rho_o$, $\rho_o = 0.0007 \mu\Omega \text{ cm}$, $\rho_i(273.2 \text{ K}) = 2.429 \mu\Omega \text{ cm}$, and smoothed values of $\rho_i(T)/\rho_i(273.2 \text{ K})$ 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 $\mu\Omega \text{ cm}$.
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.	1966	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.	1966	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 Arecco Products Inc.; density 2.700 g cm ⁻³ at 23°C; results corrected for thermal expansion by multiplying the room temperature dimensions by (1 + α ₀ T) where α 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 Keithly 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	Neely, 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	Neely, 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 Rheinfeiden GmbH, Rheinfeiden; 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	99.9% 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 $\rho(273\text{ K})/\rho(4.2\text{ K}) = 400$, $\rho(293\text{ K})/\rho(20.4\text{ K}) = 328$.
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 $\rho(273\text{ K})/\rho(4.2\text{ K}) = 55.2$, $\rho(293\text{ K})/\rho(20.4\text{ K}) = 57.1$.
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 $\rho(273\text{ K})/\rho(4.2\text{ K}) = 28.3$, $\rho(293\text{ K})/\rho(20.4\text{ K}) = 28.6$.
125	60	Moore, J.P., McElroy, D.L., and Barlisoni, M.	1966	A	100-360		99.999 Al; RRR = 520; cylindrical specimen machined from a stock obtained from Reynolds Aluminum Co.; estimated uncertainty $\pm 0.6\%$.
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 obtained from British Aluminum Co.; specimen 2.53 cm in dia. and 20.4 cm long.
128	62	Powell, R.W., et al.	1965	A	323-873		99.3 Al; from British Aluminum Co.; specimen 2.81 cm in diam. and 20.4 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; $\rho_0 = 0.00903 \times 10^{-8} \Omega \text{ m}$.
136	66	Fenton, E.W., et al.	1963		2-21	Al 6	Same as the above except $\rho_0 = 0.000568 \times 10^{-8} \Omega \text{ m}$.
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 $2.7 \times 10^{-6} \Omega \text{ cm}$ (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.C. 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 $2.7 \times 10^{-6} \Omega \text{ cm}$ (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; $\rho_{273 \text{ K}} = 2.417 \times 10^{-6} \Omega \text{ m}$ assumed; data of Fochapsky [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; $\rho_{\text{H},2}/\rho_{\text{H},3} = 3.4 \times 10^{-5}$; below $<14 \text{ K}$, $\rho \sim T^3$; 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'kev, 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 Rodet, F.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	GFP	<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 $\rho_{300} = 2.77 \times 10^{-8} \Omega \cdot m$; 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 $\rho(20^\circ C) = 2.70 \pm 0.12 \mu\Omega \cdot cm$; therefore, standard value of $\rho(20^\circ C) = 2.6548 \mu\Omega \cdot cm$.
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. Trogett; 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% NiOH 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 $\mu\Omega \cdot cm$) = $0.0146 \cdot T(K) + 10.56$.
158*	79	Broom, T.	1952	B	90-373		99.996 ⁺ Al; impurities 0.302 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; $\rho_0 = 0.00304 \times 10^{-8} \Omega \cdot m$; 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; $\rho_0 = 0.00385 \times 10^{-8} \Omega \text{ m}$.
161*	80	Andrews, F.A., et al.	1951	A	4.2, 273	Al III	99.99 ⁺ 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; $\rho_0 = 0.00551 \times 10^{-8} \Omega \text{ m}$.
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. Menhansen, 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 2.718 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	Fucken, A. and Warrertup, H.	1935		273.2		99.7 Al.
171*	85	Kapitza, P.	1929	A	88	Al _I	99.951 Al, 0.02 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 $\Omega \text{ cm}$.

*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, J.	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 $\text{W cm}^{-1}\text{K}^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 1.77 and 1.27 $\times 10^{-8} \Omega \text{W K}^{-2}$ 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 $\text{W cm}^{-1}\text{K}^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 1.97 and 1.32 $\times 10^{-8} \text{W K}^{-2}$ 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 $\text{W cm}^{-1}\text{K}^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.18 and 1.47 $\times 10^{-8} \Omega \text{W K}^{-2}$ 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 $\text{W cm}^{-1}\text{K}^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.20 and 1.55 $\times 10^{-8} \Omega \text{W K}^{-2}$ 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 $\text{W cm}^{-1}\text{K}^{-1}$ at 21.2 and 83.2 K, respectively; Wiedemann-Franz-Lorenz number 2.20 and 1.66 $\times 10^{-8} \Omega \text{W K}^{-2}$ 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, $l = 62.3$ mm, $\sigma_{\text{em}} = 25.5 \times 10^{-6}$.

*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, V.H.	1925	A	289-814		99.7 Al; free from discontinuities between core and surrounding layer, inclusion of dross, oxidized skin, and unroundness; supplied by British Aluminum 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 601 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		29-195		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	Nicolai, 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 , $10^{-8} \Omega \cdot m$]

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
DATA SET 1*																			
1.600	0.93577 x 10 ⁻⁴	2.631	0.69215 x 10 ⁻⁴	3.770	1.3720	3.593	2.9857	1.294	110.640 x 10 ⁻⁴	2.166	22.461	DATA SET 21 (cont.)*							
1.650	0.93631	3.796	0.71259 x 10 ⁻⁴	3.978	1.3836	3.785	2.9967	1.535	110.642	2.620	22.470								
1.700	0.93686	4.221	0.73419 x 10 ⁻⁴	4.132	1.3929	3.978	3.0090	1.774	110.645	3.016	22.481								
1.755	0.93750	DATA SET 5*		4.220	1.3985 x 10 ⁻⁴	4.133	3.0198 x 10 ⁻⁴	1.990	110.648	3.402	22.496								
1.800	0.93804	DATA SET 9*						2.167	110.651	3.699	22.509								
1.850	0.93867	2.362	0.68624 x 10 ⁻⁴					2.611	110.661	3.945	22.523								
1.904	0.93937	2.582	0.69098	1.501	1.3135 x 10 ⁻⁴	DATA SET 14*		3.011	110.675	4.211	22.540 x 10 ⁻⁴								
1.950	0.94001	2.728	0.69456	1.700	1.3143	1.501	2.9268 x 10 ⁻⁴	3.400	110.694	DATA SET 22*									
2.000	0.94073	2.969	0.70186	1.800	1.3151	1.700	2.9290	3.800	110.721	1.5	15.4 x 10 ⁻⁴								
2.050	0.94148	3.1875	0.70819	2.050	1.3160	1.800	2.9303	4.200	110.755 x 10 ⁻⁴	4.1	15.4								
2.100	0.94226	3.378	0.71501	2.101	1.3169	1.900	2.9317	DATA SET 19*											
2.145	0.94299	3.576	0.72343	2.171	1.3172	2.000	2.9332	1.224	6.6282 x 10 ⁻⁴	4.1	15.4								
2.156	0.94318	3.797	0.73302	2.329	1.3200	2.171	2.9362	1.443	6.6298	6.2	15.9								
2.167	0.94336	3.997	0.74195 x 10 ⁻⁴	2.468	1.3232	2.360	2.9402	1.600	6.6314	8.0	17.0								
2.170	0.94341	DATA SET 6*		DATA SET 10*				2.578	2.9457	11.6	19.2								
2.171	0.94343 x 10 ⁻⁴	4.154	0.74837 x 10 ⁻⁴	1.292	1.3060 x 10 ⁻⁴	2.988	2.9584	1.773	6.6332	13.3	20.8								
DATA SET 2*																			
1.302	0.93308	4.224	0.733804 x 10 ⁻⁴	1.402	1.3069	3.380	2.9749	1.989	6.6361	15.5	23.5								
1.322	0.93324	DATA SET 7*		1.501	1.3079	4.221	3.0264 x 10 ⁻⁴	2.167	6.6388	17.4	25.6								
1.355	0.93351	1.180	0.67147 x 10 ⁻⁴	1.541	1.3083	DATA SET 15*				2.628	6.6481	19.0	28.8						
1.362	0.93356	1.151	0.67154	1.601	1.3090	DATA SET 16*				3.019	6.6594	21.4	33.1						
1.363	0.93358	1.225	0.67176	1.650	1.3095	4.209	3.0254 x 10 ⁻⁴	3.407	6.6742	23.9	40.0								
1.402	0.93390	1.258	0.67231	1.701	1.3101	DATA SET 17*				3.793	6.6935	25.7	46.4						
1.453	0.93436	1.461	0.67316	1.750	1.3107	1.254	2.9246 x 10 ⁻⁴	4.101	6.7066	27.8	55.4								
1.500	0.93479	1.560	0.67406	1.800	1.3114	1.302	2.9250	4.206	6.7198 x 10 ⁻⁴	29.5	65.5								
1.550	0.93526	1.661	0.67506	1.850	1.3121	1.353	2.9254	DATA SET 20*											
2.171	0.94341	1.701	0.67616	1.900	1.3128 x 10 ⁻⁴	1.402	2.9259	1.371	6.0091 x 10 ⁻⁴	32.2	86.8								
2.647	0.95297	1.801	0.67737	DATA SET 11*		1.541	2.9272	1.663	6.0118	34.4	109.0								
2.905	0.95982	1.901	0.67868	1.253	1.3056 x 10 ⁻⁴	1.601	2.9279 x 10 ⁻⁴	1.931	6.0151	36.0	129.0								
3.149	0.96749	2.001	0.68014	1.289	1.3059	DATA SET 12*				2.102	6.0176	37.6	135.0						
3.401	0.97660	2.101	0.68168	1.352	1.3065	1.522	106.801 x 10 ⁻⁴	3.022	6.0392	39.5	184.0								
3.646	0.98661	2.172	0.68286 x 10 ⁻⁴	1.451	1.3074 x 10 ⁻⁴	1.763	106.804	3.395	6.0534	41.6	222.0 x 10 ⁻⁴								
3.842	0.99557	DATA SET 8*		DATA SET 13*				3.803	6.0737	DATA SET 23*									
4.042	1.00556	2.578	1.3260 x 10 ⁻⁴	2.049	2.9341 x 10 ⁻⁴	1.986	106.881	4.129	6.0981	1.5	1.60 x 10 ⁻⁴								
4.106	1.0092 x 10 ⁻⁴	2.725	1.3300	2.100	2.9349 x 10 ⁻⁴	2.162	106.811	4.229	6.0995 x 10 ⁻⁴	4.3	1.63								
DATA SET 3*																			
1.600	0.93577 x 10 ⁻⁴	3.186	1.3382	2.994	106.834	2.610	106.821	4.229	6.0981	5.9	1.12								
2.171	0.94341 x 10 ⁻⁴	3.378	1.3454	3.389	106.852	2.994	106.834	4.129	6.0981	8.2	1.68								
3.596	1.3632	3.596	1.3632	3.80	106.879	3.389	106.852	4.218	106.916 x 10 ⁻⁴	10.1	1.70								
3.596	1.3632	3.183	2.9662 x 10 ⁻⁴	4.218	106.916 x 10 ⁻⁴	3.389	106.852	1.241	22.449 x 10 ⁻⁴	11.8	2.25								
3.596	1.3632	3.183	2.9662 x 10 ⁻⁴	4.218	106.916 x 10 ⁻⁴	3.80	106.879	1.521	22.452	13.6	3.33								
3.596	1.3632	3.183	2.9662 x 10 ⁻⁴	4.218	106.916 x 10 ⁻⁴	3.80	106.879	1.762	22.454	15.6	3.88								
3.596	1.3632	3.183	2.9662 x 10 ⁻⁴	4.218	106.916 x 10 ⁻⁴	3.80	106.879	1.982	22.458	18.8	6.57								

*Not shown in figure.

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

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
DATA SET 104													
300	2.65	321	3.03	20.4	67.1×10^{-4}	883	10.3	4.2	0.00111	973	25	DATA SET 126*	
400	3.85	340	3.09	21.8	69.5	922	10.8	20.4	0.00238	DATA SET 127			
500	4.90	367	3.57	23.0	72.1	933	20.1	77	0.221	DATA SET 128			
600	6.05	397	3.85	24.4	75.1	936	20.2	195	1.44	DATA SET 129			
700	7.15	424	4.12	25.4	78.3	939	20.6	273	2.46	DATA SET 130			
800	8.30	441	4.32	26.4	82.3	943	20.7	DATA SET 131					
900	9.40	496	4.94	27.8	88.7	944	20.4	4.2	0.00575	DATA SET 132*			
DATA SET 105													
10	0.00075	605	6.24	28.9	95.0	947	20.5	4.2	0.00766	DATA SET 133			
20	0.00143	655	6.79	30.2	102.6	960	20.6	20.4	0.224	DATA SET 134			
30	0.00532	662	6.92	31.4	110.8	963	20.7	77	1.50	DATA SET 135			
40	0.01867	693	7.33	32.3	118.1	974	20.7	195	2.30	DATA SET 136			
50	0.04807	DATA SET 110											
60	0.09640	77	0.221	34.1	126.8	998	21.0	273	2.30	DATA SET 137			
70	0.1632	273	2.425	34.7	144.2×10^{-4}	1001	21.0	DATA SET 138					
80	0.2455	DATA SET 111*											
90	0.3400	4.6	0.00261	6.7	22.7×10^{-4}	1004	21.1	DATA SET 139					
100	0.4425	15.1	0.00383	9.4	23.5	1006	21.1	DATA SET 140					
120	0.6631	17.7	0.00380	11.4	24.5	1008	21.2	DATA SET 141					
140	0.8934	21.0	0.00380	13.3	25.6	1014	21.2	DATA SET 142					
160	1.127	27.8	0.00380	16.1	27.7	1025	21.4	DATA SET 143					
180	1.361	30.1	0.0103	18.5	30.2	1034	21.3	DATA SET 144					
200	1.593	35.4	0.0156	21.8	34.7	1044	21.7	DATA SET 145					
220	1.824	41.9	0.0302	23.3	37.8	1050	21.6	DATA SET 146					
240	2.053	48.1	0.0461	24.7	41.1	1078	22.1	DATA SET 147					
260	2.280	54.0	0.0647	26.9	48.1	1080	22.2	DATA SET 148					
273.2	2.430	61.3	0.103	27.9	52.4	DATA SET 117							
295	2.678	69.8	0.169	29.0	57.2	4.2	0.00725	DATA SET 149					
DATA SET 106*													
273.2	2.485	80.0	0.260	29.9	61.9	DATA SET 118							
DATA SET 107													
193.7	1.52	80.3	0.375	30.6	66.4	298	2.74	DATA SET 125					
248.2	2.14	31.6	0.734	31.6	73.4	373	3.57	DATA SET 126					
298.2	2.72	32.6	0.88.6	32.6	81.6	473	4.71	DATA SET 127					
351.2	3.33	33.4	88.6	33.4	88.6	573	5.86	DATA SET 128					
408.4	4.05	34.0	95.3	34.0	95.3	673	7.06	DATA SET 129					
DATA SET 108*													
293	2.9	34.3	100.6×10^{-4}	34.3	100.6×10^{-4}	DATA SET 119							
DATA SET 109													
8.7	57.7×10^{-4}	20.4	40.9×10^{-4}	20.4	40.9×10^{-4}	DATA SET 120							
11.2	58.6	77.78	0.2257	77.78	0.2257	DATA SET 121*							
13.2	59.7	194.6	1.554	194.6	1.554	DATA SET 122*							
15.8	61.7	273.2	2.450	273.2	2.450	DATA SET 123							
18.9	65.0	298.5	2.724	298.5	2.724	DATA SET 124							
DATA SET 110													
8.7	57.7×10^{-4}	20.4	40.9×10^{-4}	20.4	40.9×10^{-4}	DATA SET 125							
11.2	58.6	77.78	0.2257	77.78	0.2257	DATA SET 126							
13.2	59.7	194.6	1.554	194.6	1.554	DATA SET 127							
15.8	61.7	273.2	2.450	273.2	2.450	DATA SET 128							
18.9	65.0	298.5	2.724	298.5	2.724	DATA SET 129							

*Not shown in figure.

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

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
DATA SET 133*																			
20.4	0.698	273	2.417	DATA SET 142*		47.00	0.08630	DATA SET 143 (cont.)		895.0	10.117	DATA SET 150 (cont.)		17.9	106.3	DATA SET 154 (cont.)		18.8	108.8
DATA SET 134*																			
473	4.619	473	2.500	DATA SET 143*		76.04	0.2301	DATA SET 149		915.9	10.449	DATA SET 151		19.7	111.4 x 10 ⁻⁴	DATA SET 155		339	3.26
573	5.801	573	7.046	DATA SET 144*		2.7 80.6 x 10 ⁻⁴		DATA SET 152		927.8	10.644	DATA SET 152		339 3.26		DATA SET 158*		404	4.11
773	8.346	773	8.346	DATA SET 145*		2.7	80.6 x 10 ⁻⁴	DATA SET 153		2.7 80.6 x 10 ⁻⁴		DATA SET 153		339 3.26		DATA SET 159*		459	4.82
823	9.170	823	9.170	DATA SET 146*		4.1	80.6	DATA SET 154		4.1 80.6		DATA SET 154		404 4.11		DATA SET 159*		552	6.04
873	9.755	873	9.755	DATA SET 147*		5.3	80.9	DATA SET 155		5.3 80.9		DATA SET 155		459 4.82		DATA SET 159*		634	7.01
898	10.139	898	10.139	DATA SET 148		6.3	82.0	DATA SET 156		6.3 82.0		DATA SET 156		552 6.04		DATA SET 159*		728	8.36
923	10.540	923	10.540	DATA SET 149		6.7	82.0	DATA SET 157		6.7 82.0		DATA SET 157		634 7.01		DATA SET 159*		795	9.34
DATA SET 135																			
2.24	9.0 x 10 ⁻⁴	10.2	10.4	DATA SET 150		7.2	82.8	DATA SET 158		7.2 82.8		DATA SET 158		728 8.36		DATA SET 159*		823	9.170
4.00	9.1	12.3	12.3	DATA SET 151		8.7	83.9	DATA SET 159		8.7 83.9		DATA SET 159		823 9.170		DATA SET 159*		873	9.755
6.40	9.4	15.3	15.0	DATA SET 152		10.3	85.6	DATA SET 160		10.3 85.6		DATA SET 160		898 10.139		DATA SET 159*		923	10.540
8.40	9.5	19.6	22.2	DATA SET 153		11.0	83.7	DATA SET 161		11.0 83.7		DATA SET 161		923 10.540		DATA SET 159*			
8.55	10.0	23.4	40.4	DATA SET 154		11.7	83.9	DATA SET 162		11.7 83.9		DATA SET 162				DATA SET 159*			
9.35	10.2	28.0	96.3 x 10 ⁻⁴	DATA SET 155		12.6	84.5	DATA SET 163		12.6 84.5		DATA SET 163				DATA SET 159*			
12.51	12.3	2.19	5.70 x 10 ⁻⁴	DATA SET 156		13.4	87.5	DATA SET 164		13.4 87.5		DATA SET 164				DATA SET 159*			
15.3	15.0	2.56	5.70	DATA SET 157		14.5	87.5	DATA SET 165		14.5 87.5		DATA SET 165				DATA SET 159*			
19.6	22.2	3.06	5.70	DATA SET 158		14.5	87.5	DATA SET 166		14.5 87.5		DATA SET 166				DATA SET 159*			
23.4	40.4	3.58	5.72	DATA SET 159		14.5	87.5	DATA SET 167		14.5 87.5		DATA SET 167				DATA SET 159*			
28.0	96.3 x 10 ⁻⁴	3.91	5.77	DATA SET 160		16.1	91.4	DATA SET 168		16.1 91.4		DATA SET 168				DATA SET 159*			
DATA SET 136																			
2.19	5.70 x 10 ⁻⁴	7.31	6.31	DATA SET 161		19.1	99.4	DATA SET 169		19.1 99.4		DATA SET 169				DATA SET 159*			
2.56	5.70	8.94	6.98	DATA SET 162		21.9	106.0	DATA SET 170		21.9 106.0		DATA SET 170				DATA SET 159*			
3.06	5.70	8.94	6.98	DATA SET 163		26.1	126.0 x 10 ⁻⁴	DATA SET 171		26.1 126.0 x 10 ⁻⁴		DATA SET 171				DATA SET 159*			
3.58	5.72	9.56	7.07	DATA SET 164		294	2.8	DATA SET 172		294 2.8		DATA SET 172				DATA SET 159*			
3.91	5.77	9.56	7.07	DATA SET 165		372	3.8	DATA SET 173		372 3.8		DATA SET 173				DATA SET 159*			
7.31	6.31	13.68	9.82	DATA SET 166		492	5.4	DATA SET 174		492 5.4		DATA SET 174				DATA SET 159*			
8.94	6.98	16.38	13.3	DATA SET 167		618	6.7	DATA SET 175		618 6.7		DATA SET 175				DATA SET 159*			
13.68	9.82	17.10	14.4	DATA SET 168		721	7.5	DATA SET 176		721 7.5		DATA SET 176				DATA SET 159*			
16.38	13.3	21.39	26.5 x 10 ⁻⁴	DATA SET 169		822	9.5	DATA SET 177		822 9.5		DATA SET 177				DATA SET 159*			
17.10	14.4	2.19	5.70 x 10 ⁻⁴	DATA SET 170		914	9.7	DATA SET 178		914 9.7		DATA SET 178				DATA SET 159*			
21.39	26.5 x 10 ⁻⁴	2.56	5.70	DATA SET 171		942	25.5	DATA SET 179		942 25.5		DATA SET 179				DATA SET 159*			
DATA SET 137																			
4	20.0 x 10 ⁻⁴	2.56	5.70	DATA SET 172		976	25.9	DATA SET 180		976 25.9		DATA SET 180				DATA SET 159*			
20	23.2	3.06	5.70	DATA SET 173		1024	26.1	DATA SET 181		1024 26.1		DATA SET 181				DATA SET 159*			
30	69.9 x 10 ⁻⁴	3.58	5.72	DATA SET 174		1073	27.7	DATA SET 182		1073 27.7		DATA SET 182				DATA SET 159*			
DATA SET 138																			
4	0.00106	20.08	0.070	DATA SET 175		287.4	2.586	DATA SET 183		287.4 2.586		DATA SET 183				DATA SET 159*			
20	0.00201	80.13	0.422	DATA SET 176		289.4	2.609	DATA SET 184		289.4 2.609		DATA SET 184				DATA SET 159*			
30	0.00514	186.6	1.252	DATA SET 177		293.0	2.653	DATA SET 185		293.0 2.653		DATA SET 185				DATA SET 159*			
DATA SET 139*																			
20.4	0.698	272.6	2.362	DATA SET 178		372.0	3.445	DATA SET 186		372.0 3.445		DATA SET 186				DATA SET 159*			
4	20.0 x 10 ⁻⁴	4.00	0.02488	DATA SET 179		438.4	4.304	DATA SET 187		438.4 4.304		DATA SET 187				DATA SET 159*			
20	23.2	7.33	0.02489	DATA SET 180		502.0	5.041	DATA SET 188		502.0 5.041		DATA SET 188				DATA SET 159*			
30	69.9 x 10 ⁻⁴	13.40	0.02606	DATA SET 181		583.6	6.006	DATA SET 189		583.6 6.006		DATA SET 189				DATA SET 159*			
DATA SET 140*																			
4	20.0 x 10 ⁻⁴	16.60	0.02642	DATA SET 182		688.3	7.286	DATA SET 190		688.3 7.286		DATA SET 190				DATA SET 159*			
20	23.2	19.77	0.02805	DATA SET 183		728.8	7.802	DATA SET 191		728.8 7.802		DATA SET 191				DATA SET 159*			
30	69.9 x 10 ⁻⁴	21.98	0.02992	DATA SET 184		764.4	8.264	DATA SET 192		764.4 8.264		DATA SET 192				DATA SET 159*			
DATA SET 141*																			
4	0.00106	25.01	0.03404	DATA SET 185		770.9	8.355	DATA SET 193		770.9 8.355		DATA SET 193				DATA SET 159*			
20	0.00201	28.91	0.04018	DATA SET 186		794.1	8.663	DATA SET 194		794.1 8.663		DATA SET 194				DATA SET 159*			
30	0.00514	35.08	0.05346	DATA SET 187		831.3	9.185	DATA SET 195		831.3 9.185		DATA SET 195				DATA SET 159*			
DATA SET 142*																			
4	0.00106	4.00	0.02488	DATA SET 188		843.3	9.345	DATA SET 196		843.3 9.345		DATA SET 196				DATA SET 159*			
20	0.00201	7.33	0.02489	DATA SET 189		854.3	9.516	DATA SET 197		854.3 9.516		DATA SET 197				DATA SET 159*			
30	0.00514	13.40	0.02606	DATA SET 190		872.5	9.774	DATA SET 198		872.5 9.774		DATA SET 198				DATA SET 159*			
DATA SET 143*																			
4	20.0 x 10 ⁻⁴	16.60	0.02642	DATA SET 191		878.1	9.868	DATA SET 199		878.1 9.868		DATA SET 199				DATA SET 159*			
20	23.2	19.77	0.02805	DATA SET 192		919.9	10.39	DATA SET 200		919.9 10.39		DATA SET 200				DATA SET 159*			
30	69.9 x 10 ⁻⁴	21.98	0.02992	DATA SET 193		951.6	10.74	DATA SET 201		951.6 10.74		DATA SET 201				DATA SET 159*			
DATA SET 144*																			
4	20.0 x 10 ⁻⁴	25.01	0.03404	DATA SET 194		982.5	11.16	DATA SET 202		982.5 11.16		DATA SET 202				DATA SET 159*			
20	23.2	28.91	0.04018	DATA SET 195		1000.0	11.59	DATA SET 203		1000.0 11.59		DATA SET 203				DATA SET 159*			
30	69.9 x 10 ⁻⁴	35.08	0.05346	DATA SET 196		1024.0	11.99	DATA SET 204		1024.0 11.99		DATA SET 204				DATA SET 159*			
DATA SET 145*																			
4	20.0 x 10 ⁻⁴	4.00	0.02488	DATA SET 197		1073.0	12.77	DATA SET 205		1073.0 12.77		DATA SET 205				DATA SET 159*			
20	23.2	7.33	0.02489	DATA SET 198		1173.0	13.71	DATA SET 206		1173.0 13.71		DATA SET 206				DATA SET 159*			
30	69.9 x 10 ⁻⁴	13.40	0.02606	DATA SET 199		1473.0	15.17	DATA SET 207		1473.0 15.17		DATA SET 207				DATA SET 159*			
DATA SET 146*																			
4	20.0 x 10 ⁻⁴	16.60	0.02642	DATA SET 199		19.9	73.5 x 10 ⁻⁴	DATA SET 208		19.9 73.5 x 10 ⁻⁴		DATA SET 208				DATA SET 159*			
20	23.2	19.77	0.02805	DATA SET 200		2.0	91.6 x 10 ⁻⁴	DATA SET 209		2.0 91.6 x 10 ⁻⁴		DATA SET 209				DATA SET 159*			
30	69.9 x 10 ⁻⁴	21.98	0.02992	DATA SET 201		3.0	91.7	DATA SET 210		3.0 91.7		DATA SET 210				DATA SET 159*			
DATA SET 147*																			
4	20.0 x 10 ⁻⁴	25.01	0.03404	DATA SET 202		4.2	91.9	DATA SET 211		4.2 91.9		DATA SET 211				DATA SET 159*			
20	23.2	28.91	0.04018	DATA SET 203		4.2	91.9	DATA SET 212		4.2 91.9		DATA SET 212				DATA SET 159*			
30	69.9 x 10 ⁻⁴	35.08	0.05346	DATA SET 204		13.9	98.6	DATA SET 213		13.9 98.6		DATA SET 213				DATA SET 159*			
DATA SET 148																			
4	20.0 x 10 ⁻⁴	4.00	0.02488	DATA SET 205		14.9	100.0	DATA SET 214		14.9 100.0		DATA SET 214				DATA SET 159*			
20	23.2	7.33	0.02489	DATA SET 206		15.9	102.0	DATA SET 215		15.9 102.0		DATA SET 215				DATA SET 159*			
30	69.9 x 10 ⁻⁴	13.40	0.02606	DATA SET 207		16.9	103.9	DATA SET 216		16.9 103.9		DATA SET 216				DATA SET 159*			

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

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
<u>DATA SET 160*</u>											
4.2	0.00385	273.2	2.695	21.2	0.340	83.2	0.663	273	2.53	648	7.638
273.2	2.603	<u>DATA SET 171*</u>		273.2	2.84	<u>DATA SET 180*</u>		293	2.75	673	7.991
<u>DATA SET 161*</u>											
88	0.318	88	0.394	<u>DATA SET 181</u>		<u>DATA SET 187*</u>		<u>DATA SET 188*</u>			
4.2	0.00551	<u>DATA SET 172*</u>		959.15	26.0	20	0.108	20	0.108	<u>DATA SET 189</u>	
273.2	2.573	88	0.394	1018.15	26.4	80.1	0.367	80.1	0.367	<u>DATA SET 190*</u>	
<u>DATA SET 162*</u>											
20	0.0241	88	0.382	1047.15	26.8	81.1	0.380	81.1	0.380	<u>DATA SET 191 (cont.)</u>	
90	0.371	<u>DATA SET 173*</u>		1089.15	27.6	194.7	1.64	194.7	1.64		
297	2.7414	88	0.382	1198.15	29.2	<u>DATA SET 182*</u>					
<u>DATA SET 163*</u>											
20	0.0293	<u>DATA SET 174*</u>		296.2	2.96	973	27.80	973	27.80		
90	0.381	88	0.342	<u>DATA SET 183</u>		1073	29.28	1073	29.28		
297	2.7330	<u>DATA SET 175*</u>		<u>DATA SET 184*</u>		1173	30.75	1173	30.75		
<u>DATA SET 164*</u>											
89	0.725	89	0.725	289.4	2.83	1273	32.22	1273	32.22		
273	2.70	273	2.70	290.0	2.81	<u>DATA SET 185*</u>		<u>DATA SET 190*</u>			
374	3.92	476	5.16	346.2	3.45	293	2.828	293	2.828		
297	2.740	<u>DATA SET 176*</u>		350.2	3.53	<u>DATA SET 191</u>					
<u>DATA SET 165*</u>											
20	0.0281	21.2	0.0183	433.2	4.47	84	0.641	84	0.641		
90	0.377	83.2	0.3065	434.2	4.48	98	0.795	98	0.795		
297	2.7359	273.2	2.50	575.9	6.15	123	1.038	123	1.038		
<u>DATA SET 166*</u>											
20	0.0261	83.2	0.319	577.6	6.23	148	1.282	148	1.282		
90	0.406	273.2	2.52	579.4	6.24	173	1.535	173	1.535		
297	2.7350	<u>DATA SET 177*</u>		672.2	7.39	198	1.782	198	1.782		
<u>DATA SET 167*</u>											
20	0.0261	21.2	0.0351	773.2	8.77	223	2.067	223	2.067		
90	0.406	83.2	0.319	775.6	8.79	248	2.321	248	2.321		
297	2.7350	273.2	2.52	813.9	9.31	273	2.618	273	2.618		
<u>DATA SET 168*</u>											
20	0.0261	21.2	0.0157	<u>DATA SET 186*</u>		298	2.928	298	2.928		
90	0.406	83.2	0.458	273	2.74	323	3.237	323	3.237		
297	2.7350	273.2	2.65	293	2.99	348	3.562	348	3.562		
<u>DATA SET 169*</u>											
20	0.0261	21.2	0.0157	<u>DATA SET 187*</u>		373	3.858	373	3.858		
90	0.406	83.2	0.458	273	2.64	398	4.192	398	4.192		
297	2.7350	273.2	2.65	293	2.87	423	4.498	423	4.498		
<u>DATA SET 170*</u>											
20	0.0261	21.2	0.0157	273	2.64	448	4.827	448	4.827		
90	0.406	83.2	0.458	293	2.87	473	5.172	473	5.172		
297	2.7350	273.2	2.65	<u>DATA SET 188*</u>		498	5.518	498	5.518		
<u>DATA SET 171*</u>											
20	0.0261	21.2	0.219	273	2.61	523	5.850	523	5.850		
90	0.406	83.2	0.525	293	2.84	548	6.204	548	6.204		
297	2.7350	273.2	2.72	<u>DATA SET 189</u>		573	6.559	573	6.559		
<u>DATA SET 172*</u>											
20	0.0261	21.2	0.219	273	2.61	598	6.917	598	6.917		
90	0.406	83.2	0.525	293	2.84	623	7.274	623	7.274		
297	2.7350	273.2	2.72	<u>DATA SET 190*</u>		<u>DATA SET 191</u>					
<u>DATA SET 173*</u>											
20	0.0261	21.2	0.219	273	2.61	<u>DATA SET 191</u>					
90	0.406	83.2	0.525	293	2.84	<u>DATA SET 191</u>					
297	2.7350	273.2	2.72	<u>DATA SET 191</u>		<u>DATA SET 191</u>					

*Not shown in figure.

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.

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-Gervais³⁰² demonstrated that the room-temperature electrical resistivity dropped from 205×10^{-8} to 144.2×10^{-8} Ω m after annealing the specimen at 898 K.

Meaden³⁰³ (data set 10), Bellou and Coles³⁰⁶ (data set 14), and White and Woods³⁰⁷ (data set 15), have reported T^2 dependence of the temperature-dependent resistivity (ρ_i) below 17 K. This was confirmed by Nagasawa and Senba³⁰⁰ (data set 4) and by Murayama and Nagasawa³¹⁰ (data set 19). The recommended values from 20–325 K are based on the generally agreed upon data of Nagasawa and Senba³⁰⁰ (data set 4), Meaden and Pelloux-Gervais³⁰² (data set 12), Bellou and Coles³⁰⁶ (data set 14), and of White and Woods³⁰⁷ (data set 16). The recommended values below 20 K for $\rho_0 = 6.9 \times 10^{-8}$ Ω m are based on the data of Meaden³⁰³ (data set 10) and Meaden and Pelloux-Gervais³⁰⁴ (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 four to five 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. Brunke³¹¹ obtained a value of

91×10^{-8} Ω m for the electrical resistivity of β -Mn. Potter *et al.*³¹² and Erfling³¹³ have reported about 40×10^{-8} Ω m for the room-temperature electrical resistivity to 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 Speidel³⁰⁸ (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 Speidel³⁰⁸ (data set 17) is twice as much as the recommended value, and indicates a high impurity in their sample. The value of 38×10^{-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 144×10^{-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 Speidel³⁰⁸ (data set 17) reported a constant value of 40×10^{-8} Ω m from 1523 to 1543 K. Summarizing this, the electrical resistivity at the melting point varies from 40 to 190×10^{-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 4 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.

Electrical resistivity of slightly less pure manganese with different residual resistivity can be calculated from the recommended values using the Matthiessen rule. This procedure involves subtracting ρ_0 from the recommended ρ value to obtain the temperature-dependent part to which ρ_0 of the specimen in question be added to generate a set of values applicable to that specimen. However, it should be pointed out that this procedure neglects contributions due to deviations from the Matthiessen rule. Based on the available data it is safe to assume that the deviation from Matthiessen's rule

TABLE 4. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF MANGANESE^a[Temperature, T, K; Electrical Resistivity, ρ , $10^{-8} \Omega \text{ m}$]

T	ρ		T	ρ	
	uncorrected	corrected		uncorrected	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			

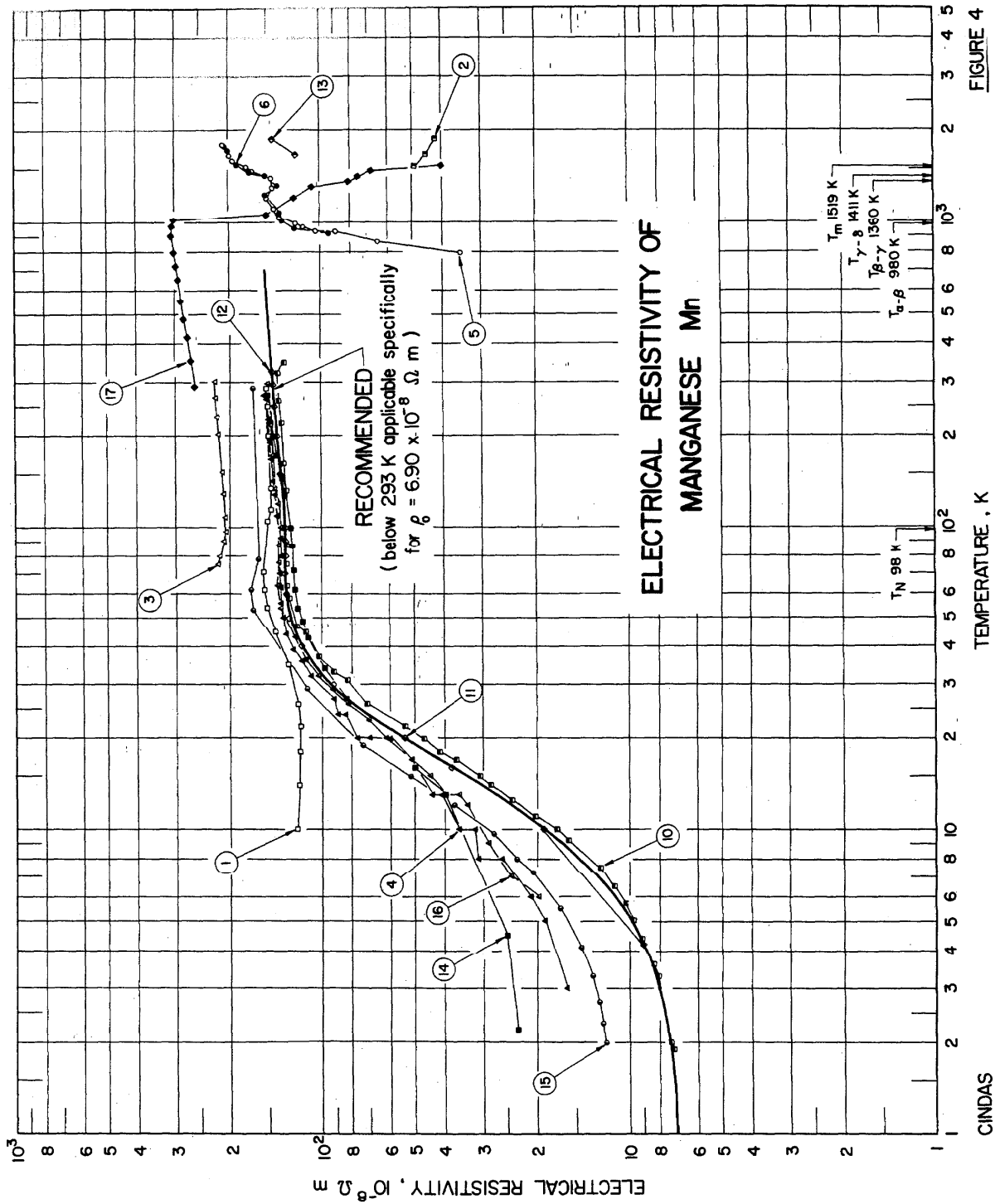
^aThe values are for well-annealed manganese of purity 99.99% or higher, but those below room temperature are applicable specifically to manganese having a residual resistivity of $6.90 \times 10^{-8} \Omega \text{ m}$. The columns headed uncorrected and corrected refer to values uncorrected and corrected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

(DMR) is small below 20 K for $7 \times 10^{-8} < \rho_0 < 28 \times 10^{-8} \Omega \text{ m}$. Above 20 K, the behavior is rather complex and needs further study.

The effect of a magnetic field on the resistivity of manganese at low temperature is relatively small compared with that for pure copper. Meaden³⁰³ 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 Nagasawa³¹⁰ (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 Grassie²⁹⁷ (data set 1) studied the temperature dependence of the electrical resistivity of a thin manganese film. For a film of thickness 4000 Å 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-Gervais³⁰² (data set 12) and by White and Woods³⁰⁷ (data sets 15,16). Additional information/data on films are reported in Refs. 342–351. The pressure dependence of the electrical resistivity is reported in Refs. 352–355.



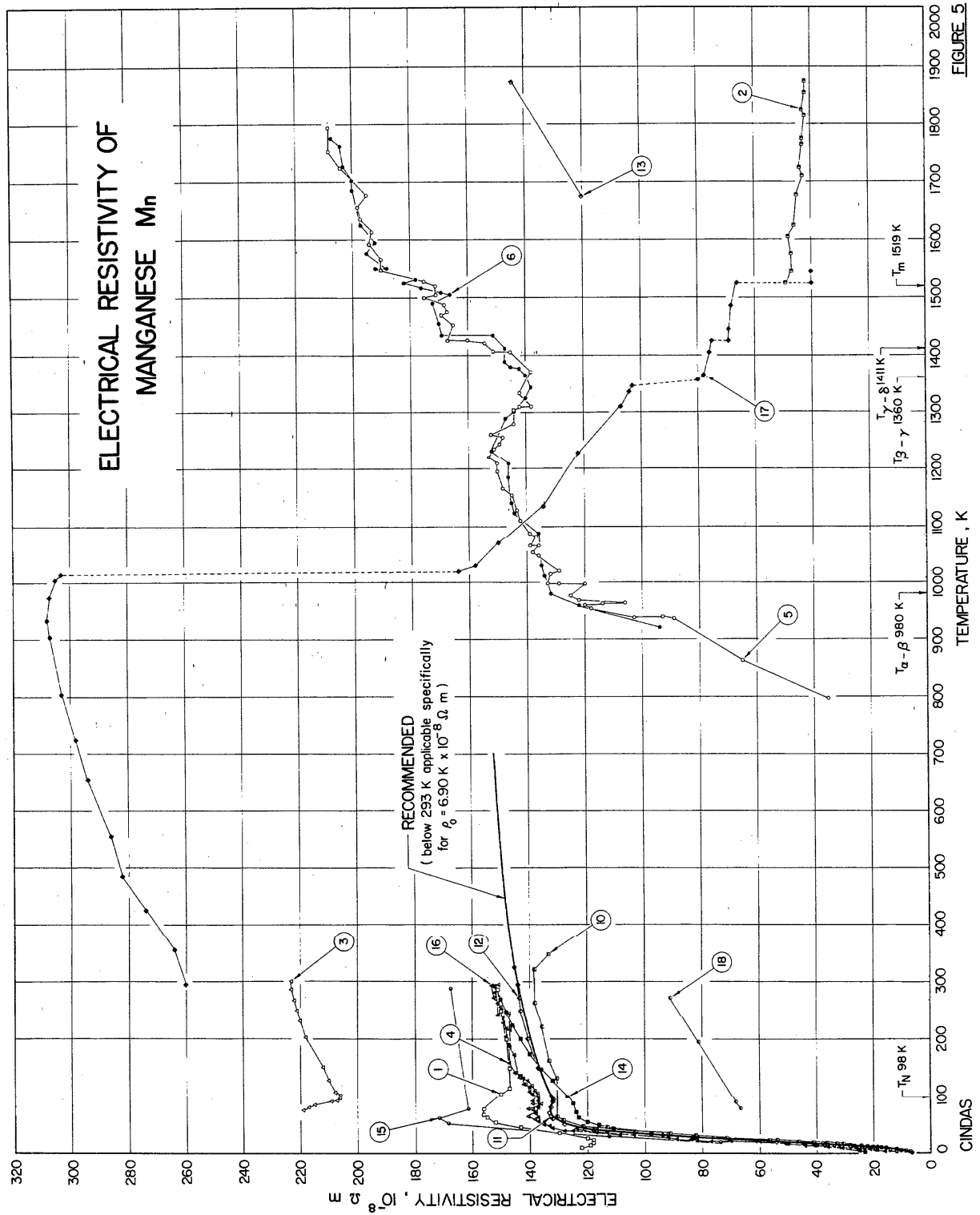


TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MANGANESE Mn

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, E.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 $120 \times 10^{-9} \Omega \text{ m}$ is attributed to several atoms driven into spin fluctuations.
2	298	Levin, E.S., Zamaryev, V.N., and Gel'd, F.V.	1976	+	1523-1873		Liquid manganese; remelted electrolytic distilled in a vacuum; average of heating and cooling experiments; measurements with contactless 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, N.	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, F.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 parallelepipeds 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 $1-8 \times 10^{-6}$ 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 $1-8 \times 10^{-6}$ 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 $1-8 \times 10^{-6}$ 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^{-6} torr vacuum for 7 hr at 893 K; extrapolated ρ_0 from 2 K is $6.87 \times 10^{-8} \Omega \cdot m$; 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 $0.965 \times 4.92 \times 24.95$ mm; the specimens were annealed under a vacuum of 10^{-6} to 8×10^{-6} 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 averages of heating and cooling experiments.
13	305	Vostriyakov, A.A., Vatolin, N.A., and Esin, O.A.	1964	-	1673-1873		Electrolytic manganese.
14	306	Bellu, 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 $\rho_{300} - \rho_{4.2} = 1.30 \times 10^{-8} \Omega \cdot m$ 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 $\rho_0 = 11.3 \times 10^{-8} \Omega \cdot m$ 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 $\rho_0 = 16.8 \times 10^{-8} \Omega \cdot m$.
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 $91.0 \times 10^{-8} \Omega \cdot m$ 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 , $10^{-9} \Omega \cdot m$]

DATA SET 1		DATA SET 3 (cont.)		DATA SET 4 (cont.)		DATA SET 5 (cont.)		DATA SET 6		DATA SET 7 (cont.)*	
T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
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	129.3	142.1	1127	143.3	1028	135	DATA SET 8*	
35.2	130	203.0	217.7	129.3	142.1	1153	145.1	1086	136	300	345(185)
44.7	143	231.0	219.5	132.7	143.0	1165	148.6	1121	144	300	320(175)
54.1	152	250.9	221.4	137.8	143.8	1194	150.4	1139	145	DATA SET 9*	
61.7	155	268.4	222.0	142.8	145.5	1209	150.4	1183	146	300	290(160)
67.4	156	287.1	222.6	147.1	147.1	1220	153.9	1209	146	300	253(155)
71.2	156	301.1	222.6	183.3	147.1	1235	151.0	1232	152	4.2	(15.0)
76.8	156	DATA SET 4		190.0	148.0	1244	149.3	1288	147	DATA SET 10	
105.2	150	3.5	16.8	205.2	148.7	1261	152.8	1300	144	1.90	7.21
114.7	147	5.2	19.4	218.7	148.7	1256	148.1	1323	140	2.01	7.32
120.3	147	6.9	21.0	228.8	149.5	1279	144.6	1341	138	3.30	8.04
135.5	147	8.6	26.1	240.6	149.5	1291	144.7	1364	140	3.65	8.37
150.6	147	8.7	31.2	244.0	151.2	1303	147.2	1376	142	4.46	9.02
197.9	148	10.4	32.8	250.7	150.3	1309	142.4	1379	145	5.19	9.73
250.8	150	10.4	36.2	257.5	150.3	1332	142.4	1411	147	5.74	10.33
286.8	151	13.8	41.3	264.2	152.0	1370	138.9	1434	151	6.03	10.68
		13.9	44.6	282.8	152.8	1405	145.3	1454	170	6.50	11.22
		17.3	51.4	DATA SET 5		1420	154.8	1504	166	6.84	11.94
1523	49	17.3	51.4	797	35.9	1425	160.0	1507	169	7.56	12.55
1543	47	20.7	60.6	863	65.2	1425	167.0	1489	172	9.25	15.83
1573	47	20.8	70.7	935	89.9	1452	165.9	1516	176	10.2	17.31
1603	48	20.9	77.5	938	93.9	1469	169.4	1530	178	11.6	20.23
1623	46	24.3	84.2	938	103.3	1475	167.7	1524	182	12.2	22.23
1673	45	24.4	89.3	964	106.8	1487	168.3	1550	188	12.5	24.31
1708	43	27.8	92.6	961	114.4	1504	171.2	1550	192	13.8	26.79
1723	44	33.0	109.5	952	118.5	1519	171.8	1576	195	14.5	28.37
1763	43	36.4	117.1	952	118.5	1519	171.8	1576	195	15.3	30.51
1773	43	39.8	125.5	958	120.3	1498	175.3	1594	192	16.1	32.87
1813	42	39.9	128.0	975	119.1	1527	175.9	1644	197	17.3	36.57
1823	43	44.9	132.2	967	122.0	1547	190.6	1685	200	18.2	41.45
1853	42	48.3	133.9	978	121.4	1565	190.6	1702	200	20.2	46.38
1873	42	50.0	135.6	996	120.9	1591	194.7	1726	204	22.4	53.75
		56.8	137.2	975	125.5	1612	193.6	1761	204	22.9	56.50
		63.5	137.2	996	129.7	1635	197.7	1775	207	26.6	71.64
		70.3	138.0	996	133.2	1655	198.4	1775	207	31.9	82.29
		73.7	138.0	1019	129.7	1676	195.4	DATA SET 7*			
80.3	217.0	80.4	137.2	1013	132.6	1676	195.4	300	210(149)		
83.8	214.6	83.8	136.1	1045	136.1	1752	208.4	300	205(148)		
89.7	209.1	87.1	136.3	1051	138.5	1793	208.4	300	205(148,2)		
92.0	207.3	92.2	137.2	1063	136.2						

*Not shown in figure.

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