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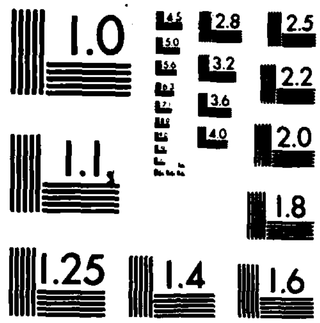

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ELECTRICAL RESISTIVITY OF ALKALINE EARTH ELEMENTS

By

T. C. CHI

CINDAS REPORT 42

December 1976

Prepared for

DEFENSE SUPPLY AGENCY
U. S. Department of Defense
Alexandria, Virginia 22304

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This technical report presents and discusses the available data and information on the electrical resistivity of alkaline earth elements (beryllium, magnesium, calcium, strontium, barium, and radium) and contains recommended or provisional reference values. The compiled data include all the experimental data available from the literature. The temperature range covered by the compiled data is from cryogenic temperatures to above the melting temperature of the elements. The recommended values are generated from critical evaluation, analysis, and synthesis of the available data and

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information and are given for both the total electrical resistivity and the intrinsic electrical resistivity. For most of the elements, the recommended values cover the temperature range from 1 K to 1000 K.

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PREFACE

This technical report was prepared by the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC), a Department of Defense Information Analysis Center. This Center is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under Contract No. DSA900-76-C-0860 with the Defense Supply Agency (DSA), Alexandria, Virginia, with Mr. J. L. Blue being the Program Manager, and under the technical direction of the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts, with Mr. Samuel Valencia being the Contracting Officer's Technical Representative.

This report reviews the recorded world knowledge on the electrical resistivity of alkaline earth elements in a most comprehensive and detailed form making it possible for all users of the subject to have access to the original data without having to duplicate the laborious and costly process of literature search and data extraction. It is quite appropriate at this point to mention that only original sources of data have been used for the critique of the data and that all cited documents are available at CINDAS. Also, for the active researchers in the field, a detailed discussion is presented for each material, reviewing the available information together with the considerations used by the author in arriving at the final recommended reference values.

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

While this work is prepared by the staff of TEPIAC/CINDAS's Reference Data Division, it would not have been possible without the direct input of TEPIAC/CINDAS' Scientific Documentation Division. Furthermore, valuable suggestions and guidance to this work have come from Dr. H. M. James and Dr. C. Y. Ho of CINDAS' senior staff.

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December 1976

ABSTRACT

This technical report presents and discusses the available data and information on the electrical resistivity of alkaline earth elements (beryllium, magnesium, calcium, strontium, barium, and radium) and contains recommended or provisional reference values. The compiled data include all the experimental data available from the literature. The temperature range covered by the compiled data is from cryogenic temperatures to above the melting temperature of the elements. The recommended values are generated from critical evaluation, analysis, and synthesis of the available data and information and are given for both the total electrical resistivity and the intrinsic electrical resistivity. For most of the elements, the recommended values cover the temperature range from 1 K to 1000 K.

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LIST OF SYMBOLS

A	Code for d.c. potentiometer method
B	Magnetic flux density; Code for d. c. bridge method
C	Code for a.c. potentiometer method; constant
D	Code for a.c. bridge method
E	Code for eddy current method
G	Code for galvanometer amplifier method
I	Code for induction method
L_F	Latent heat
M	Atomic weight
P	Pressure; constant
Q	Code for Q-meter method
R	Resistance
S_1	Constant
S_2	Constant
S_3	Constant
T	Temperature
T_m	Melting point
T_c	Critical temperature
V	Voltmeter and ammeter direct reading
ρ	Electrical resistivity
ρ_0	Residual electrical resistivity
ρ_i	Intrinsic electrical resistivity
ρ	Electrical resistivity parallel to the principal crystal-axis
ρ	Electrical resistivity perpendicular to the principal crystal-axis
θ_D	Debye temperature
θ_R	Empirical temperature
—	Code for miscellaneous methods

1. INTRODUCTION

The purpose of this work is to present and discuss the available data and information on the electrical resistivity of alkaline earth elements, to critically evaluate, analyze, and synthesize the data, and to make recommendations for the most probable values of the electrical resistivity over a wide temperature range. Of this group of elements experimental electrical resistivity data are available in the world literature for Be, Mg, Ca, Sr, and Ba and there is no resistivity data for Ra.

Table 1 contains information on the densities, crystal structures, phase transition temperatures, and certain other pertinent physical constants of the alkaline earth elements. This information is very useful in data analysis and synthesis. For example, the electrical resistivity of a material generally changes abruptly when the material undergoes any transformation. One must, therefore, be extremely cautious in attempting to extrapolate the electrical resistivity value across any transition temperature. No attempt has been made to critically evaluate the temperatures and constants given in Table 1, and they should not be considered as recommended values.

This work is organized in six sections. In the theoretical background section, some results of the theory of electrical resistivity are presented and briefly discussed. In the section on data evaluation and generation of recommended values, the general procedures and methods for data evaluation and for the generation of recommended values are outlined.

In the data presentation section, the electrical resistivity of each of the alkaline earth elements is presented separately in the order of increasing atomic number. Values of electrical resistivities are given for both the solid and liquid states. For an element at moderate and high temperatures the true electrical resistivity values for different high-purity (99.9^{+}) samples at each temperature should be but little different; therefore, a set of recommended electrical resistivity values can be given for a high-purity element. At low temperatures, however, the electrical resistivity values for different samples with small differences in impurity and/or imperfection differ greatly, and a set of recommended values applies only to a sample with that particular amount of impurity and imperfection. Thus, the low-temperature electrical resistivity of an element could be presented as a family of curves, each of which would be recommended for a sample with a particular amount of impurity and degree of imperfection, and hence a particular residual resistivity, ρ_0. In this work, two well-defined curves are recommended for the full temperature range: one representing the intrinsic electrical resistivity, ρ_i, which is a unique function of temperature and is zero at absolute zero, and the other representing the total resistivity, ρ, for the purest form of each element on which measurements have

TABLE 1. PHYSICAL CONSTANTS OF ALKALINE EARTH ELEMENTS[a]

Name	Atomic No.	Atomic Weight[b]	Density[c] kg m^{-3}x10^3	Crystal Structure[d]	Phase Transition Temp., K	Debye Temperature[e] at 0 K	Debye Temperature[e] 293 K	Melting Point, K	Normal Boiling Point, K	Critical Temp., K
Beryllium (Be)	4	9.01218	1.85	c.p.h. (α) b.c.c. (β)	1530 (α–β)	1160	1031	1562	2749	6170
Magnesium (Mg)	12	24.305	1.74	c.p.h.		396±54	330	922	1364	3537
Calcium (Ca)	20	40.08	1.55	f.c.c. (α) b.c.c. (β)	720±2 (α–β)	234±5	230	1113±2	1759	3273
Strontium (Sr)	38	87.62	2.60	f.c.c. (α) b.c.c. (γ)	830 (α–γ)	147±1	148	1042	1652	3064
Barium (Ba)	56	137.4	3.5	b.c.c. (α)		110.5±1.8	116	1002±2	2174	3670
Radium (Ra)	88	226.0254	5			89		973	1900	

a Information taken from Ref. [1].

b Atomic weights based on $^{12}C = 12$ as adopted by the International Union of Pure and Applied Chemistry in 1971. The number in parentheses is the mass number of the isotope of longest known half life.

c Density values given for 293 K.

d Structure below the melting temperature.

e Deduced from specific heat measurements.

been made. The latter curve at low temperatures is only applicable to the particularly characterized specimen with residual electrical resistivity clearly specified. These two curves approach each other closely, on a logarithmic scale, for temperatures above about 100 K. Figure 1 shows the relationship between ρ_i, ρ_0, and ρ.

The recommended or provisional electrical resistivities are tabulated with uniform but step-wise increasing increments in temperature as the temperature increases. The estimated accuracy of the recommended or provisional values for each element in each different temperature range is given in the discussion. The asterisked values in the tables are interpolated, extrapolated, or estimated in the temperature ranges where no experimental data are available.

From the recommended values of ρ and ρ_i which are tabulated in this work, the electrical resistivity of a particular sample at low temperatures can be estimated in either of the following two ways. One way is to find the difference between the measured resistivity value and the recommended ρ value at the same low temperature (i.e. below 100 K) and then add this difference to the recommended ρ values at other temperatures. The second way is to compare the measured low temperature value with ρ_i, get the difference which is the residual resistivity of this particular sample, and then add this ρ_0 to the recommended ρ_i at the other temperatures.

In the figure showing experimental data, a data set that consists of a single point is denoted by a number enclosed by a square, and a curve that connects a set of data points is denoted by a ringed number. These numbers correspond to those in the data table and in the accompanying table on specimen characterization and measurement information. When several sets of data are too close together to be distinguishable, some of the data sets or data points, though listed in the table, are omitted from the figure for the sake of clarity. For all elements except francium, both logarithmic plotting and linear plotting of electrical resistivity are used in order that details may be clearly shown for both the low and high temperature regions. The recommended curves are presented in the same figure. The solid curve represents recommended values, and the dashed curves give provisional values. In the figure, the melting point (M.P.), normal boiling point (N.B.P.), and critical temperature (C.T.) of the elements are indicated. Some of these transition points are also mentioned in the text. At the melting point the resistivity exhibits large discontinuity.

The tables on specimen characterization and measurement information give for each set of data the following information: the publication reference number, author's name, year of publication, experimental method used for the measurement, temperature

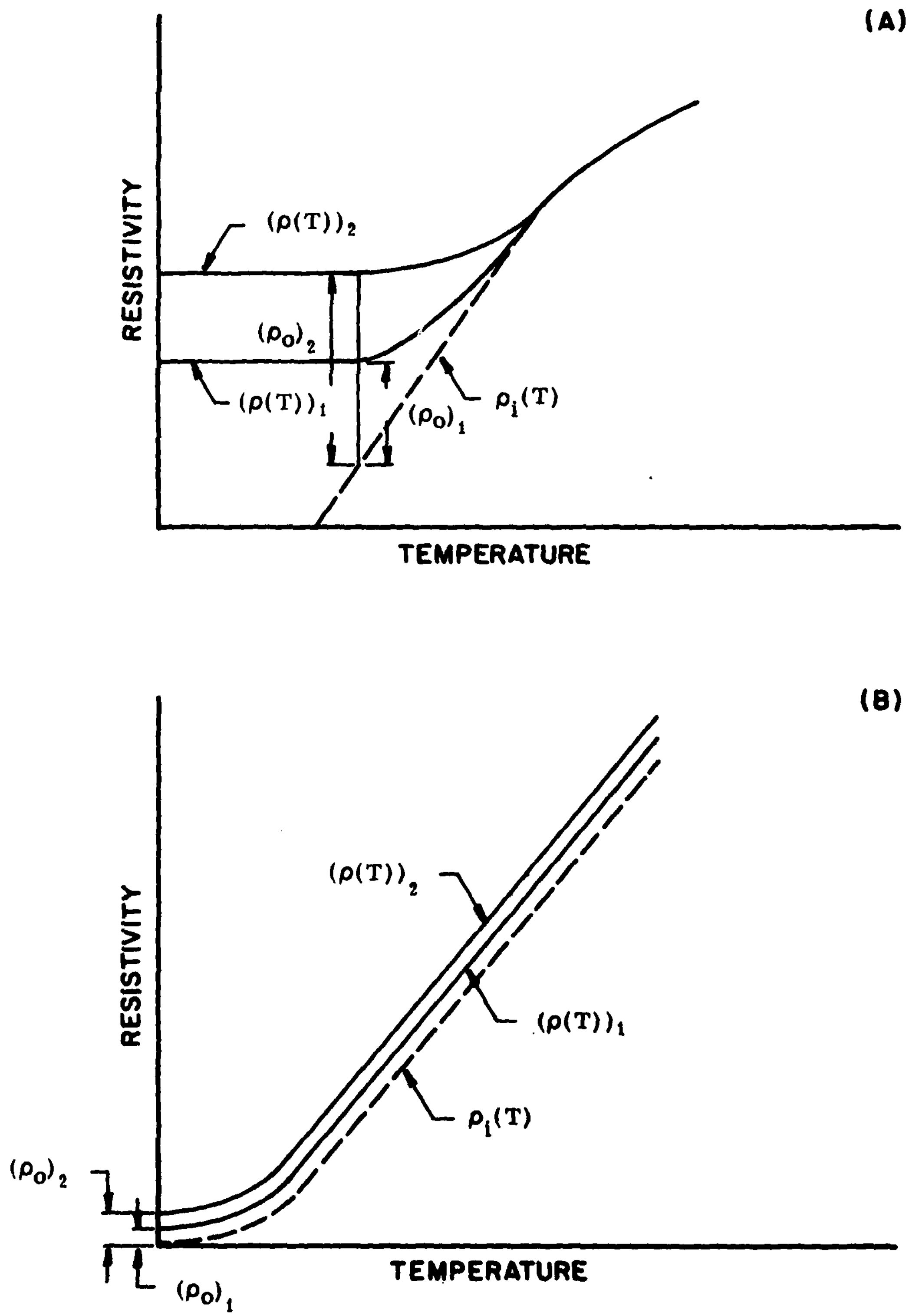


Figure 1. Relationship between intrinsic resistivity $\rho_i(T)$, residual resistivity, ρ_o, and total resistivity, $\rho(T)$. (A) logarithm scale, (B) linear scale.

range covered by the data, substance name and specimen designation, as well as the detailed description and characterization of the specimen and information on measurement conditions that are reported in the original paper. In these tables the code designations used for the experimental methods for electrical resistivity determination are as follows:

A	D.C. Potentiometer Method
B	D.C. Bridge Method
C	A.C. Potentiometer Method
D	A.C. Bridge Method
E	Eddy Current Method
G	Galvonometer Amplifier Method
I	Induction Method
Q	Q-Meter Method
V	Voltmeter and Ameter Direct Reading
→	Other than above and described in the remarks

For a comprehensive yet concise review of all these methods, the reader is referred to the references given in Appendix 7.1.

In the Thirteenth General Conference on Weights and Measures held in October 1967 in Paris, the unit "ohm-meter" (symbol: Ω m) was adopted as the SI unit for electrical resistivity. In this work, the SI units are used. Table 2 gives conversion factors which may be used to convert the electrical resistivity values in Ω m presented in this work to values in any of the several other units listed.

In the summary and conclusions section, figures are presented in which all the recommended curves on the intrinsic electrical resistivity are grouped together in order to facilitate a visual comparison.

TABLE 2. CONVERSION FACTORS FOR UNITS OF ELECTRICAL RESISTIVITY*

MULTIPLY ↓ by appropriate factor to OBTAIN →	abΩ cm	μΩ cm	Ω cm	statΩ cm	Ω m	Ω cir. mil ft^{-1}	Ω in.	Ω ft.
abohm-centimeter (emu)	1	0.001	10^{-9}	1.113×10^{-21}	10^{-11}	6.015×10^{-3}	3.937×10^{-10}	3.281×10^{-11}
microohm-centimeter	1000	1	10^{-6}	1.113×10^{-18}	10^{-8}	6.015	3.937×10^{-7}	3.281×10^{-8}
ohm-centimeter	10^{9}	10^{6}	1	1.113×10^{-12}	0.01	6.015×10^{6}	0.3937	0.0328
statohm-centimeter (esu)	8.987×10^{20}	8.987×10^{17}	8.987×10^{11}	1	8.987×10^{9}	5.406×10^{18}	3.538×10^{11}	2.949×10^{10}
ohm-meter	10^{11}	10^{8}	100	1.113×10^{-10}	1	6.015×10^{8}	39.37	3.281
ohm-circular mil per foot	166.2	0.1662	1.662×10^{-7}	1.850×10^{-19}	1.662×10^{-9}	1	6.54×10^{-8}	5.45×10^{-9}
ohm-inch	2.54×10^{9}	2.54×10^{6}	2.54	2.827×10^{-12}	0.0254	1.528×10^{7}	1	0.083
ohm-foot	3.048×10^{10}	3.048×10^{7}	30.48	3.3924×10^{-11}	0.3048	1.833×10^{8}	12	1

* This table is based on the universal constants from "The International System of Units (SI)," National Bureau of Standards, NBS Special Publication 330, 43 pp, 1974.

2. THEORETICAL BACKGROUND

The electrical resistivity, ρ, of a metal is often described approximately by the Matthiessen rule [2]

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

where ρ_0 is the residual resistivity at absolute zero temperature and ρ_i is the intrinsic resistivity, which is the temperature-dependent resistivity of an ideally pure sample of the metal. The quantity ρ_0 arises from the presence of impurities, defects, and strains in the metal lattice, while ρ_i is caused by the interaction of the conduction electrons with the thermally induced vibrations of the lattice ions; that is, the phonons in the crystal. For a pure annealed sample at room temperature, ρ_0 is only a small fraction of the total resistivity. There are a number of mechanisms that could produce a deviation from the Matthiessen rule, resulting in a term $\Delta\rho$ appearing on the right-hand side of equation (1). The first comprehensive survey of such deviations was made by J. Bass [3]. A more recent study by Cimberle et al. [4] brings references up to date.

The intrinsic resistivity due to electron-phonon interactions may be approximated by the Bloch-Grüneisen-relation [5]

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

where C is a constant, M is the atomic weight, T is the absolute temperature, and θ_R is an empirical temperature characterizing the metal's ideal electrical resistivity in the same way that the Debye temperature, θ_D, characterizes a solid's lattice specific heat. It is often true that $\theta_R \approx \theta_D$. Below about 0.1 θ_R this relation reduces to

$$\rho_i(T) \approx 124.4\,\frac{C}{M}\,\frac{T^5}{\theta_R^{\,6}} \tag{3}$$

At high temperatures, as $T \geq \theta_R$,

$$\rho_i(T) \approx \frac{C}{4M}\,\frac{T}{\theta_R^{\,2}}\ . \tag{4}$$

The Grüneisen-Bloch equation is derivable only for idealized monovalent metals with Debye phonon spectra and spherical Fermi surfaces, totally neglecting the effect of Umklapp processes. However, because of its comparative simplicitiy, this equation is still a most valuable tool for analyzing and discussing experimental data.

The Grüneisen-Bloch equation never holds over the entire temperature range for the alkaline earth metals. By inverting the computation, one may intercompare the behavior of different metals by interpreting the experimental results in terms of deviations from the Gruneisen-Bloch equation. This is often done by employing θ_R as a variable parameter and computing the value that it must possess at any temperature in order that the Gruneisen-Bloch equation may agree with the experiment at that temperature.

In all alkaline earth metals the electrical resistivity increases abruptly at the melting point and shows weakly negative temperature dependence in the liquid phase. The sudden change is due to the greater disorder of the liquid state and the disappearance of any definite crystal structure.

Mott [6] has presented a simple and fairly successful theory of liquid metals. He ignored the disordered positions and diffusive movements of the vibrating ions and assumed that near the melting point the ions of the liquid metal still maintain a more or less regular pattern. With an Einstein model of single frequency oscillators he obtained

$$\left(\frac{\rho_L}{\rho_S}\right)_{T_m} = \exp\left(\frac{80\ L_F}{T_m}\right), \tag{5}$$

where ρ_L and ρ_S are the electrical resistivities of the liquid and solid phases, T_m is the melting point, and L_F is the latent heat of fusion in kilojoules per mole. The calculated values of $(\rho_L/\rho_S)_{T_m}$ according to this formula compare moderately well with experimental data for alkaline earth metals.

A single crystal of a metal with a cubic crystal structure has an isotropic resistivity, and the resistivity of the polycrystalline material is the same, apart from a small extra contribution in a polycrystal that may sometimes be caused by grain boundaries. But in a single crystal of noncubic metal, the resistivity is often very anisotropic, its value depening on the direction of the flow current. Likewise, polycrystalline specimens of such metals, if preferentially oriented, as by rolling or drawing, will have direction-dependent resistive properties.

In isotropic metals with the close-packed hexagonal and rhombohedral (trigonal) structures, the electrical resistivity parallel to the principal crystalline axis is designated as $\rho_{/\!/}$ and electrical resistivity perpendicular to the principal axis is designated as $\rho_\perp$. When values for $\rho_{/\!/}$ and $\rho_\perp$ have been determined for a single crystal, one may calculate a value of ρ for a polycrystalline sample without preferential orientation by using the equation of Voigt [7]:

$$\rho = \frac{3\rho_{/\!/}\,\rho_\perp}{2\rho_{/\!/} + \rho_\perp} \tag{6}$$

Equation (6) has been used fairly commonly for the determination of ρ of a polycrystalline specimen from single crystal axial resistivities, and it usually gives satisfactory agreement with direct observation on polycrystals. However, Nichols [8] has found the relation

$$\rho = \frac{1}{3}(\rho_{/\!/} + 2\rho_{\perp}) \tag{7}$$

to be more suitable for metals with large anisotropy ratio, and to be perfect in the case of c.p.h. Mg.

3. DATA EVALUATION AND GENERATION OF RECOMMENDED VALUES

The data analysis and synthesis employed in this work whenever possible included critical evaluation of available data and related information, reconciliation of disagreements in conflicting data, correlation of data in terms of various parameters, and curve fitting with theoretical or empirical equations. Besides critical evaluation and analysis of the existing data, semiempirical techniques have been employed to fill gaps in data and to extrapolate existing data so that the resulting recommended values are internally consistent and cover as wide a range of temperature as possible.

In the critical evaluation of the validity of electrical resistivity data, any unusual dependence or anomaly was carefully investigated, the experimental technique was reviewed to see whether the actual boundary conditions in the experiment agreed with those assumed in the theory, and the author's estimations of uncertainty were checked to ensure that all the possible sources of errors were considered. The sources of errors may have included uncertainty in the measurement of specimen dimensions and of the distance between the potential probes, uncertainty due to the effects of thermal expansion, uncertainty in temperature measurements, uncertainty in the sensitivity of measuring circuits, and so on.

Many authors have included detailed error estimates in their published papers, and from these it is possible to evaluate the uncertainty for a particular method. However, experience has shown that the uncertainty estimates of most authors are unreliable. In many cases the difference between the results of two sets of data is much larger than the sum of their stated uncertainties.

Besides evaluating and analyzing individual data sets, correlating data in terms of various relevant parameters was a valuable technique and frequently used in data analysis. These parameters may include purity, density, residual electrical resistivity and so on.

For a meaningful data correlation, information on specimen characterization is very important. A full description of the specimen should include, wherever applicable, the following: purity or chemical composition, type of crystal, crystal axis orientation for a single crystal, microstructure, grain size, preferred grain orientation, inhomogeneity or additional phases for a polycrystalline specimen, specimen shape and dimensions, method and procedure of fabrication, sample history or treatment, test environment, and pertinent physical properties such as density, hardness, and transition temperature. Data on poorly characterized materials can hardly be analyzed or used for data correlation.

Besides specimen characterization, a full description of experimental details should be given by the author in order that his data can be meaningfully evaluated and fully utilized. Sometimes, as an initial method of evaluating the quality of a paper, consideration might be given to the amount of experimental detail reported in the paper; lack of experimental detail might lead to the results being given less weight.

Our preliminary recommended values for the electrical resistivity of the alkaline earth elements were derived from experimental data that were considered reliable, using computer least-mean-square error fit to a modified Bloch-Grüneisen formula of the form

$$\rho_i(T) = [S_1 + S_2 \times (T/\theta_R) + S_3 \times (\theta_R/T)^P] \; \Phi(\theta_R/T) \qquad (8)$$

where S_1, S_2 and S_3 are the coefficients,

$$\theta_R = (\theta_R)_0 - CT , \qquad (9)$$

$$\Phi(\theta_R/T) = 4(T/\theta_R)^5 \int_0^{\theta_R/T} \frac{z^5\, dz}{(e^z-1)(1-e^{-z})} , \qquad (10)$$

$(\theta_R)_0$, C, P, S_1, S_2 and S_3 are used as the variable parameters.

The first term represents the basic Bloch-Grüneisen form; the second term was added in order to get better fit to high temperature data and the third term can represent a dominating low power law at very low temperatures. The computer provides a best fit to a fixed number of specified data points (T_n, ρ_n) minimizing the sum Q of the squares of the fractional errors with which ρ_n are represented by the fitting function $\rho = f(T)$. If desired, variable weights are assigned to the data points, minimizing

$$Q = \sum_n W_n[(f(T_n) - \rho_n)/\rho_n]^2 \qquad (11)$$

The suitability of the form of eq. (8) has been tested by fitting it to previously smoothed data for a number of metals. The r.m.s. fractional errors in these fits were as follows:

Li	(80-450 K),	.0024
Na	(50-350 K),	.012
K	(40-300 K),	.0044
Rb	(30-273 K),	.012
Cs	(30-273 K),	.009
Cu	(60-1200 K),	.005
Ag	(40-1200 K),	.004
Au	(40-1200 K),	.0044
Mg	(60-900 K),	.007

Ca	(40-306 K),	.0056
Zn	(60-600 K),	.006
Al	(60-900 K),	.0033
Ni	(60-600 K),	.015
Fe	(80-1000 K),	.0095
Pd	(80-1300 K),	.003

In some cases errors in the smoothing contributed to these fractional errors.

The final recommended values are obtained by extrapolating the resulting values from curve fitting values to somewhat lower and higher temperatures and correcting them for thermal linear expansion.

In estimating the uncertainty of our recommended values, the accuracy that can be achieved by the various experimental techniques, the scatter of data, and the purity of the materials, among other factors, were taken into consideration. The ranges of uncertainties of recommended and provisional values are less than or equal to ±5% and greater than ±5%, respectively.

4. ELECTRICAL RESISTIVITY OF ALKALINE EARTH ELEMENTS

4.1. Beryllium

Beryllium, with atomic number 4, is a steel-gray, very hard metal, similar to magnesium in appearance and in chemical properties. It has a close-packed hexagonal crystalline structure with a density of 1.85 g cm^{-3} at 293 K. It has been reported that the crystal transforms to a body-centered cubic form at 1530 K, only 32 degrees below the melting point of 1562 K. The normal boiling point is about 2749 K. Its critical temperature has been estimated to be about 6170 K. Beryllium has only one stable isotope, ^9Be, but four other radioactive isotopes are known. Beryllium ranks 46th in the order of abundance of elements in the continental crust of the earth (0.00028% by weight).

Temperature Dependence

There are 80 sets of experimental data available for the electrical resistivity of beryllium. The information on specimen characterization and measurement conditions for each of the data sets is given in Table 4. The data are tabulated in Table 5 and shown in Figures 2 and 3. Determinations of the electrical resistivity for the solid phase cover continuously the temperature range from 1.35 to 1454 K.

Since beryllium is an anisotropic metal, resistivity values will vary according to the relation of the direction of the resistivity measurements to the hexagonal axis of the crystal. Grüneisen and Adenstedt [9] (curves 16 and 17), Grüneisen and Erfling [10,11] (curves 12-14, 48-50), Martin, Bunel and Tilbury [12] (curves 59 and 60) and Mitchell [13] (curves 51 and 52) are the investigators who have made measurements on single crystals. However, their results are inconsistent and a need clearly exists for further determination to be made.

Falge [14] has found that bulk beryllium becomes superconducting when cooled below 0.026 K. Yoshihivo and Glover [15] have measured the resistivity of thin film crystalline beryllium on a quartz substrate (curve 53) and found a superconducting transition temperature at about 9.3 K. Williams, Hinkle and Eatherly [16] investigated the neutron irradiation effects on the electrical resistivity of polycrystalline beryllium samples from 72 to 400 K (curves 34-43).

Most earlier determinations of the electrical resistivity of polycrystalline beryllium resulted in higher resistivities than the later ones. These results can be explained by the lower purity of the specimens and by the omission of a heat treatment, which appears to be essential. Powell [17] (curves 18-33) demonstrated the important effect that annealing at 973 K has on the resistivity; for his best polycrystalline specimen, ρ_{293} was lowered from 6.7 to 3.2 x 10^{-8} Ω m by such treatment. The resistivity values obtained by Losana [18] (curves 9-11) form an anomalous group from which it would seem that the samples have much lower purity than was claimed.

From the examination of the data available for the electrical resistivity, it is evident that there are deviations from the Matthiessen's Rule. The lowest values of ρ for polycrystalline beryllium were reported by Berteaux [19] (curve 44). From his graph, we obtained ρ_{300} = 3.0 x 10^{-8} Ω m. However, this value is lower than those for all single crystal samples with perpendicular orientation, and the reported residual resistance ratio $R_{300}/R_{4.2} = 49$ is inconsistent with that shown in his graph, which gives $\rho_{300}/\rho_{4.2} = 200$. Therefore, his data were not considered in the generation of recommended values. Reich, Quang, Kinch, and Boumain [20] (curve 3) and Powell [17] (curve 23) have the next lowest electrical resistivity values for polycrystalline samples, and they are in fair agreement. Comparison of their data with the single crystal data indicates that these samples had highly preferred perpendicular orientation, as is known for the sample of Reich et al. (Although Powell has annealed his sample at 973 K, this temperature was too low for sample recrystallization). The above data and the low-temperature single-crystal data of Grüneisen were used to generate provisional values for the single crystal measured perpendicular to the c-axis. A least mean-square-error fit to the selected values of $\rho-\rho_0$ was made with a modified Bloch-Grüneisen equation (8), from 20 to 873 K. The following values were found for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$25.945\cdot10^{-8}\Omega$ m	$-1.996\cdot10^{-8}$ Ω m	$0.3377\cdot10^{-8}$ Ω m	1327.9 K	0.373	1.90

The resulting values calculated from eq. (8) were extrapolated to lower and higher temperatures, corrected for thermal linear expansion, and the final provisional values were obtained.

Assuming that the anisotropy ratio of the resistivity can be used for the pure element and using the results of Grüneisen and Erfling [10] and of Mitchell [13] and the provisional values of electrical resistivity for single crystals measured perpendicular to the c-axis, the resistivity values for single crystals measured parallel to the c-axis were obtained. These values and the data of Grüneisen et al. were then fitted by the modified Bloch-Grüneisen equation (8) and the following results were obtained:

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$32.258\cdot10^{-8}\Omega m$	$11.776\cdot10^{-8}\Omega m$	$0.1815\cdot10^{-8}\Omega m$	1196.1 K	.02085	1.90

By using equation (7) and the above single-crystal results, resistivity values for the polycrystalline specimen were calculated from 10 to 1200 K. Above 1200 K, our provisional values follow the trend of the experimental data of Tye [21] (curves 63-68) and of Ho and Wright [22] (curves 73-80). These values were then fitted by the modified Bloch-Grüneisen equation (8) with the following constants:

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$28.117\cdot10^{-8}\Omega m$	$2.0718\cdot10^{-8}\Omega m$	$0.2676\cdot10^{-8}\Omega m$	1267.28 K	0.2253	1.90

No data are available for the electrical resistivity of beryllium above the phase transition temperature (1530 K) or in the liquid state.

The provisional values for the total and intrinsic electrical resistivities are listed in Table 3, and those for the total resistivity are also shown in Figures 2 and 3. The provisional values are corrected for the thermal linear expansion. The correction amounts to -0.15% at 1 K, -0.1% at 200 K, 0.3% at 500 K, 1.3% at 1000 K and 2.4% at 1500 K. The provisional values for the total electrical resistivity are for 99.9+% beryllium and those below 100 K are applicable to specimens with residual resistivities of $0.00718 \times 10^{-8}\ \Omega\,m$ ($\perp$ to c-axis), $0.00426 \times 10^{-8}\Omega\,m$ (// to c-axis), and $0.0332 \times 10^{-8}\ \Omega\,m$ (Polycrystalline). The uncertainty of the provisional values for the total electrical resistivity is believed to be within ±8% below 1000 K and within ±10% from 1000 K to 1500 K. Above 40 K, the uncertainty of the provisional values for the intrinsic resistivity is a little higher than that of the total electrical resistivity because of possible deviations from the Matthiessen's Rule; below 40 K the uncertainty can be very large and values are not listed in the table.

TABLE 3. PROVISIONAL ELECTRICAL RESISTIVITY OF BERYLLIUM (Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, $10^{-8}\,\Omega$m; Intrinsic Resistivity, ρ_i, $10^{-8}\,\Omega$m]

	Solid					
T	⊥ to c-axis		// to c-axis		Polycrystalline	
	ρ	ρ_i†	ρ	ρ_i†	ρ	ρ_i†
1	0.0072		0.0043		0.0336	
4	0.0072		0.0043		0.0332	
7	0.0072		0.0043		0.0332	
10	0.0072		0.0043		0.0332	
15	0.0073		0.0044		0.0334	
20	0.0076		0.0046		0.0336	
25	0.0080		0.0049		0.0339	
30	0.0086		0.0054		0.0345	
35	0.0096		0.0062		0.0354	
40	0.0109	0.0037	0.0074	0.0031	0.0367	0.0035
45	0.0127	0.0055	0.0090	0.0047	0.0384	0.0052
50	0.0150	0.0078	0.0112	0.0069	0.0407	0.0075
60	0.0218	0.0146	0.0180	0.0137	0.0675	0.0143
70	0.0325	0.0253	0.0293	0.0250	0.0584	0.0252
80	0.0483	0.0411	0.0471	0.0428	0.0748	0.0416
90	0.0711	0.0639	0.0736	0.0693	0.0989	0.0657
100	0.103	0.0954	0.111	0.107	0.133	0.0993
110	0.144	0.137	0.163	0.159	0.178	0.145
120	0.199	0.192	0.232	0.228	0.237	0.204
130	0.266	0.259	0.318	0.314	0.311	0.278
140	0.349	0.342	0.424	0.420	0.401	0.368
150	0.447	0.440	0.550	0.546	0.510	0.477
175	0.758	0.751	0.956	0.952	0.851	0.818
200	1.16	1.15	1.48	1.48	1.29	1.26
225	1.64	1.63	2.11	2.11	1.82	1.79
250	2.18	2.17	2.82	2.82	2.42	2.39
273.15	2.72	2.71	3.54	3.54	3.02	2.99
293	3.21	3.20	4.19	4.19	3.56	3.53
300	3.38	3.38	4.43	4.43	3.76	3.73
350	4.70	4.69	6.20	6.20	5.22	5.19
400	6.08	6.07	8.07	8.07	6.76	6.73
450	7.48	7.47	9.99	9.99	8.33	8.30
500	8.91	8.90	12.0	12.0	9.94	9.91
550	10.3	10.3	14.0	14.0	11.5	11.5
600	11.8	11.8	16.0	16.0	13.2	13.2

† At temperatures below 40 K, the uncertainty of ρ_i is so large that values are not listed.

The provisional values for the total electrical resistivity are for 99.9$^+$% beryllium and those below 100 K are applicable to specimens with residual resistivities of 0.00718 x $10^{-8}\,\Omega$ m (⊥ to c-axis), 0.00426 x $10^{-8}\,\Omega$ m (//to c-axis), and 0.0332 x $10^{-8}\,\Omega$ m (Polycrystalline).

TABLE 3. PROVISIONAL ELECTRICAL RESISTIVITY OF BERYLLIUM (Continued)
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, 10^{-8} Ωm; Intrinsic Resistivity, ρ_i, 10^{-8} Ωm]

	Solid					
T	⊥ to c-axis		// to c-axis		Polycrystalline	
	ρ	ρ_i	ρ	ρ_i	ρ	ρ_i
650	13.3	13.3	18.1	18.1	14.8	14.8
700	14.8	14.8	20.2	20.2	16.5	16.5
750	16.3	16.3	22.3	22.3	18.3	18.3
800	17.9	17.9	24.5	24.5	20.0	20.0
850	19.5	19.5	26.7	26.7	21.8	21.8
900	21.1	21.1	28.9	28.9	23.7	23.7
950	22.7	22.7	31.2	31.2	25.6	25.6
1000	24.4	24.4	33.5	33.5	27.5	27.5
1100	27.8	27.8	38.3	38.3	31.5	31.5
1200	31.5	31.5	43.3	43.3	35.7	35.7
1300					40.1	40.1
1400					44.8	44.8
1500					49.9	49.9

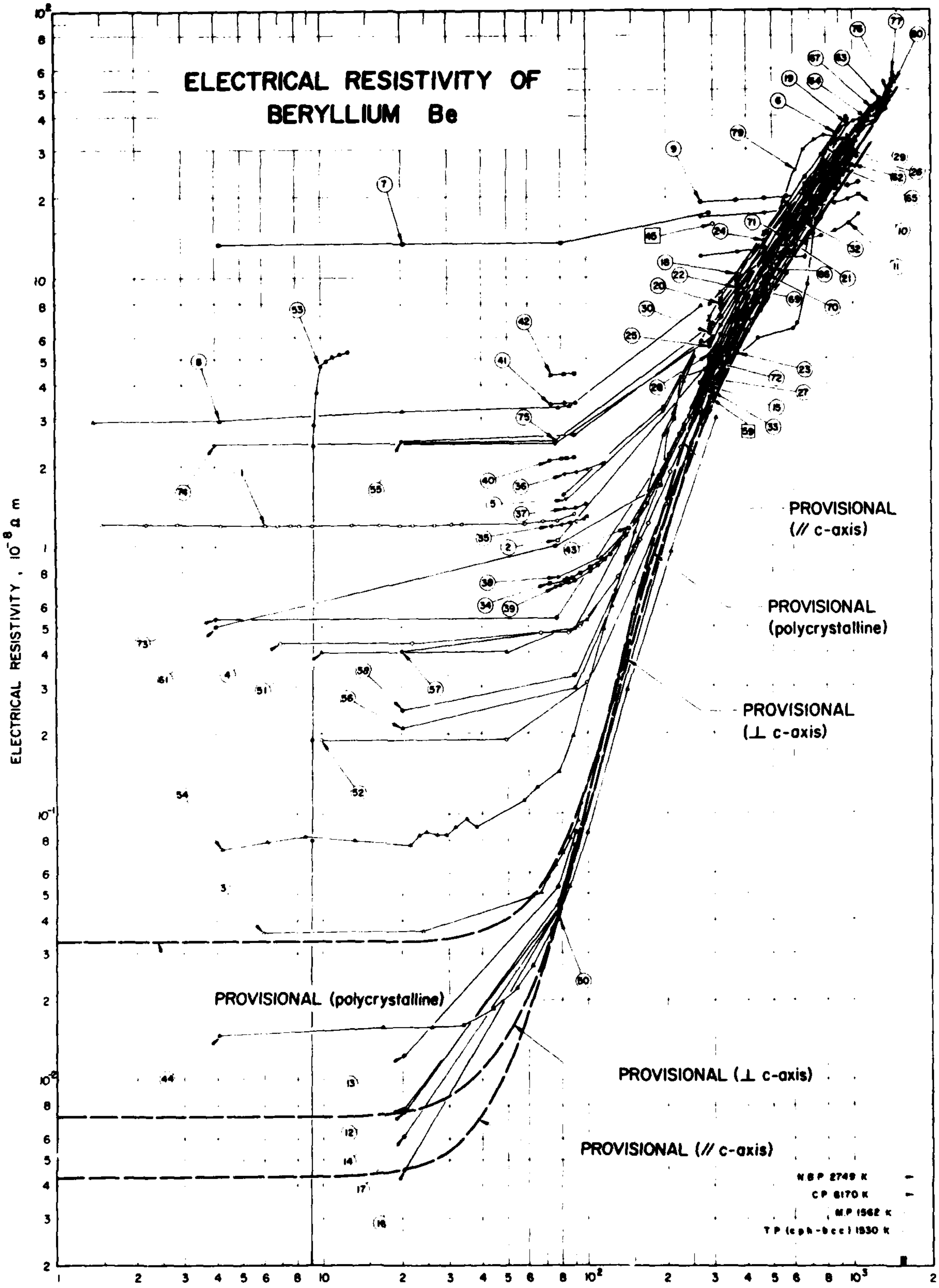

ELECTRICAL RESISTIVITY OF
BERYLLIUM Be
PROVISIONAL (// c-axis)
PROVISIONAL (polycrystalline)
PROVISIONAL (⊥ c-axis)
PROVISIONAL (polycrystalline)
PROVISIONAL (⊥ c-axis)
PROVISIONAL (// c-axis)
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS

FIGURE 2

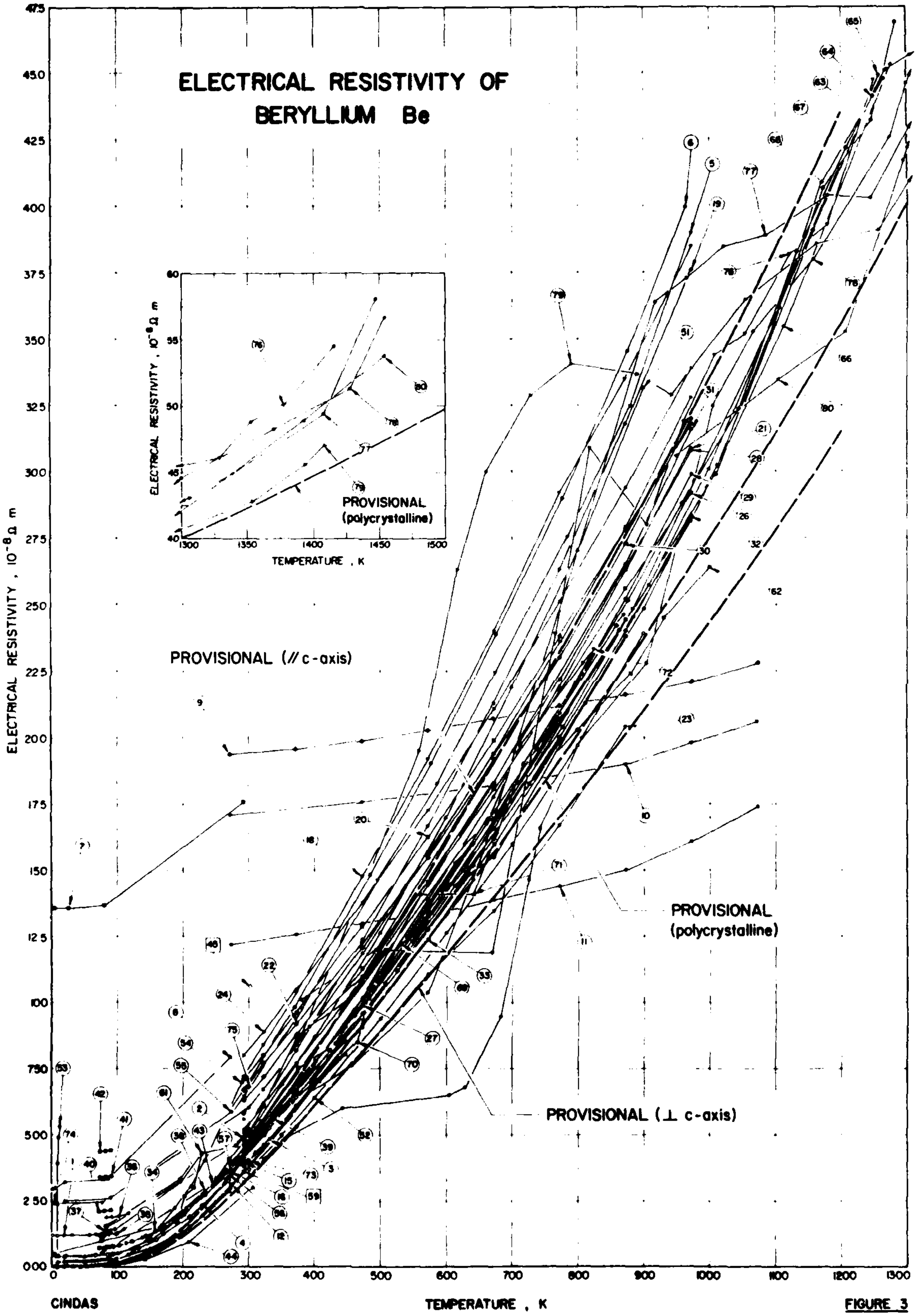

ELECTRICAL RESISTIVITY OF BERYLLIUM Be
PROVISIONAL (// c-axis)
PROVISIONAL (polycrystalline)
PROVISIONAL (⊥ c-axis)
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS

FIGURE 3

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	23	White, G.K. and Woods, S.B.	1955	A	2-295	Be 2	High purity; <0.1 Mg, trace of Fe; specimen was obtained from A.D. Mackay; sintered rod specimen, 4 mm in diameter; the connections to rods were made with indium solder.
2	24	Spangler, G.E., Herman, M., Arndt, E.J., Hoover, D.B., Damiano, V.V., Tint, G.S., and Lee, C.H.	1962	E, A	77, 293	Be	Commercial purity; cylindrical rod specimen 0.635 cm (1/4 in.) in diameter and 10 to 15 cm (4 to 6 in.) long.
3	20	Reich, R., Kinh, V.Q., and Bonmarin, J.	1963		4.2-400	H1209	Pure; 0.2 BeO, 0.0085 Fe, <0.003 Al, <0.001 each Ni, Cr, 0.0015 Si, and <0.0005 Mn; cast by induction; grain size 30-200 μ; specimen was annealed at 800 C for 150 hr.
4	20	Reich, R., et al.	1963		4.2-400	H978	Pure; 0.1 BeO, 0.126 Fe, 0.0045 Al, 0.009 Ni, 0.002 Si, <0.001 Cr, and 0.0007 Mn; specimen was cast by induction; grain size 30-100 μ; specimen was annealed at 800 C for 150 hr.
5	25	Lewis, E.J.	1929		84-973	Be 1	Commercially pure; 99.5 Be, trace of Al, Cr, Fe, Mn, Si, and <0.5 Mg; specimen was obtained from the Beryllium Co. of America; specimen cross section was 0.792 cm^2 and 22.5 cm long.
6	25	Lewis, E.J.	1929		84-973	Be 2	Similar to the above specimen; sample cross section was 0.803 cm^2 and length was 18 cm.
7	26	McLennan, J.C. and Niven, C.D.	1927	B	4.2-293	Be	Pure; specimen was obtained from Beryllium Corp. of America.
8	27	Meissner, W. and Voigt, B.	1930		1.35-273.16	Be 3	0.5 Fe; specimen was prepared by melting; rod specimen dimension 1.5 x 1.5 x 8 mm; electrical resistivity data were calculated from the resistance ratio, resistance at 273.16 K, specimen cross section, and potential probes distance; no thermal expansion correction.
9	18	Losana, L.	1939		273-1073	Be 5	99.58 pure, 0.21 Al, 0.182 Fe, 0.0121 Cu, trace of Ca, C, Ni; specimen was refined in beryllia crucibles under Ar atm.
10	18	Losana, L.	1939		273-1073	Be 6	99.781 pure, 0.17 Al, 0.042 Fe, and 0.011 Cu; specimen was refined in beryllia crucibles under Ar atm.
11	18	Losana, L.	1939		273-1073	Be 9	99.962 pure, trace of Zn, Fe; specimen was refined in beryllia crucibles under Ar atm; density 1.816 g cm^{-3} at 291 K.
12	10	Grüneisen, E. and Erfling, H.D.	1940	A	20.36-273	$Be_{\perp}3$	Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J,X) = 12^\circ$, where $\angle(J,X)$ is the angle between the current and secondary axis.
13	10	Grüneisen, E. and Erfling, H.D.	1940	A	20.37-273	$Be_{\perp}4$	Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J,X) = 2^\circ$.
14	10	Grüneisen, E. and Erfling, H.D.	1940	A	20.34-273	$Be_{\perp}8$	Pure; single crystal specimen with length perpendicular to hexagonal axis; $\angle(J,X) = 30^\circ$.
15	28	Campbell, J.E., Goodwin, H.B., Wagner, H.J., Douglas, R.W., and Allen, B.C.	1961		293.15	Be	Pure; melting point = 1550.8 K, density = 1.856 g cm^{-3}.
16	9	Grüneisen, E. and Adenstedt, H.	1938	A	20.33-273	Be 2	Pure; single crystal specimen with length parallel to hexagonal axis; specimen 1 mm in diameter and 1.55 cm in length; density 1.84 g cm^{-3}. Reported error 1.5%.
17	9	Grüneisen, E. and Adenstedt, H.	1938	A	20.32-273	Be 1	Similar to the above specimen; length 1 cm. Reported error 1.5%.

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	17	Powell, R.W.	1953		293-973	Be No. B.7 (D) (i)	96.5 Be, 1.81 Mg, 1.52 F, 0.55 Fe, 0.06 Al, 0.035 Ca, 0.008 Cu, 0.005 Mn, and 0.032 C; bar 0.5 cm square section, 13.1 cm long machined from a chilled cast bar prepared from the Brush Beryllium's crude reactor products; density 1.826.
19	17	Powell, R.W.	1953		293-973	Be No. B.7 (D) (i)	The above specimen; heat treated at 973 K.
20	17	Powell, R.W.	1953		293-973	Be No. B.26 (1) (ii)	Bar 2.25 cm diameter and 7.7 cm long was machined from a chilled cast bar prepared from the Brush Beryllium Company's crude reactor products; density 1.842.
21	17	Powell, R.W.	1953		293-973	Be No. B.26 (1) (ii)	The above specimen; heat treated at 973 K.
22	17	Powell, R.W.	1953		293-873	Be No. B.26 (2) A (iii)	Bar 0.865 cm diameter and 1.884 cm long; this had come from the same casting as No. B.26(1) but after an attempt had been made to extrude the metal at 1000 C; subsequently the metal had been heated in vacuum for 1 hr and furnace cooled.
23	17	Powell, R.W.	1953		293-873	Be No. B.26 (2) A (iii)	The above specimen; heat treated at 973 K.
24	17	Powell, R.W.	1953		293-973	Be No. B.28 (2) (iv)	98.5 Be, 0.13 Al, 0.18 Fe, 0.03 Cu, 0.05 Cl, Be insoluble in HCl 0.18; bar 2.23 cm diameter and 11.1 cm long was machined from a chilled cast bar prepared from German flake beryllium; density 1.823 g cm^{-3}.
25	17	Powell, R.W.	1953		293-973	Be No. B.28 (2) (iv)	The above specimen; heat treated at 973 K.
26	17	Powell, R.W.	1953		293-973	Be No. B47B (v)	Bar 2.287 cm diameter and 15.72 cm long was machined from a chilled cast bar prepared from the Brush Beryllium Company's crude reactor product.
27	17	Powell, R.W.	1953		293-973	Be No. B47B (v)	The above specimen; heat treated at 973 K.
28	17	Powell, R.W.	1953		293-973	Be No. 2(b) (vi)	Bar 1.0 cm square section, 6.6 cm long; this was a block of beryllium by the "sintering" process by the American G.E.C.; density 1.83 g cm^{-3}.
29	17	Powell, R.W.	1953		293-973	Be No. 2(b) (vi)	The above specimen; heat treated at 973 K.
30	17	Powell, R.W.	1953		293-973	Be (vii)	Slice approximately 0.33 cm thick, 0.62 cm wide, and 5 cm long; density 1.85 g cm^{-3}.
31	17	Powell, R.W.	1953		293-973	Be (vii)	The above specimen; heat treated at 973 K.
32	17	Powell, R.W.	1953		293-973	Be (xi)	Bar 1 in. in diameter and 6 in. long; density 1.865 g cm^{-3}; Mg and C main impurities, 0.34 Mg.
33	17	Powell, R.W.	1953		293-973	Be (xi)	The above specimen; heat treated at 973 K.
34	16	Williams, J.M., Hinkle, N.E., and Eatherly, W.P.	1972	A	72.5-402.5	K38-1	Pure; specimen axis was parallel to the pressing condition. Reported error 2%.
35	16	Williams, J.M., et al.	1972	A	73.75-100.41	K38-1	The above specimen; sample was irradiated by 7.41 x 10^{17} neutrons/cm^2 with E >1.0 MeV. Reported error 2%.

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
36	16	Williams, J.M., Hinkle, N.E., and Eatherly, W.P.	1972	A	82.78–59.57	K38-1	The above specimen; sample was irradiated by 1.02 x 10[illegible] neutrons/cm^2 with E > 1.0 MeV. Reported error 2%.
37	16	Williams, J.M., et al.	1972	A	82.52–117.74	K38-1	The above specimen; sample was irradiated by 2.15 x 10^{18} neutrons/cm^2 with E > 1.0 MeV. Reported error 2%.
38	16	Williams, J.M., et al.	1972	A	88.25–294.75	K38-1	The above specimen; after irradiation the sample was annealed at 324.3 K.
39	16	Williams, J.M., et al.	1972	A	76.55–370.16	K37-1	Pure; specimen axis was perpendicular to the pressing condition. Reported error 2%.
40	16	Williams, J.M., et al.	1972	A	72.91–90	K37-1	The above specimen; sample was irradiated by 2.53 x 10[illegible] neutrons/cm^2 with E > 1 MeV. Reported error 2%.
41	16	Williams, J.M., et al.	1972	A	73.35–90	K37-1	The above specimen; sample was irradiated by 6.19 x 10^{18} neutrons/cm^2 with E > 1 MeV. Reported error 2%
42	16	Williams, J.M., et al.	1972	A	73.74–92.66	K37-1	The above specimen; sample was irradiated by 10.53 x 10^{18} neutrons/cm^2 with E > 1 MeV. Reported error 2%.
43	16	Williams, J.M., et al.	1972	A	71.28–329.76	K37-1	The above specimen; after irradiation the sample was annealed at 338.6 K.
44	19	Berteaux, F.	1970		4.1– 307.6		High purity; Debye temperature θ = 1160 K; data were extracted from the smooth graph.
45	29	Bridgman, P.W.	1927	A	303		Pure; the specimen was a casted rod 4.6 mm in diameter and 9 cm long; the specimen was obtained from Dr. H.S. Cooper of the Kemet Laboratories; density at 293 K was found to be 1.820.
46*	30	Babkina, M.A., Zhermunskaya, L.B., Timofeeva, Z.A., and Tsukanova, N.V.	1972		~293		99.6 pure; 0.09 mm diameter wire specimen was obtained by casting, hot extraction, and hot drawing.
47*	30	Babkina, M.A., et al.	1972		~293		Similar to the above specimen; except it was tempered at 773 K.
48*	11	Erfling, H.D. and Grüneisen, E.	1942	A	79–273.15	Be// 2	Pure; single crystal specimen with its axis parallel to hexagonal axis.
49*	11	Erfling, H.D. and Grüneisen, E.	1942	A	273.15	Be$\perp$8	Pure; single crystal specimen with its axis perpendicular to hexagonal axis.
50	11	Erfling, H.D. and Grüneisen, E.	1942	A	78–273.15	Be// 6	Pure; single crystal specimen with its axis parallel to hexagonal axis.
51	13	Mitchell, M.A.	1975	A	10–900		Pure; single crystal specimen with its axis parallel to the hexagonal axis; sample dimension 2 x 2 x 19 mm; the specimen was grown by triple pass zone refining of pure Be in vacuum at the Franklin Institute Research Labs., data are extracted from the smoothed table; reported error 1.8%.
52	13	Mitchell, M.A.	1975	A	10–900		Similar to the above specimen except its axis is perpendicular to the hexagonal axis and sample dimension 4 x 4 x 41 mm.; reported error 1.8%.
53	15	Yoshihiro, K. and Glover, R.E. III.	1974	A	9.0–13		99.95 pure; beryllium film were prepared by vacuum evaporation of distillation purified Be on crystalline quartz substrate; film thickness 150 Å; Ge resistance thermometer was used to measure the temperature; resistance per square data were reported; data were extracted from graph.
54	31	Yamaguchi, M., Takahashi, Y., Takasaki, Y., and Ohta, T.	1974		80–300		0.01 Ni, 0.008 Fe, 0.003 Mn, 0.002 Al, 0.002 Mg, 0.002 Si, 0.0001 Ca, 0.0001 Na, and < 0.0001 Cu; polycrystalline specimen was obtained from Johnson Matthey Co.; ρ_{290} = 7 x 10^{-8} Ωm; data were extracted from the graph.

* Not shown in the figure.

TABLE 4. MEASUREMENT INFORMATION OF THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
55	32	Denton, H.W.	1947	A	20.2-273.2		Pure; cylindrical specimen 3.5 cm long and 0.3 cm in diameter was prepared by "sintering" process by the American G.E.C.; result of the x-ray examination show that the grains of order 10^{-3} cm in size, almost completely stain free, and with a small proportion of considerably smaller grains.
56	32	Denton, H.W.	1947	A	20.2-273.2		Similar to the above specimen except it was annealed at 988 K for 12 hr and for shorter periods over the temperature ranges: 943 K and 838-813 K during cooling; result of x-ray examination showed the removal of any residual strain and removal of very small grains.
57	32	Denton, H.W.	1947	A	20.2-273.2		Similar to the above specimen except it was further "quenched" in water from above 1023 K.
58	32	Denton, H.W.	1947	A	20.2-273.2		Similar to the above specimen except it was again receiving the 988 K heat. treatment.
59	12	Martin, A.J., Bunce, J.E., and Tilburg, P.D.	1962	A	293	8C	Pure; 0.024 Mg, 0.003 Al, 0.037 Si, and 0.1 Fe; single crystal specimen approximately 0.5 in. in diameter and 6 in. long; crystal was extruded ingot stock by zone refining three times; the specimen was annealed in argon at 1133 K for 16 hr.
60	12	Martin, A.J., et al.	1962	A	293	15B	Similar to the above specimen except it was zone refining twice.
61	33	Kuczynski, G.C.	1960		4-300	QMV	Pure; the specimen was obtained from Brush Beryllium Corp., Cleveland, Ohio; melting point 1558 K; density 1.83 g/cm³; the specimen was annealed at 973 K for 1/2 hr; data were extracted from the figure.
62	33	Kuczynski, G.C.	1960		270-1000	QMV	Similar to the above specimen; the measurements were done by Battelle Institute staff; data were extracted from the figure.
63	21	Tye, R.P.	1968		295-1283	Be 2 (4921)	98.4 Be, 1.08 BeO, 0.15 C, 0.13 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g cm³; hot pressed specimen is obtained from Brush Beryllium Company; cylindrical sample 13 mm in diameter and 100 mm in length; reported error 1%.
64	21	Tye, R.P.	1968		295-1249	Be 4 (5085)	98.2 Be, 1.7 BeO, 0.12 C, 0.13 Fe, 0.12 Al, 0.03 Mg, 0.04 Si, 0.01 Mn, other metallic impurity 0.04; density 1.853 g/cm³; other specifications are similar to the above specimen; reported error 1%.
65	21	Tye, R.P.	1968		299-1258	Be 6 (4814)	98.46 Be, 1.6 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g/cm³; other specifications are similar to the above specimen; reported error 1%.
66	21	Tye, R.P.	1968		295-1276	Be 8 (4814)	Similar to the above specimen; reported error 1%.
67	21	Tye, R.P.	1968		297-1268	Be 9 (4811)	98.41 Be, 1.64 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.01 Mg, 0.03 Si, 0.01 Mn, other metallic impurity 0.04; density 1.86 g/cm³; other specifications are similar to the above specimen; reported error 1%.
68	21	Tye, R.P.	1968		298-1266	Be 11 (4811)	Similar to the above specimen; reported error 1%
69	34	Tye, R.P. and Quinn, J.F.	1968		293-859	Be 1	Pure; 2 BeO, 0.15 C, 0.18 Fe, 0.08 Si, 0.08 Mg, 0.16 Al, and 0.04 other metallic impurities; specimen are obtained from Brush Beryllium Company; cylindrical specimen 13 mm in diameter and 100 mm in length.

TABLE 4. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
70	34	Tye, R.P. and Quinn, J.F.	1968		293-860	Be 2	Similar to the above specimen.
71	34	Tye, R.P. and Quinn, J.F.	1968		293-807	Be 3	Similar to the above specimen.
72	34	Tye, R.P. and Quinn, J.F.	1968		293-825	Be 5	Similar to the above specimen.
73	22	Ho, J. and Wright, E.S.	1960	B	4-300	T1 Y2-2	Pure; 0.087 nonmetallic impurity, 0.094 metallic impurity; the specimens were 2 in. long and 0.1 in. by 0.5 in. rectangular bars or 0.25 in. diameter cylinders; Leeds and Northup Precision Kelvin Bridge was used for measurements; measurements were made in vacuum.
74	22	Ho, J. and Wright, E.S.	1960	B	4-300	T3 Y2-3	Pure; 0.144 nonmetallic impurity, 0.222 metallic impurity; other specifications similar to the above specimen.
75	22	Ho, J. and Wright, E.S.	1960	B	4-300	T3 Y2-4	Similar to the above specimen.
76	22	Ho, J. and Wright, E.S.	1960	B	295-1416	Y6825	0.947 O, 0.0013 H, 0.0071 N, 0.003 Mg, 0.015 Al, 0.01 Si, 0.001 Ca, 0.002 Ti, 0.008 Cr, 0.005 Mn, 0.15 Fe, 0.01 Ni, and 0.004 Cu; measurements below 973 K were made in vacuum, purified argon are admitted at higher temperatures to retard the evaporation of specimen; data were extracted from the figure; other specifications are similar to the above specimens.
77	22	Ho, J. and Wright, E.S.	1960	B	292-1447	Y9384	0.54 O, 0.0106 N, 0.006 Mg, 0.05 Al, 0.008 Si, 0.002 Ca, 0.004 Ti, 0.01 Cr, 0.008 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; other specifications are similar to the above specimen.
78	22	Ho, J. and Wright, E.S.	1960	B	295-1454	Y6826	0.827 O, 0.0012 H, 0.0026 N, 0.01 Mg, 0.03 Al, 0.02 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.006 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; other specifications are similar to the above specimen.
79	22	Ho, J. and Wright, E.S.	1960	B	303-1409	YB 1000	0.786 O, 0.0056 N, 0.015 Mg, 0.03 Al, 0.008 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.01 Mn, 0.15 Fe, 0.02 Ni, and 0.015 Cu; other specifications are similar to the above specimen.
80	22	Ho, J. and Wright, E.S.	1960	B	360-1454	LYB 1102	0.635 O, 0.0101 H, 0.005 N, 0.02 Mg, 0.04 Al, 0.04 Si, 0.002 Ca, 0.004 Ti, 0.02 Cr, 0.008 Mn, 0.2 Fe, 0.02 Ni, and 0.01 Cu; other specifications are similar to the above specimen.

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ, 10^{-8} Ωm]

CURVE 1

T	ρ
1.5	1.22
2.2	1.22
2.9	1.22
4.2	1.20
6.2	1.20
6.9	1.20
7.7	1.20
8.3	1.20
9.3	1.20
13.1	1.20
16.7	1.20
19.9	1.20
22.3	1.20
26.3	1.20
31.1	1.22
34.0	1.22
58.8	1.22
68.4	1.25
77.7	1.25
90.0	1.33

CURVE 2

T	ρ
77	1.06±0.07
293	4.90±0.07

CURVE 3

T	ρ
6	0.036
24	0.0365
62	0.0495
67	0.0510
71	0.0595
76	0.0649
81	0.0719
96	0.0820
92	0.0949
95	0.111
123	0.276
144	0.561
170	0.630
192	1.01
209	1.52
229	1.95
246	2.39
270	2.86
300	4.31

CURVE 3 (cont.)

T	ρ
331	4.83
372	6.07
407	7.12
447	8.17

CURVE 4

T	ρ
7	0.435
22	0.435
67	0.476
85	0.476
94	0.50
132	0.774
159	1.06
170	1.23
209	1.92
229	2.35
269	3.25
289	3.98
309	4.70
331	5.23
372	6.44
407	7.51
447	8.57

CURVE 5

T	ρ
84	1.50
196	3.22
294	6.45
381.5	9.75
496	14.64
588	18.60
674	22.45
785	27.55
880	32.45
973	39.00

CURVE 6

T	ρ
82	1.56
196	3.33
295	6.76
370	9.83
485	14.85
578	19.05
676	23.90

CURVE 6 (cont.)

T	ρ
777	29.00
877	34.55
963	40.00

CURVE 7

T	ρ
4.2	13.6
20.6	13.6
81	13.7
293	17.6

CURVE 8

T	ρ
1.41	2.972
4.20	2.972
20.45	3.217
78.42	3.306
86.14	3.352
273.16	7.946

CURVE 9

T	ρ
273	19.4
373	19.6
473	19.9
573	20.3
673	20.7
773	21.2
873	21.6
973	22.1
1073	22.8

CURVE 10

T	ρ
273	17.1
473	17.6
673	18.2
873	19.0
973	19.8
1073	20.6

CURVE 11

T	ρ
273	12.2
373	12.6
473	13.0
573	13.4

CURVE 11 (cont.)

T	ρ
673	13.9
773	14.4
873	15.0
973	16.1
1073	17.4

CURVE 12

T	ρ
20.36	0.0078
78	0.0452
91.17	0.0755
273.15	3.12

CURVE 13

T	ρ
20.37	0.0124
77.83	0.0537
90.35	0.0868
273.15	3.13*

CURVE 14

T	ρ
20.35	0.0076
78.05	0.0473
89.86	0.0770
273.15	3.12*

CURVE 15

T	ρ
293.15	4.0

CURVE 16

T	ρ
20.33	0.00458
79.02	0.0454*
273.15	3.58

CURVE 17

T	ρ
20.32	0.00616
78.52	0.047*
273.15	3.56*

CURVE 18

T	ρ
293	7.2
323	8.4

CURVE 18 (cont.)

T	ρ
373	10.4
473	14.8
573	19.2
673	24.0
773	29.2
873	33.5
973	38.5

CURVE 19

T	ρ
293	5.1
323	6.2
373	8.2
473	12.4
573	16.7
673	21.3
773	26.3
873	31.8
973	37.6

CURVE 20

T	ρ
293	7.1
323	8.0
373	9.6
473	12.9
573	16.3
673	19.9
773	23.8
873	27.8
973	31.8

CURVE 21

T	ρ
293	4.1
323	5.1
373	6.7
473	10.2
573	13.9
673	17.8
773	21.9
873	26.3
973	30.9

CURVE 22

T	ρ
293	6.7

CURVE 22 (cont.)

T	ρ
323	7.7
373	9.2
473	12.3
573	15.5
673	19.2

CURVE 23

T	ρ
293	3.2
323	4.1
373	5.3
473	8.1
573	11.1
673	13.5
773	16.7
873	20.4

CURVE 24

T	ρ
293	8.0
323	8.9
373	10.5
473	13.8
573	17.3
673	21.1
773	25.1
873	29.4
973	33.9

CURVE 25

T	ρ
293	5.6
323	6.7
373	8.4
473	11.9
573	15.5*
673	19.4
773	23.6
873	27.9
973	32.8

CURVE 26

T	ρ
293	5.9
323	6.7*
373	8.2*
473	11.3

* Not shown in figure.

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

T	ρ
CURVE 26 (cont.)	
573	14.6
673	18.1
773	21.8
873	25.6
973	29.2
CURVE 27	
293	4.2
323	5.0
373	6.6
473	9.9
573	13.3
673	16.9
773	20.7
873	24.4
973	29.2*
CURVE 28	
293	5.2
323	6.2*
373	7.7
473	10.9
573	14.5
673	18.2*
773	22.2
873	26.4
973	30.8
CURVE 29	
293	4.1*
323	5.0*
373	6.6*
473	9.9*
573	13.5
673	17.1
773	20.9
873	25.2
973	29.9
CURVE 30	
293	6.3
323	7.2
373	8.9
473	12.1
573	15.5*
CURVE 30 (cont.)	
673	19.2*
773	23.0
873	27.3
973	32.0
CURVE 31	
293	5.1*
323	6.1
373	7.7
473	11.0
573	14.5*
673	18.3
773	22.2*
873	26.5
973	31.6
CURVE 32	
293	4.3
323	5.2
373	6.6*
473	9.6
573	12.8
673	16.2
773	20.0
873	24.0
973	28.3
CURVE 33	
293	3.8
323	4.6
373	6.1
473	9.1
573	12.4
673	16.0
773	19.8
873	23.8
973	28.3*
CURVE 34	
72.5	0.7207
84.7	0.7532
88.4	0.7666
94.9	0.7939
95.0	0.7904*
103.8	0.8351
CURVE 34 (cont.)	
122.6	0.9631
159.1	1.363
201.0	2.107
225.1	2.639
265.5	3.662
300.1	4.637
325.1	5.375
348.2	6.093
366.0	6.638
402.5	7.799
CURVE 35	
73.75	1.195
80.64	1.214
86.18	1.231
91.18	1.247
92.12	1.253*
97.70	1.279
100.41	1.292
CURVE 36	
82.52	1.865
91.77	1.899
101.34	1.948
115.90	2.053
117.74	2.066
CURVE 37	
82.78	1.382
90.12	1.407
99.57	1.453
CURVE 38	
88.25	0.7697
114.85	0.9032
139.38	1.126
171.55	1.564
205.87	2.219
234.48	2.863
265.20	3.655*
294.75	4.487
CURVE 39	
76.55	0.7058
CURVE 39 (cont.)	
79.83	0.7113
85.58	0.7303
91.01	0.7478
103.37	0.8021
111.13	0.8466
117.91	0.8901
141.81	1.105
170.68	1.455
197.64	1.967
234.31	2.751
257.97	3.339
282.62	3.985
312.70	4.783
339.64	5.609
364.16	6.341
370.16	6.518*
CURVE 40	
72.91	2.109
80.46	2.132
84.21	2.149
90.00	2.168
CURVE 41	
73.35	3.410
82.81	3.435
91.00	3.458
CURVE 42	
73.74	4.376
82.45	4.401
90.00	4.425
92.66	4.385*
CURVE 43	
71.28	0.7213*
82.95	0.7445
102.42	0.8256*
145.03	1.173
194.01	1.925
214.21	2.945*
245.83	3.060
286.44	4.121
302.62	4.563*
329.76	5.343
CURVE 44	
4.1	0.0148
10.7	0.0158
26.0	0.0138
34.6	0.0162
44.3	0.0186
54.3	0.0224
62.4	0.0269
73.8	0.0371
85.5	0.0537
100.0	0.0851
142.9	0.295
208.9	0.955
307.6	3.02
CURVE 45	
303	10.6
CURVE 46*	
293	5.0
CURVE 47*	
293	4.5
CURVE 48*	
78.95	0.045
89.97	0.0763
273.15	3.58
CURVE 49*	
273.15	3.12
CURVE 50	
78.29	0.00404
79.63	0.04125
89.97	0.0728
273.15	3.56
CURVE 51	
10	0.41
50	0.41
100	0.53
150	1.00
200	2.00
CURVE 51 (cont.)	
250	3.35
300	5.10
350	6.90
400	8.70
500	12.70
600	17.10
700	21.90
800	27.10
900	33.20
CURVE 52	
10	0.19
50	0.19
100	0.31
150	0.73
200	1.45
250	2.45
300	3.67
350	5.00
400	6.40
500	9.40
600	12.63
700	16.03
800	19.70
900	23.90
CURVE 53	
9.00	0.00
9.15	0.08
9.27	0.19
9.40	2.40
9.47	2.84
9.61	3.76
9.75	3.98
10.09	4.72
10.54	4.96
11.10	5.17
11.97	5.29
12.79	5.34
CURVE 54	
4.2	0.074
6.2	0.079
8.6	0.083
13.3	0.080
21.5	0.077

* Not shown in figure.

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

CURVE 54 (cont.)

T	ρ
23.3	0.094
24.8	0.086
27.2	0.084
29.4	0.081
31.6	0.080
35.0	0.086
38.0	0.090
39.8	0.097*
57.4	0.114
64.9	0.127
76.2	0.145
88.3	0.195
116.4	0.451
124.7	0.600
129.8	0.689
141.9	0.903
151.4	1.14
162.9	1.39
167.5	1.55*
177.0	1.86
187.5	2.21
195.4	2.63
211.3	3.15
216.8	3.39*
224.4	3.67*
233.3	4.13
255.9	5.13
276.1	6.30*
290.4	7.00

CURVE 55

T	ρ
20.2	2.49
90.2	2.61
273.2	5.86

CURVE 56

T	ρ
20.2	0.21
90.2	0.297
273.2	3.50

CURVE 57

T	ρ
20.2	0.407
90.2	0.499
273.2	3.700

CURVE 58*

T	ρ
20.2	0.243
90.2	0.333
273.2	3.500*

CURVE 59

T	ρ
293	3.60

CURVE 60*

T	ρ
293	4.38

CURVE 61

T	ρ
4	0.5
76	1.0
191	1.7
202	2.7
215	3.0
228	4.3
251	4.6
292	4.9*
302	5.2

CURVE 62

T	ρ
270	4.1
320	5.5
376	7.5
423	8.2
727	18.3
800	20.3
880	22.4
931	24.5
1000	26.4

CURVE 63

T	ρ
295.1	4.05*
395.5	6.99
526.3	11.22
635.5	14.98
677	15.53
812	21.30
900	24.83
1012.5	30.22
1099	35.60

CURVE 63 (cont.)

T	ρ
1173.5	40.66
1246	44.20
1283	46.90

CURVE 64

T	ρ
295.2	4.50*
371.3	6.51*
549	12.32
641.5	15.20
864.3	24.03
1010.1	29.92
1158	39.10
1249	44.10

CURVE 65

T	ρ
296.6	4.61*
374.3	6.88
493.4	10.18
630	15.15
769	20.42
908	25.72
999	30.12
1121	37.10
1258	44.90

CURVE 66

T	ρ
295	4.25*
396	7.10
506.3	10.74
614.2	14.42
746.2	18.93
885.2	24.52
972.9	28.12
1113.5	35.50
1276	45.30

CURVE 67

T	ρ
299.3	4.72
393	7.40
500.5	10.95
665.5	16.95
739.3	19.60
876.3	25.15

CURVE 67 (cont.)

T	ρ
959.3	28.81
1045.5	32.40
1133	38.30
1208	42.20
1268	45.60

CURVE 68

T	ρ
297.5	4.70*
396	7.43*
495	10.82
626.5	15.03
778.2	20.41
883	24.83
1107.5	36.20
1172	40.90
1266	44.80

CURVE 69

T	ρ
293	4.56*
293	4.58*
293	4.64
404	7.73*
441	8.92
461	9.55
531	12.23
550	12.58
859	24.20

CURVE 70

T	ρ
293	4.66*
293	4.70*
293	4.73*
367	6.24
466	8.54
492	10.30
614	15.30
641	16.00
663	16.80
713	18.70
808	22.80
870	24.60

CURVE 71

T	ρ
293	4.66*
293	4.78*
432.5	8.43
447	9.10
562	14.10
642	14.10
718	19.02
807	22.40

CURVE 72

T	ρ
293	4.58*
294	4.76*
303.5	4.88
628	16.00
674	17.00
755	20.20
825	23.30

CURVE 73

T	ρ
4	0.54
77	0.54
300	4.03

CURVE 74

T	ρ
4	2.42
77	2.43
300	6.03

CURVE 75

T	ρ
4	2.40*
77	2.49
300	6.80

CURVE 76

T	ρ
295	6.5*
393	9.1
452	10.1
508	12.0
670	11.9
766	23.9
819	30.9
905	28.0

CURVE 76 (cont.)

T	ρ
962	31.9
1008	34.4
1055	35.2
1122	38.2
1180	39.3
1250	44.7
1329	46.1
1353	48.8
1378	50.1
1416	54.5

CURVE 77

T	ρ
292	5.1*
456	7.6
572	10.4
655	15.7
704	19.5
918	36.4
967	37.3
1022	38.5
1085	38.9
1160	40.4
1245	40.3
1306	43.1
1339	44.9
1408	49.4
1447	58.1

CURVE 78

T	ρ
295	4.1*
442	6.0
605	6.5
628	6.8
682	9.5
726	14.7
743	16.6
807	20.0
904	22.8
1005	32.5
1067	35.3
1158	38.0
1274	42.6
1300	44.6
1370	48.3
1428	51.3
1434	56.[illegible]

* Not shown in figure.

TABLE 5. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BERYLLIUM Be (Temperature Dependence) (continued)

T	ρ
CURVE 79	
303	4.8*
350	6.8
560	15.5
617	26.3
661	30.0
730	32.9
791	34.1
891	33.7
943	32.9
1055	36.5
1163	34.6
1257	39.1
1374	42.8
1394	45.6
1409	47.0
CURVE 80	
350	10.1
454	12.0
950	30.6
1105	36.0
1207	37.8
1295	41.7
1393	48.9
1454	53.8

* Not shown in figure.

4.2. Magnesium

Magnesium, with atomic number 12, is a silvery-white, light, and fairly tough metal. It has a close-packed hexagonal crystalline structure with a density of 1.74 g cm^{-3} at 293 K, which is 35% lighter than aluminum. It melts at 922 K and boils at about 1364 K. Its critical temperature has been estimated to be 3537 K. Naturally occuring magnesium is composed of three stable isotopes, the most abundant being ^{24}Mg, which constitutes 78.7%. Five other radioactive isotopes are known to exist. Magnesium is the seventh most abundant element in the continental crust of the earth (2.33% by weight).

Temperature Dependence

There are 59 sets of experimental data available for the electrical resistivity of magnesium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 7. The data are tabulated in Table 8 and shown in Figures 4 and 5. Determinations of the electrical resistivity for both the solid and liquid phases cover continuously the temperature range from 1 to 1171 K.

Since monocrystalline magnesium is an anisotropic metal, resistivity values will vary with the direction of the resistivity measurements relative to the hexagonal axis of the crystal. Goens and Schmidt [35-37] (curves 46-59), Alderson and Hund [38] (curves 41 and 42), and Nichols [8] (curves 12-17) have made measurements on single crystals up to 473 K.

Only one data set is available for amorphous magnesium. Ferrier and Herrell [39] (curve 44) have measured the electrical resistivity of an amorphous specimen, which was produced by vapor quenching at liquid nitrogen temperature (curve 44). At 273 K the electrical resistivity of amorphous magnesium is about 4.5 times that of the polycrystalline material.

The resistivity minimum apparent in the results of Rorschack and Herlin [40] (curve 11), Spohr and Webber [41] (curves 19 and 20), and Sharkoff [42] (curves 38-40), can be attributed to an impurity effect caused by trace amounts of certain transition metals in solid solution [43].

Most earlier determinations of the electrical resistivity of polycrystalline magnesium resulted in higher resistivities than the recent ones. These results can be explained by the lower purity of the specimens. The present recommended values are based on the data of Roll and Motz [44] (curve 8), Delaplace et al. [45] (curves 23 and 24), Das and Gerritsen [46] (curve 29), Hedgcock and Muir [47] (curve 32), Seth and Wood [48] (curve

34), and Powell, Hickman and Tye [49] (curves 36 and 37). A least-mean-square-error fit to weighted values of $\rho-\rho_0$, uncorrected for thermal expansion of the material, was made with the modified Bloch-Grüneisen equation (8) from 20 to 900 K. Weights are assigned to individual data sets in such a way that they have approximately equal weight at the low and high temperature range. The following results were obtained for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$6.83\cdot10^{-8}\Omega$ m	$-0.302\cdot10^{-8}\Omega$ m	$0.141\cdot10^{-8}\Omega$ m	426 K	0.044	1.90

The Debye temperature deduced from the specific heat measurements is 396±54 K, in rough agreement with our θ_R. Correction to the fitted values for thermal linear expansion yielded the final recommended values.

The recommended electrical resistivity values for single crystals of magnesium as measured along the c-axis are based on the data of Alderson and Hund [38] (curve 41), Toens and Schmidt [35] (curves 46-59), and Nichols [8] (curve 17). A least-mean-square-error fit to their data for $\rho-\rho_0$ was made with the modified Bloch-Grüneisen equation (8) from 15 to 472 K. The following values were found for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$5.06\cdot10^{-8}\Omega$ m	$0.670\cdot10^{-8}\Omega$ m	$0.074\cdot10^{-8}\Omega$ m	363 K	-0.109	1.90

The resulting values were corrected for thermal linear expansion to get the final recommended values. The recommended values above 472 K are estimated.

The recommended electrical resistivity values for single crystals measured perpendicular to the c-axis are based on the data of Alderson and Hund [38] (curve 42), Goens and Schmidt [35] (curves 46-59), and Nichols [8] (curve 12). A least-mean-square-error fit to their data for $\rho-\rho_0$ was made with the modified Bloch-Grüneisen equation (8) from 15 to 469 K. The following values were found for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$8.04\cdot10^{-8}\Omega$ m	$-1.06\cdot10^{-8}\Omega$ m	$0.349\cdot10^{-8}\Omega$ m	522 K	0.202	1.90

The resulting values were corrected for thermal linear expansion to get the final recommended values. The recommended values above 469 K are estimated.

By using equation (7) and the above single crystal results, the resistivity values for the polycrystalline material can be calculated. The resulting calculated values are within ±3% of the recommended values obtained from the experimental data for polycrystalline specimens. This indicates that the grains in the polycrystalline specimens were essentially random in orientation.

There are three data sets available on the electrical resistivity of magnesium in the liquid state. Van Zytveld et al. [50] (curve 28) found a very small temperature dependence of the electrical resistivity. Scala and Robertson [51] (curve 43) found a weak negative temperature dependence, while Roll and Motz [44] (curve 8) found a positive temperature dependence. Comparision with the electrical resistivity data of other alkaline earth elements in the liquid state suggests that the electrical resistivity of liquid magnesium should have a weak negative temperature dependence. The data of Scala et al. have been normalized by matching their values with the data of Van Zytveld et al. at the melting point, 922 K. The normalized values from 922 to 1171 K were fitted with a linear equation to obtain:

$$\rho(T) = 26.1 - 0.0016 \times (T - 922) \qquad 922\ K \le T \le 1200\ K \qquad (12)$$

where ρ is in units of $10^{-8}\Omega$ m and T in K. At the melting point (922 K), the electrical resistivity of magnesium in the liquid state is about 76% higher than that of the solid state.

The recommended values for the total and intrinsic electrical resistivities are listed in Table , and those for the total resistivity are also shown in Figures 4 and 5. The recommended values are corrected for the thermal expansion. The correction amounts to -0.48% at 1 K, -0.20% at 200 K, 0.57% at 500 K and 1.90% at 900 K. The recommended values for the total electrical resistivity are for 99.9^{+}% magnesium and those below 100 K are applicable only to specimens with residual resistivities of $0.008 \cdot 10^{-8}\Omega$ m(// to c-axis), $0.01 \cdot 10^{-8}\Omega$ m ($\perp$ to c-axis), and $0.0062 \cdot 10^{-8}\Omega$ m (polycrystalline). The uncertainty in the recommended values for the total electrical resistivity is believed to be within ±8% below 30 K, ±5% from 30 to 100 K, ±3% from 100 to 600 K, ±5% from 600 to 922 K, and within ±10% above 922 K. Above 30 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity, because of possible deviations from the Matthiessen's Rule; below 30 K the values are very uncertain and are not listed in the table.

TABLE 6. RECOMMENDED ELECTRICAL RESISTIVITY OF MAGNESIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, 10^{-8} Ωm; Intrinsic Resistivity, ρ_i, 10^{-8} Ωm]

	Solid					
T	// to c-axis		⊥ to c-axis		Polycrystalline	
	ρ	ρ_i	ρ	ρ_i	ρ	ρ_i
1	0.0080*		0.0100*		0.0062*	
4	0.0080*		0.0100*		0.0062*	
7	0.0082*		0.0100*		0.0064*	
10	0.0086*		0.0108*		0.0069*	
15	0.0101*		0.0130*		0.0086*	
20	0.0136*		0.0175*		0.0123*	
25	0.0204*		0.0255*		0.0193*	
30	0.0320	0.0240	0.0383	0.0283	0.0309	0.0247
35	0.0502	0.0422	0.0572	0.0472	0.0488	0.0426
40	0.0760	0.0680	0.0837	0.0737	0.0744	0.0682
45	0.110	0.102	0.119	0.109	0.109	0.102
50	0.151	0.143	0.164	0.154	0.151	0.145
60	0.255	0.247	0.282	0.272	0.261	0.255
70	0.381	0.373	0.430	0.420	0.398	0.392
80	0.520	0.512	0.603	0.593	0.557	0.551
90	0.671	0.663	0.789	0.778	0.728	0.722
100	0.827	0.819	0.983	0.973	0.908	0.902
110	0.986	0.978	1.18	1.17	1.10	1.09
120	1.15	1.14	1.38	1.37	1.28	1.27
130	1.31	1.30	1.58	1.57	1.47	1.46
140	1.47	1.46	1.77	1.76	1.66	1.65
150	1.63	1.62	1.96	1.95	1.84	1.83
175	2.02	2.01	2.44	2.43	2.30	2.29
200	2.42	2.41	2.90	2.89	2.75	2.74
225	2.81	2.80	3.35	3.34	3.19	3.18
250	3.19	3.18	3.80	3.79	3.61	3.60
273.15	3.54	3.53	4.20	4.19	4.05	4.04
293	3.84	3.83	4.55	4.54	4.39	4.38
300	3.94	3.93	4.67	4.66	4.51	4.50
350	4.68	4.67	5.52	5.51	5.36	5.35
400	5.42	5.41	6.39	6.38	6.19	6.18
450	6.16	6.15	7.25	7.24	7.03	7.02
500	6.90	6.89	8.09	8.08	7.86	7.85
550	7.53	7.52	8.93	8.92	8.69	8.68
600	8.35	8.34	9.76	9.75	9.52	9.51

* Provisional Values

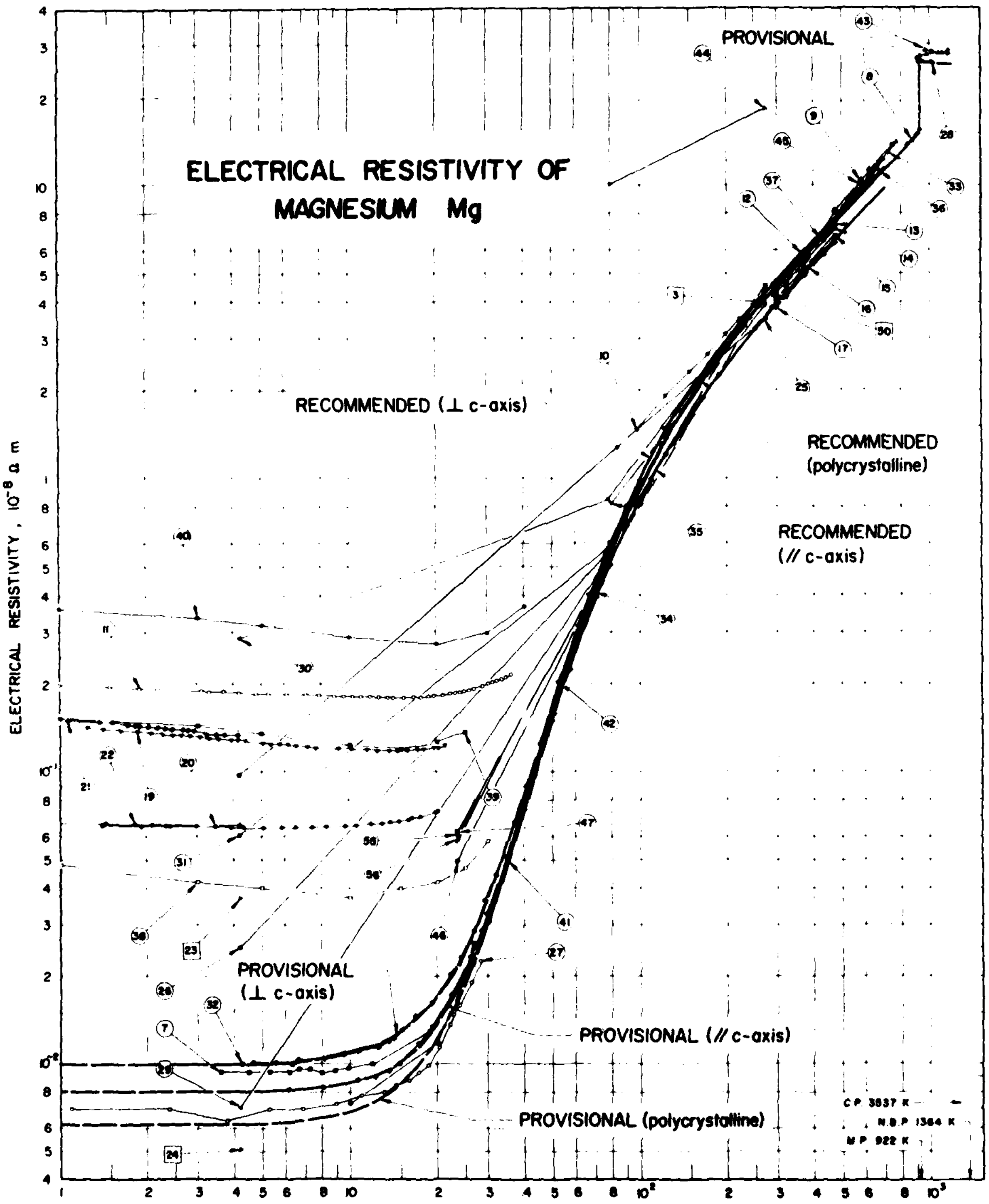
The recommended values for the total electrical resistivity are for 99.9^{+}% magnesium and those below 100 K are applicable only to specimens with residual resistivities of $0.008 \cdot 10^{-8}$ Ω m (// to c-axis), $0.01 \cdot 10^{-8}$ Ω m (⊥ to c-axis), and $0.0062 \cdot 10^{-8}$ Ω m (polycrystalline).

TABLE6. RECOMMENDED ELECTRICAL RESISTIVITY OF MAGNESIUM (Continued)
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, 10^{-8} Ωm; Intrinsic Resistivity, ρ_i, 10^{-8} Ωm]

Solid							Liquid	
T	// to c-axis		⊥ to c-axis		Polycrystalline		T	ρ
	ρ	ρ_i	ρ	ρ_i	ρ	ρ_i		
650	9.07	9.06	10.6	10.6	10.4	10.4	922	26.1*
700	9.78	9.77	11.4	11.4	11.2	11.2	950	26.1*
750					12.0	12.0	1000	26.0*
800					12.8	12.8	1050	25.9*
850					13.6	13.6	1100	25.8*
900					14.4	14.4	1150	25.7*
922					14.7	14.7	1200	25.6*

* Provisional Values.



ELECTRICAL RESISTIVITY OF MAGNESIUM Mg
PROVISIONAL
RECOMMENDED (⊥ c-axis)
RECOMMENDED (polycrystalline)
RECOMMENDED (// c-axis)
PROVISIONAL (⊥ c-axis)
PROVISIONAL (// c-axis)
PROVISIONAL (polycrystalline)
C.P. 3537 K
N.B.P. 1364 K
M.P. 922 K
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS

FIGURE 4

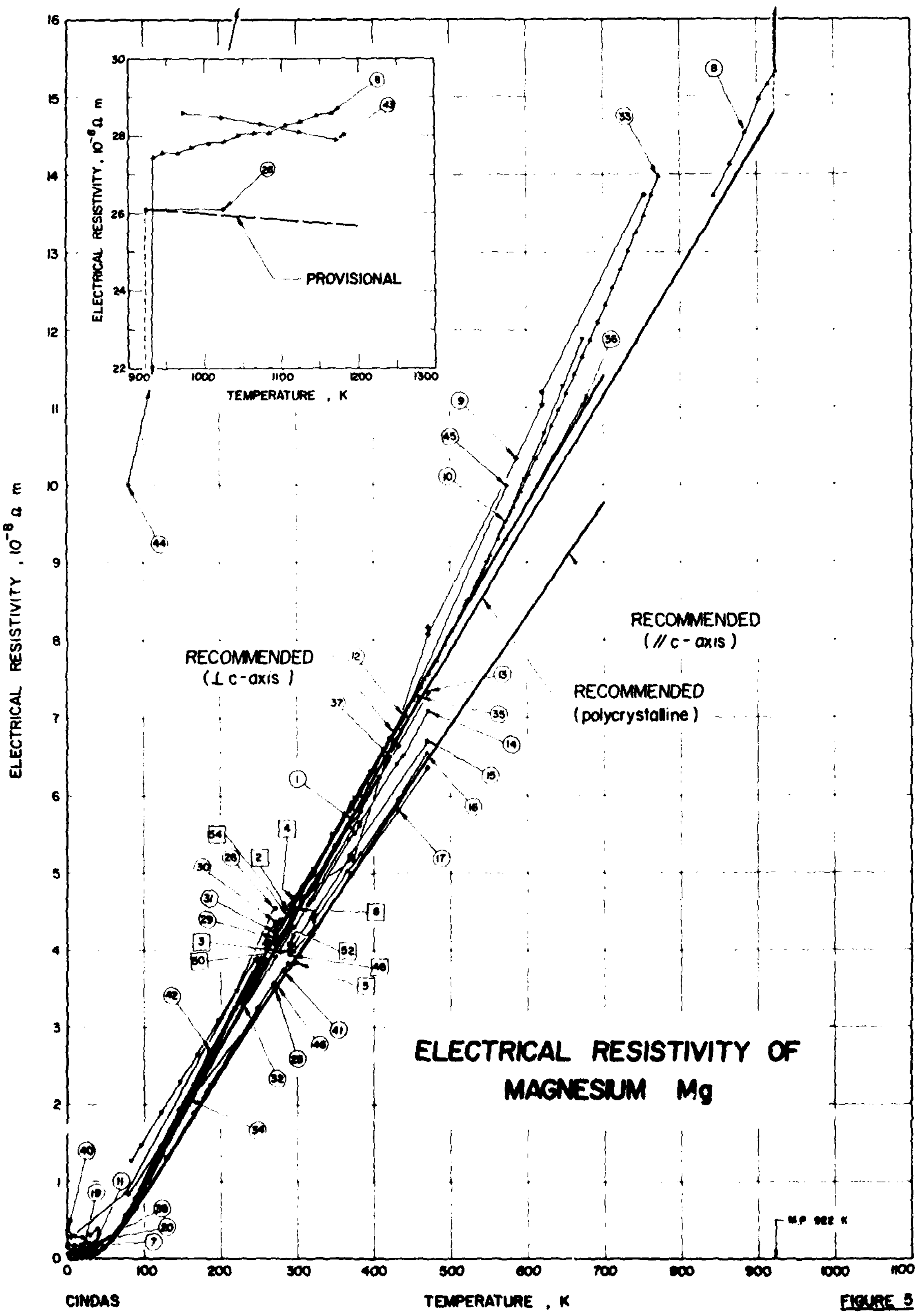

ELECTRICAL RESISTIVITY OF
MAGNESIUM Mg
RECOMMENDED
(⊥ c-axis)
RECOMMENDED
(// c-axis)
RECOMMENDED
(polycrystalline)
PROVISIONAL
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
M.P. 922 K
CINDAS
FIGURE 5

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	52	Lorentz, L.	1881		273, 373	Mg	Pure.
2	53	Das, K.B. and Gerritsen, A.N.	1962		293	Mg	Spectrographically pure magnesium (Johnson-Matthey, Ltd., Lab. No. 4220); samples were alternately annealed at 400 C for 90 min; the samples varied in width from 0.15 to 0.311 cm, in thickness from 0.0037 to 0.0167 cm, and in length from 3.59 to 10.55 cm.
3	54	Vand, V.	1943		273	Mg	Pure.
4	55	Baveja, K.D.	1961	M	299	Mg	Pure; the electrical resistivity was measured by magnetic damping method; unannealed specimen; diameter 0.2497 cm, thickness 0.0858 cm disc sample.
5	33	Kuczynski, G.C.	1960		300	Mg ⊥	Pure.
6	33	Kuczynski, G.C.	1960		300	Mg //	Pure.
7	56	Hedgcock, F.T., Muir, W.B. and Wallingfold, E.	1960		3-26, 300	Mg	<0.001 each Al, Fe, Mn, Pb, Si, Zn, <0.01 each Ca, Sn, <0.0005 Ni; the sample was made by Dow Chemical Co; the sample was annealed at 450 C for 48 hr in atm of helium gas. Reported error 1%.
8	44	Roll, A. and Motz, H.	1957	R	844-1166		99.8 pure; in solid and liquid states; M.P. 923 K; data corrected for thermal linear expansion. Reported error 1%.
9	57	Schofield, F.H.	1924	V	293-753		99.6 purity magnesium specimen was extruded to 0.75 in. diameter from a billet 5 in. in diameter; annealed at 360 C for 6 hr, and allowed to cool slowly; density at 294 K = 1.75 gm/cm³. Reported error 1%.
10	58	Niccolai, G.	1908		84-673		Pure.
11	40	Rorschach, H.E. and Herlin, M.A.	1951		1.5-36		Pure, bulk cylindrical sample; the resistivity was obtained by measuring the mutual inductance of two coaxial coils surrounding the sample.
12	8	Nichols, J.L.	1955	B	273-497		0.0036 C, 0.0005 Fe, 0.0002 Mn, 0.001 Ca, 0.0019 each K, Na, 0.0004 H_g, <0.01 Zn, <0.0005 Pb, <0.0001 each Al, Cu, Sr, B, <0.001 each Si, Sn, <0.0003 Ni; single crystal samples, 0.50 in. in diameter and 7 in. long, were grown in a gradient furnace; a Kelvin Double Bridge was used in conjunction with a high-sensitivity D'Arsonval type galvanometer for the resistance measurements; $\cos^2 \phi = 0.002$, ϕ is the angle between sample's axis and c-axis.
13	8	Nichols, J.L.	1955	B	273-497		Similar to the above specimen; $\cos^2 \phi = 0.213$.
14	8	Nichols, J.L.	1955	B	273-497		Similar to the above specimen; $\cos^2 \phi = 0.430$.
15	8	Nichols, J.L.	1955	B	273-497		Similar to the above specimen; $\cos^2 \phi = 0.667$.
16	8	Nichols, J.L.	1955	B	273-497		Similar to the above specimen; $\cos^2 \phi = 0.841$.
17	8	Nichols, J.L.	1955	B	273-497		Similar to the above specimen; $\cos^2 \phi = 0.990$.
18*	59	Salkovitz, E.I.,	1957		300		99.98 pure, annealed extruded polycrystalline stripes; specimen width from 0.412 cm to 0.640 cm, thickness from 0.212 cm to 0.240 cm, and length from 9.54 cm to 29.3 cm; resistivity was obtained by using the Reeves modification of Kelvin double bridge.
19	41	Spohr, D.A. and Webber, R.T.	1957		1-25	Mg (Fe)	99.98⁺ Mg, 0.013 Fe, 0.0013 Pb, 0.0023 Mn; cold-worked polycrystal from Johnson-Matthey and Co., London, England; the rod specimen was about 3.2 mm in diameter and 9 cm long. Reported error 0.3%.

* Not shown in figure.

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	41	Spohr, D.A. and Webber, R.T.	1957		1-25	Mg (Mn)	99.95+ Mg, 0.043 Mn, 0.001 each Fe, Si, 0.0011 each Pb, Sn, 0.0002 Al, 0.0001 each Cu, Ni, 0.0046 Zn, 0.0012 Ca; annealed polycrystal rod, 3.2 mm in diameter and 9 cm long; prepared by Dow Chemical Co. Reported error 0.3%.
21	60	Hein, R.A. and Falge, R.L.	1957		0.3-4.3	Mg (Fe)	99.98+ Mg, 0.013 Fe, 0.0023 Mn, 0.0013 Pb; cold-worked polycrystal rod 3.2 mm in diameter and 9 cm long; specimen was obtained from Johnson-Matthey and Co., England.
22	60	Hein, R.A. and Falge, R.L.	1957		0.3-4.3	Mg (Mn)	99.95+ Mg, 0.043 Mn, 0.001 each Fe, Si, 0.0011 each Pb, Sn, 0.0002 Al, 0.0001 each Cu, Ni, 0.0046 Zn, 0.0012 Ca; annealed polycrystal rod 3.2 mm in diameter and 9 cm long; specimen was prepared by Dow Chemical Co.
23	45	Delaplace, J.,	1968		4.2, 300	Mg 1	99.95 pure wire specimen; 0.2 mm in diameter; $R_{300\,K}/R_{4.2\,K}$ = 120.
24	45	Delaplace, J.,	1968		4.2, 300	Mg 2	99.999 pure zone refined wire specimen; 0.2 mm in diameter; $R_{300\,K}/R_{4.2\,K}$ = 870.
25	61	Hedgcock, F.T. and Muir, W.B.	1961		4.2, 273	Mg	0.04 Mn, $R_{4.2}/R_{273}$ = 0.028.
26	62	Bijvoet, J., dellon, B., Dekker, J.A., and Rathenau, G.W.	1962		4.2-273	D Mg	Pure magnesium sample was supplied by Dow Chemical International.
27	63	Panova, G.Kh., Zhernov, A.P., and Kutaitsev, V.I.	1968	A	1.2-20	Mg	Pure magnesium wire sample 1 mm in diameter and 50 mm in length was prepared by drawing through a die and annealing subsequently in helium atm at 350 C. Reported error 1.2%.
28	50	Van Zytveld, J.B., Enderby, J.E., and Collings, E.W.	1972	A	924, 1023	Mg	99.98 pure, <0.001 each Al, Si, Zn, <0.0005 each Cu, Pb, 0.003 Fe, 0.002 Mn, <0.0001 Ni, <0.003 each C, O_2, <0.005 H_2, 0.0015 N_2; sample was obtained from Koch Light Lab. Ltd. Reported error 4%.
29	46	Das, S.B. and Gerritsen, A.N.	1964	A	4.2-273	Mg	<0.01 Ca, <0.02 Zn, <0.0001 each Al, Cu, 0.001 Fe, 0.0011 Mn, <0.0002 Ni, 0.0005 Pb, <0.001 each Si, Sn; specimen was supplied by Dow Metal Products Co; polycrystalline specimen; $R_{4.2}/R_{273}$ = 1.7 x 10^{-3}.
30	46	Das, S.B. and Gerritsen, A.N.	1964	A	4.2-273	0.16 Li	0.16 Li, <0.001 each Al, Cu, Mn, Zn, <0.01 each Ca, Sn, <0.0005 Fe, 0.0009 Ni, <0.002 Pb, <0.005 Si; polycrystalline specimen was supplied by Dow Metal Products Co; $R_{4.2}/R_{273}$ = 0.0655.
31	46	Das, S.B. and Gerritsen, A.N.	1964	A	4.2-273	0.047 Sn	0.047 Sn, <0.001 each Al, Cu, Fe, Mn, <0.01 Ca, <0.0003 each Ni, Pb, <0.0001 Si, 0.003 Zn; polycrystalline specimen was supplied by Dow Metal Products Co; $R_{4.2}/R_{273}$ = 0.0144.
32	47	Hedgcock, F.T. and Muir, W.B.	1964	D	4.27-571.2	728	Pure; specimen was rolled into 0.01 in. strips, etched, cut into 0.125 x 4 in. and annealed in a helium atm at 7 cm of Hg at 450 C for 12 hr; $R_{4.2}/R_{273}$ = 2.467 x 10^{-3}.
33	64	Grube, G. and Burkhardt, A.	1929	B	373-773		99.93 Pure; 0.018 Si, 0.052 Fe, and trace of Al, Cu; the electrical resistivity was measured in 1 atm pressure of very pure hydrogen.
34	48	Seth, R.S. and Woods, S.B.		1970	10-295		<0.0014 impurity; obtained from Johnson Matthey, and Mallory, Ltd., Canada; prepared by Dow Chemical Co. from sublimed magnesium that was at least 99.98 pure after fabrication; slightly non-uniform 0.035 in. diameter wire drawn through 0.032 in. diamond die to produce uniform, smooth wire; annealed at 350 C for 8 hr in 10 torr H_2.
35	65	Staebler, J.	1929		80-460		Pure; 3 cm x 1.23 cm.

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
36	49	Powell, R.W., Hickman, M.J., and Tye, R.P.	1964		293-673	Mg 1	99.95 Mg, 0.033 Al, 0.012 Zn; 1.9 cm diameter x 30 cm long; supplied by the Metallurgy Division of the National Physical Laboratory; forged and heat treated.
37	49	Powell, R.W., et al.	1964		293-423	Mg 2	99.98 Mg, 0.017 Al, 0.004 Zn; 0.635 cm diameter x 10 cm long; supplied by Messrs. Johnson, Matthey and Co., Ltd.
38	42	Sharkoff, E.G.	1953		1.0-30	Sample No. 765	99.98* Mg, 0.01 Mn, 0.003 Zn, 0.0012 Pb, 0.001 Ca, <0.001 each Si, Sn, 0.008 Fe, 0.0002 Al, <0.0001 each Cu, Ni; 0.310 cm diameter x 9.03 cm long.
39	42	Sharkoff, E.G.	1953		1.0-25	Sample No. 767	99.95 Mg, 0.043 Mn, 0.0048 Zn, 0.0012 Ca, 0.0011 each Pb, Sn, 0.0010 Fe, <0.001 Si, 0.0002 Al, <0.0001 each Cu, Ni; 0.307 cm diameter x 8.93 cm long.
40	42	Sharkoff, E.G.	1953		1.0-40	Sample No. 370	99.87* Mg, 0.12 Mn, 0.0036 Zn, 0.0014 Pb, 0.0011 Fe, <0.001 each Si, Sn, 0.0006 Ca, 0.0002 Al, <0.0002 Ni, 0.0001 Cu; 0.305 cm diameter x 9.35 cm long.
41	38	Alderson, J.E.A. and Hurd, C.M.	1975	A	3-300	Mg 1, Mg 2	99.9 purity; single crystals; for Mg 1 specimen - 0.315 mm thick, probe separation 6.325 cm, angle between c-axis and sample's axis $\theta = 6.5°$, $\rho_{273\,K}/\rho_{res} = 420$; for Mg2 - 0.295 mm thick, probe separation 5.36 cm, $\theta = 70.5°$ $\rho_{273\,K}/\rho_{res} = 440$; longitudinal resistivity $(\rho_{//})$ data were obtained.
42	38	Alderson, J.E.A. and Hurd, C.M.	1975	A	3-300	Mg 1, Mg 2	Same as the above specimen; transverse resistivity $(\rho_{\perp})$ data were obtained.
43	51	Scala, E. and Robertson, W.D.	1953	A	973-1171		99.975 Mg, 0.01 Cu, 0.004 Al, 0.003 Pb, and 0.003 Si; in liquid state; supplied by Dominion Magnesium, Ltd.; contained in a graphite tube about 0.6 cm I.D. and 13 cm long.
44	39	Ferrier, R.P. and Herrell, D.J.	1970		80, 273		Pure; amorphous specimen was obtained by vapor quenching at liquid nitrogen temperature; data was extracted from the figure.
45	67	Heal, T.J.	1958		273-573		Pure; density 1.7398 g cm^{-3}; melting point 823 K; boiling point 1383 K.
46	35	Goens, E. and Schmid, E.	1936		20.35-373.15	Mg 50	Pure; single crystal specimens were grown from the melt of 99.95 pure starting material; cylindrical specimen is about 4.53 cm in length and 0.1369 cm in radius; angle ϕ between sample axis and the hexagonal axis is 14°30', resistance ratio are reported, the resistivity are calculated from ρ(291.15 K) = 3.813 · 10^{-8} Ωm.
47*	35	Goens, E. and Schmid, E.	1936		20.35-373.15	XI	Similar to the above specimen except the specimen is about 14.56 cm in length, 0.2463 cm in radius; ϕ = 18°20' and ρ(291.15 K) = 3.848 · 10^{-8} Ωm.
48	35	Goens, E. and Schmid, E.	1936		291.15	XV	Similar to the above specimen except the specimen is about 11.38 cm in length, 0.2452 cm in radius; and ϕ = 29°.
49*	35	Goens, E. and Schmid, E.	1936		291.15	XIX	Similar to the above specimen except the specimen is about 9.193 cm in length and 0.1647 cm in radius; and ϕ = 34°30'.
50	35	Goens, E. and Schmid, E.	1936		291.15	90	Similar to the above specimen except ϕ = 49°.
51*	35	Goens, E. and Schmid, E.	1936		291.15	XVI	Similar to the above specimen except the specimen is 6.304 cm in length, 0.16 cm in radius and ϕ = 52°45'.

* Not shown in figure.

TABLE 7. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
52	35	Goens, E. and Schmid, E.	1936		291.15	169	Similar to the above specimen except the specimen is about 6.628 cm in length, 0.2002 cm in radius and $\phi = 55°20'$.
53*	35	Goens, E. and Schmid, E.	1936		291.15	94	Similar to the above specimen except the specimen is about 10.36 cm in length, 0.1765 cm in radius and $\phi = 63°$.
54	35	Goens, E. and Schmid, E.	1936		291.15	85	Similar to the above specimen except the specimen is about 8.480 cm in length, 0.1838 cm in radius and $\phi = 73°50'$.
55*	35	Goens, E. and Schmid, E.	1936		20.35-373.15	116	Similar to the above specimen except the specimen is about 8.202 cm in length, 0.2053 cm in radius, $\phi = 80°$; resistance ratio at different temperatures were reported, the electrical resistivity data are calculated for $\rho(291.15\ K) = 4.492 \cdot 10^{-8}\ \Omega m$.
56*	35	Goens, E. and Schmid, E.	1936		20.35-373.15	188	Similar to the above specimen except $\phi = 82°$; the electrical resistivity data are calculated from resistance ratio data and $\rho(291.15\ K) = 4.516 \cdot 10^{-8}\ \Omega m$.
57*	35	Goens, E. and Schmid, E.	1936		20.35-373.15	162	Similar to the above specimen except the specimen is about 5.448 cm in length, 0.1919 cm in radius; the electrical resistivity data are calculated for resistance ratio data and $\rho(291.15\ K) = 4.492 \cdot 10^{-8}\ \Omega m$.
58*	36,37	Goens, E. and Schmid, E.	1931		291.15	$\rho_\perp$	Pure; single crystal specimen; specimen's axis perpendicular to the hexagonal axis; resistivity temperature coefficient 0.00410/K (273-373 K).
59*	36,37	Goens, E. and Schmid, E.	1931		291.15	$\rho_{//}$	Pure; single crystal specimen; specimen's axis parallel to the hexagonal axis; resistivity temperature coefficient 0.00427/K (273-373 K).

* Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ, 10^{-8} Ωm]

T	ρ
CURVE 1	
273.15	4.09
373.15	5.71
CURVE 2	
293	4.51 ± 0.15
CURVE 3	
273	4.00
CURVE 4	
299	4.663
CURVE 5	
300	3.85
CURVE 6	
300	4.55
CURVE 7	
3.6	0.0094
4.5	0.0094
5.3	0.0094
6.2	0.0094
6.7	0.0096
7.3	0.0096
8.0	0.0093
8.9	0.0095
9.9	0.0097
12.0	0.01
18.9	0.013
23.8	0.0186
26.8	0.0259
CURVE 8	
844	13.73
866	14.15
885	14.56
904	14.99
914	15.18
CURVE 8 (cont.)	
924	15.34
933	27.47
945	27.56
965	27.56
983	27.69
1006	27.82
1025	27.87
1043	28.01
1065	28.06
1085	28.08
1105	28.29
1125	28.36
1146	28.54
1166	28.59
1173	28.70
CURVE 9	
293.1	4.59
374.5	6.19*
374.2	6.21
374.2	6.18
472.3	8.17
472.6	8.08
537.1	10.35
621.7	11.21
621.1	11.04
753.2	13.74
CURVE 10	
94	1.275
98	1.471
123	1.907
148	2.300
173	2.643
198	3.105
223	3.491
248	3.894
273	4.312
298	4.700
323	5.069
348	5.507
373	5.915
398	6.318
423	6.735
CURVE 10 (cont.)	
448	7.132
473	7.576
498	8.031
523	8.508
548	9.002
573	9.536
598	10.080
623	10.672
648	11.285
673	11.893
CURVE 11	
1.0	0.1996
1.6	0.1966
1.9	0.1946
3.1	0.1906
3.3	0.1898
3.7	0.1890
4.2	0.1879
4.8	0.1868
5.3	0.1861
6.1	0.1850
7.1	0.1842
7.9	0.1835
8.9	0.1829
9.6	0.1825
10.3	0.1821
11.0	0.1817
11.8	0.1813
12.7	0.1811
13.6	0.1808
14.2	0.1806
15.5	0.1805
16.7	0.1807
17.7	0.1812
18.9	0.1820
19.6	0.1826
21.1	0.1839
22.4	0.1855
23.3	0.1867
24.1	0.1878
24.9	0.1891
25.8	0.1907
26.8	0.1929
28.9	0.1974
30.2	0.2011
CURVE 11 (cont.)	
31.2	0.2028
32.4	0.2059
33.7	0.2088
34.7	0.2118
36.3	0.2165
CURVE 12	
297.5	4.578
297.5	4.630
322.6	4.999
323.5	5.022
369.2	5.807
377.1	5.998
433.1	6.841
442.2	7.047
468.9	7.500
CURVE 13	
297.5	4.431
297.5	4.468
323.4	4.822
368.9	5.603
383.8	5.808
408.5	6.245
433.1	6.654
474.1	7.331
CURVE 14	
297.5	4.306
323.7	4.677
369.7	5.435
377.6	5.521
383.1	5.619
383.1	5.653
432.9	6.411
440.8	6.526
473.8	7.091
CURVE 15	
297.5	4.080
322.4	4.439
324.0	4.48
370.5	5.227
471.2	6.700
CURVE 16	
297.5	4.009
323.1	4.302
323.1	4.382
367.9	5.024
384.1	5.257
433.1	5.967
471.7	6.555
CURVE 17	
297.5	3.853
323.3	4.225
373.7	4.992
433.1	5.613
472.3	6.361
CURVE 18*	
300	4.45
CURVE 19	
1.25	0.1430
1.42	0.1412
1.63	0.1397
1.86	0.1385
2.08	0.1370
2.27	0.1359
2.48	0.1347
2.65	0.1340
2.84	0.1331
3.07	0.1321
3.30	0.1313
3.55	0.1303
3.93	0.1295
4.14	0.1289
4.40	0.1281
5.04	0.1265
5.34	0.1259
5.71	0.1250
6.17	0.1240
6.51	0.1233
7.11	0.1224
7.63	0.1216
9.13	0.1216
10.11	0.1200
11.55	0.1193
CURVE 19 (cont.)	
12.57	0.1189
13.70	0.1189
14.77	0.1187
15.86	0.1189
17.13	0.1194
18.06	0.1200
19.66	0.1214
20.30	0.1219
21.26	0.1231
CURVE 20	
1.41	0.0659
1.92	0.0655
2.42	0.0653
2.98	0.0651
3.46	0.0651
3.91	0.0648
4.34	0.0648
5.06	0.0646
5.85	0.0647
6.51	0.0648
7.49	0.0648
8.36	0.0650
9.70	0.0653
10.61	0.0656
11.96	0.0661
13.05	0.0668
13.88	0.0672
14.97	0.0679
16.18	0.0688
16.54	0.0692
17.65	0.0703
19.87	0.0725
20.22	0.0732
CURVE 21	
0.24	0.1692
0.25	0.1682
0.27	0.1675
0.28	0.1663
0.36	0.1647
0.40	0.1651
0.42	0.1636
0.44	0.1624
0.52	0.1613

* Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

CURVE 21 (cont.)

T	ρ
0.61	0.1604
0.65	0.1591
0.72	0.1597
0.81	0.1569
0.98	0.1570
1.07	0.1510
1.37	0.1493
1.53	0.1493
1.73	0.1460
1.84	0.1456
1.90	0.1447
2.04	0.1440
2.19	0.1429
2.32	0.1422
2.45	0.1413
2.63	0.1401
2.79	0.1400
2.93	0.1390
3.21	0.1369
3.26	0.1366*
3.49	0.1359
3.55	0.1359*
3.71	0.1352
4.15	0.1344

CURVE 22

T	ρ
0.27	0.0689
0.32	0.0689
0.39	0.0681
1.44	0.0669
1.82	0.0662
2.09	0.0660
2.54	0.0659
4.26	0.0654

CURVE 23

T	ρ
4.2	0.037
300	4.440*

CURVE 24

T	ρ
4.2	0.0051
300	4.437*

CURVE 25

T	ρ
4.2	0.098
273	3.5 ±0.5

CURVE 26

T	ρ
4.2	0.025
77	0.55
273	4.55

CURVE 27

T	ρ
1.1	0.0070
2.4	0.0070
3.8	0.0064
5.3	0.0070
6.9	0.0070
9.0	0.0073
11.0	0.0078
13.1	0.0080
14.4	0.0085
16.0	0.0088
17.3	0.0094
18.6	0.0099
20.3	0.0114
22.1	0.0136
22.9	0.0147
23.8	0.0159
26.2	0.0190
28.2	0.0225

CURVE 28

T	ρ
924	26.1 ±0.7
1024	26.1 ±0.7

CURVE 29

T	ρ
4.2	0.00709
78	0.538
273	4.17

CURVE 30

T	ρ
4.2	0.287
78	0.848
273	4.38

CURVE 31

T	ρ
4.2	0.061
78	0.573
273	4.23

CURVE 32

T	ρ
4.27	0.010
6.34	0.010
14.15	0.012*
20.10	0.016*
24.76	0.022*
34.86	0.051
41.32	0.085*
59.39	0.257
79.9	0.530*
89.3	0.720
107.4	1.053*
124.3	1.371
146.5	1.786*
177.1	2.342
196.3	2.732*
230.5	3.310
273.1	4.052*
292.2	4.368
309.6	4.656*
329.8	4.996*
351.0	5.353
371.2	5.693*

CURVE 33

T	ρ
373	5.843
383	6.019
393	6.184
403	6.357
413	6.538
423	6.719*
433	6.889
443	7.063*
453	7.244
463	7.406
473	7.591*
483	7.758
493	7.952
503	8.120
513	8.317
523	8.493*
533	8.684
543	8.839
553	9.009
563	9.307
573	9.522*
583	9.721
593	9.929

CURVE 33 (cont.)

T	ρ
603	10.141
613	10.345
623	10.558
633	10.762
643	10.980
653	11.198
663	11.436
673	11.661
683	11.880
693	12.118
703	12.347
713	12.564
723	12.803
733	13.039
743	13.262
753	13.498
763	13.751
773	14.000

CURVE 34

T	ρ
10	0.00732
20	0.01347
30	0.0311
40	0.07499
50	0.1533
60	0.2661
70	0.4072
80	0.5683
90	0.7443
100	0.9284
120	1.3078
140	1.6900
160	2.069
180	2.442
200	2.808
220	3.169
240	3.525
260	3.877
273.2	4.108
295	4.487*

CURVE 35

T	ρ
80	0.82
273	3.91
373	5.56
460	7.27

CURVE 36

T	ρ
293	4.5 *
323	5.01*
373	5.85*
473	7.57*
573	9.30
673	11.04

CURVE 37

T	ρ
293	4.34
323	4.85
373	5.70*
423	6.51

CURVE 38

T	ρ
1	0.048
3	0.042
5	0.040
10	0.037
15	0.040
20	0.042
25	0.047
30	0.058

CURVE 39

T	ρ
1	0.153
3	0.144
5	0.136
10	0.123
15	0.120
20	0.127
25	0.137

CURVE 40

T	ρ
1	0.365
3	0.34
5	0.32
10	0.29
20	0.275
30	0.30
40	0.37

CURVE 41

T	ρ
6.17	0.0082
6.67	0.0082*
8.02	0.0083
9.44	0.0086*
10.64	0.0088
11.25	0.0089*
12.36	0.0091
12.88	0.0093*
13.62	0.0095
14.09	0.0098*
14.96	0.0100
15.92	0.0111*
17.10	0.0118
17.62	0.0123*
19.23	0.0135
21.00	0.0154*
22.34	0.0171
24.16	0.0200
26.00	0.0232
27.04	0.0253*
28.78	0.0286
29.52	0.0327
30.98	0.0379*
31.34	0.0390*
34.92	0.0498
37.07	0.0604
38.38	0.0678*
40.37	0.0808
42.57	0.0871*
44.37	0.107
48.21	0.134
50.71	0.158
52.98	0.181*
57.43	0.223
61.11	0.282
67.0	0.318*
71.0	0.398
79.0	0.508
89.0	0.668
101	0.818
110	0.988
111	1.018*
123	1.208
132	1.308
146	1.628*
153	1.708*
158	1.768*
166	1.898
175	2.048*

* Not shown in figure.

TABLE 8. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF MAGNESIUM Mg (Temperature Dependence) (continued)

T	ρ
CURVE 41 (cont.)	
199	2.258
224	2.626*
250	3.248
263	3.438*
271	3.568
280	3.709*
293	3.749
299	3.938
CURVE 42	
4.65	0.0101
4.66	0.0101*
5.22	0.0101*
5.55	0.0101
6.00	0.0102*
6.61	0.0103
7.26	0.0103*
8.11	0.0105
9.55	0.0108
10.72	0.0111
11.22	0.0113*
12.20	0.0115
12.93	0.0118
13.52	0.0121
14.03	0.0123
14.79	0.0126*
15.07	0.0131
15.85	0.0138*
16.95	0.0146
17.79	0.0152*
19.15	0.0163
20.70	0.0184*
22.24	0.0201
24.16	0.0232
25.49	0.0264*
26.96	0.0285
28.78	0.0319*
29.65	0.0363
31.49	0.0430*
31.70	0.0444
34.36	0.0551*
37.67	0.0673
38.92	0.0749
40.56	0.0883
42.09	0.0947*
45.00	0.124
48.50	0.143*
CURVE 42 (cont.)	
50.83	0.174*
52.62	0.202
57.16	0.249*
61.53	0.314
63.0	0.34*
67.0	0.40
72.0	0.47*
79.0	0.60
89.0	0.79
101	0.98
109	1.20*
111	1.16*
123	1.47
132	1.56*
147	1.93
153	2.03*
157	2.11*
166	2.26
175	2.45*
188	2.69
225	3.38*
250	3.85
263	4.08
272	4.24*
280	4.40
284	4.44*
289	4.56*
CURVE 43	
973	28.6
1023	28.5
1074	28.3*
1124	28.1
1171	27.9
CURVE 44	
80	10.00
273	18.20
CURVE 45	
273.15	3.90*
373.15	5.54*
573.15	10.00
CURVE 46	
20.35	0.0492*
77.90	0.505
90.05	0.686*
273.15	3.543
291.15	3.813*
373.15	5.044*
CURVE 47*	
20.35	0.062
77.90	0.503
90.05	0.685
273.15	3.576
291.15	3.848
373.15	5.087
CURVE 48	
291.15	3.957
CURVE 49*	
291.15	3.993
CURVE 50	
291.15	4.218
CURVE 51*	
291.15	4.272
CURVE 52	
291.15	4.283
CURVE 53*	
291.15	4.373
CURVE 54	
291.15	4.468
CURVE 55*	
20.35	0.0602
77.90	0.582
CURVE 55 (cont.)*	
90.05	0.795
273.15	4.179
291.15	4.492
373.15	5.916
CURVE 56*	
20.35	0.0579
77.90	0.582
90.05	0.797
273.15	4.201
291.15	4.516
373.15	5.949
CURVE 57*	
20.35	0.0573
77.90	0.579
90.05	0.793
273.15	4.179
291.15	4.492
373.15	5.917
CURVE 58*	
291.15	4.54
CURVE 59*	
291.15	3.77

* Not shown in figure.

4.3. Calcium

Calcium, with atomic number 20, is a silvery-white moderately soft metal. It has a face-centered cubic crystalline structure, which transforms to body-centered cubic form around 720 K. Its density is 1.55 gm cm^{-3} at 293 K. It melts at 113 K and boils at 1795 K. Impure calcium can also occur in a close-packed hexagonal form, which is stabilized by the impurities in calcium and is stable between about 523 and 720 K. Naturally occuring calcium is composed of six stable isotopes, the most abundant being ^{40}Ca which constitutes 96.97%. Eight other radioactive isotopes are known to exist. Calcium is the fifth most abundant element in the earth's continental crust, of which it forms 4.15% by weight.

Temperature Dependence

There are 16 sets of experimental data available for the electrical resistivity of calcium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 10. The data are tabulated in Table 11 and shown in Figures 6 and 7. Determinations of the electrical resistivity for both the solid and liquid states cover continuously the temperature range from 1.36 to 1138 K.

The data for the electrical resistivity of calcium show considerable scatter. Around room temperature, there is a sudden jump from the low-temperature data to those above room temperature as if there is a phase transition. This discrepancy is probably due to specimen contamination at higher temperatures. Katerberg et al. [68] (curve 10) found a small discontinuity near the phase transition temperature around 720 K. The data of Smith et al. [69] (curves 4 and 5) also show slope changes near the transition, which, however, give a quite different shape from that indicated by the data of Katerberg. The data of Swischer [70] (curves 14-16) do not show any discontinuities. The recommended values were generated based on the data of Cook and Laubitz [71] (curve 12) and Kayser and Soderquist [72] (curve 1). A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the selected data for $\rho - \rho_0$ from 30 to 300 K and to the estimated values up to 1113 K. At the phase transition temperature around 720 K the possible discontinuity was ignored. The following results were obtained for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$3.341 \cdot 10^{-8} \Omega$ m	$0.296 \cdot 10^{-8} \Omega$ m	$0.087 \cdot 10^{-8} \Omega$ m	300.9 K	0.0281	2.0

The Debye temperature deduced from specific heat measurements is 234 ± 5 K which is about 20% lower that the present value for θ_R. The resulting values from equation (8) were then corrected for thermal linear expansion to become the final recommended values.

Only one data set is available on the electrical resistivity of calcium in the liquid state. Van Zytveld et al. [50] (curve 6) found that the temperature dependence of electrical resistivity is small and weakly negative. At the melting point (1113 K), the electrical resistivity of calcium in the liquid state is about 126% higher than that of solid calcium.

The recommended values for the total and intrinsic electrical resistivities are listed in Table 9, and those for the total resistivity are also shown in Figures 6 and 7. The recommended values for the total electrical resistivity are for 99.96+% calcium and those below 30 K are applicable only to a specimen with residual resistivity of $0.045 \cdot 10^{-8} \Omega$ m. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.47% at 1 K, -0.38% at 100 K and -0.2% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within ±10% below 40 K, within ±5% from 40 to 300 K, and within ±20% from 300 to 1150 K. Above 40 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiesen's Rule; below 40 K the ρ_i values are very uncertain and are not listed in the table.

TABLE 9. RECOMMENDED ELECTRICAL RESISTIVITY OF CALCIUM (Temperature Dependence)

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

Solid

T	ρ	ρ_i	T	ρ	ρ_i
1	0.045*		250	2.82	2.77
4	0.045*		273.15	3.11	3.06
7	0.046*		293	3.36	3.31
10	0.047*		300	3.45	3.40
15	0.051*		350	4.09*	4.04*
20	0.060*		400	4.73*	4.68*
25	0.075*		450	5.37*	5.32*
30	0.100*		500	6.02*	5.97*
35	0.133*		550	6.68*	6.63*
40	0.175	0.130	600	7.35*	7.30*
45	0.224	0.179	650	8.02*	7.97*
50	0.277	0.232	700	8.70*	8.65*
60	0.396	0.351	750	9.38*	9.33*
70	0.522	0.477	800	10.0 *	10.0 *
80	0.652	0.607	850	10.7 *	10.7 *
90	0.782	0.737	900	11.4 *	11.4 *
100	0.913	0.868	950	12.1 *	12.1 *
110	1.04	0.997	1000	12.8 *	12.8 *
120	1.17	1.12	1100	14.3 *	14.3 *
130	1.30	1.25	1113	14.5 *	14.5 *
140	1.43	1.38			
150	1.56	1.51			
175	1.88	1.83			
200	2.19	2.14			
225	2.51	2.46			

Liquid

T	ρ
1113	33.0*
1150	33.0*

* Provisional values.

The recommended values for the total electrical resistivity are for 99.96+% pure calcium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of 0.045 x 10^{-8} Ω m.

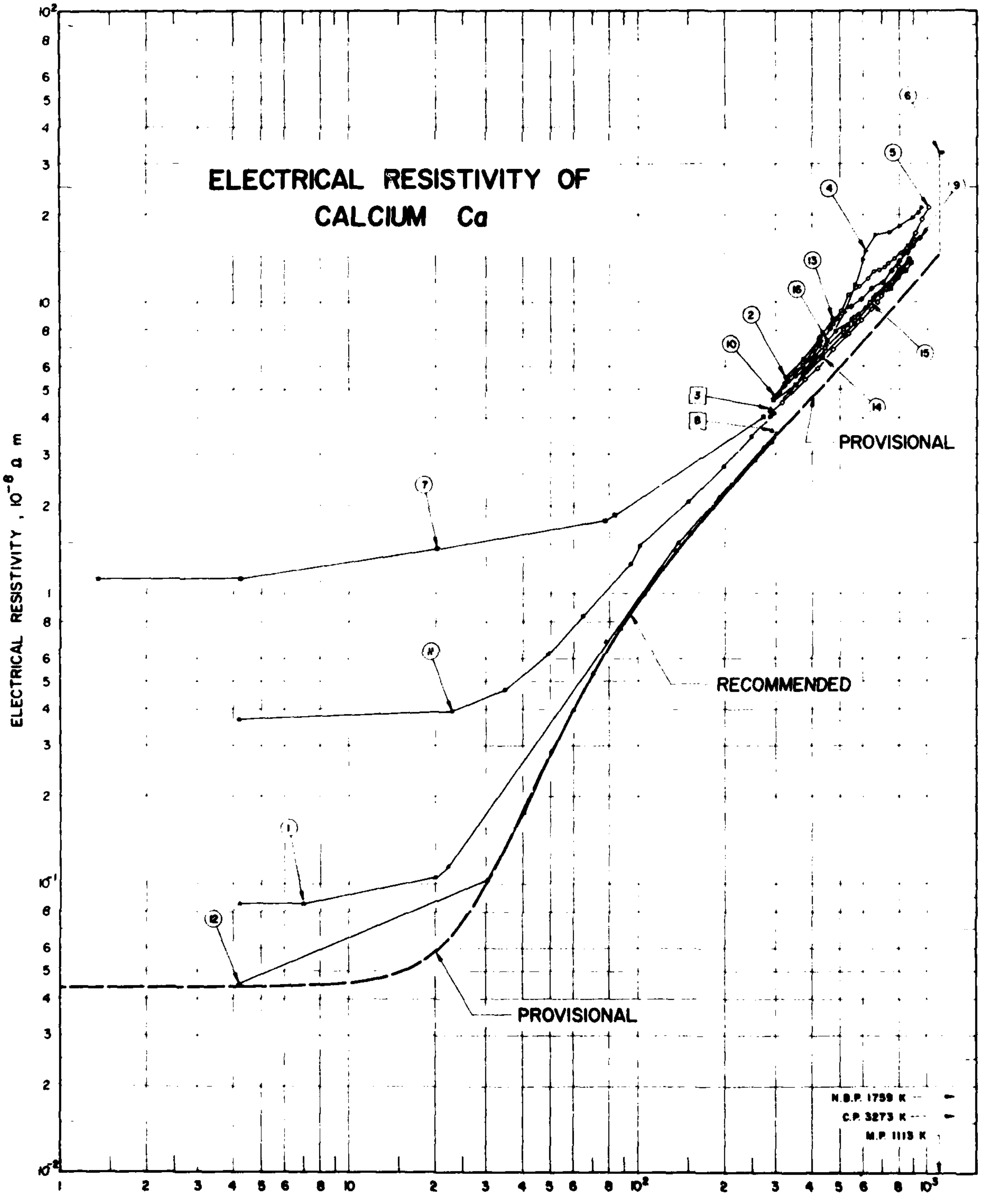

ELECTRICAL RESISTIVITY OF
CALCIUM Ca
ELECTRICAL RESISTIVITY, 10⁻⁸ Ω m
TEMPERATURE, K
PROVISIONAL
RECOMMENDED
PROVISIONAL
N.B.P. 1759 K
C.P. 3273 K
M.P. 1113 K
CINDAS

FIGURE 6

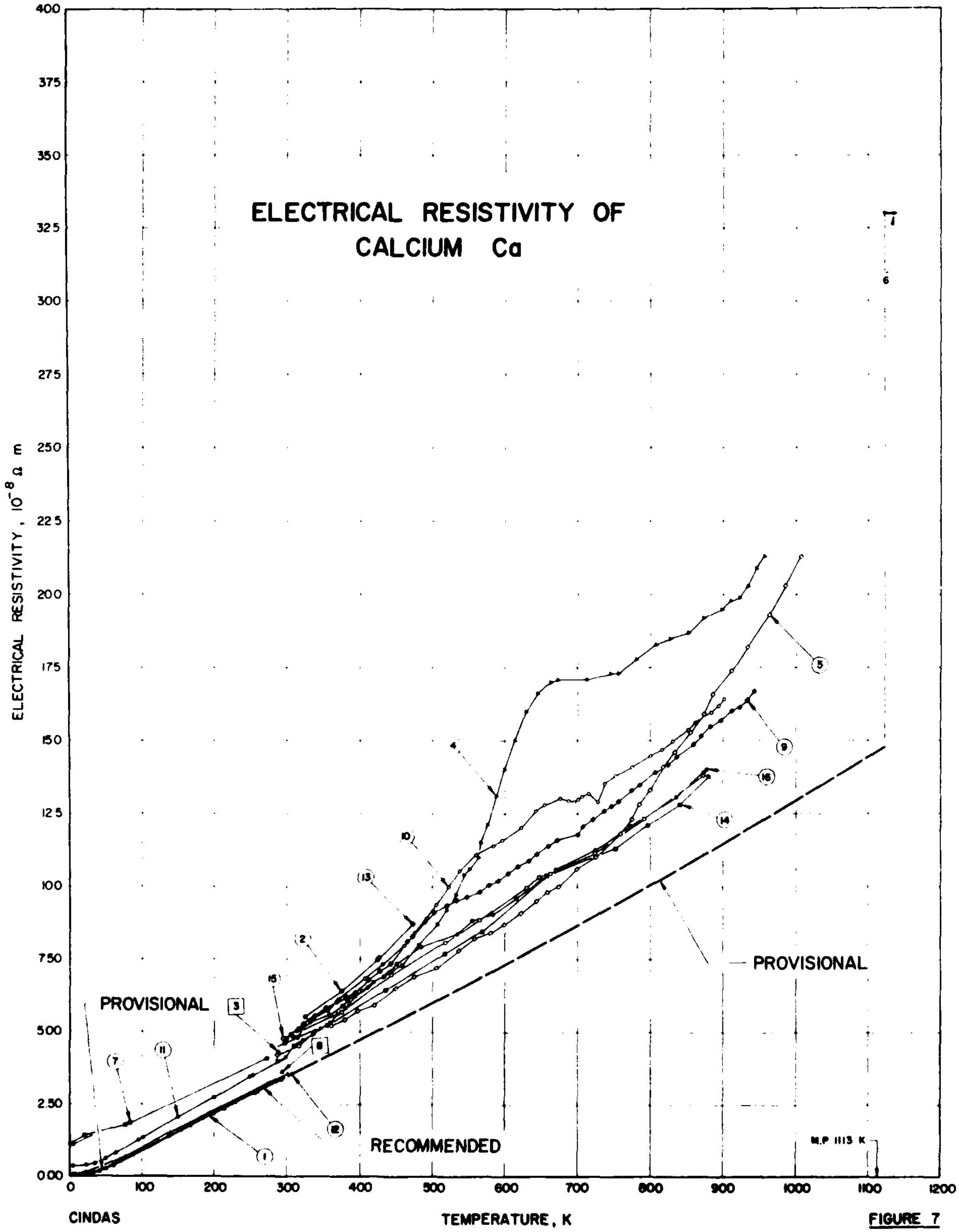

ELECTRICAL RESISTIVITY OF
CALCIUM Ca
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
PROVISIONAL
RECOMMENDED
PROVISIONAL
CINDAS
FIGURE 7

TABLE 10. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	72	Kayser, F.Y. and Soderquist, S.D.	1967		4.2-300	Ca	99.96 Ca, 0.025 Sr, 0.005 O_2, 0.003 H_2, 0.0015 Mg, 0.0011 Mn; 0.0625 in. diameter wire specimens; annealed for 2 hr at 525 K under 8×10^{-6} torr; $\rho_{273.2\ K}$ = 3.16 $\mu\Omega$ cm. reported error ≈2%.
2	73	Cook, J.G. and Van der Meer, M.P.	1973		325-425	Ca	99+ purity, smoothed values extracted from table, data uncorrected for thermal expansion; resistance ratio 3.
3	74	Rinck, E.	1931		289	Ca	Pure calcium was prepared by diffusion technique, 1.245 cm in diameter and 10 cm long cylindrical sample.
4	69	Smith, J.F., Carlson, D.N., and Vest, R.W.	1956	B	273-973	Ca A	99.66 Ca, 0.3 Mg, 0.025 N, 0.006 Fe, 0.001 Al, 0.004 Mn; sample was heated at 600 C for 8 hr after four successive distillation at 900 C; 0.2 in. in diameter and 5 in. long.
5	69	Smith, J.F., et al.	1956	B	273-973	Ca C	99.96 Ca, 0.01 Mg, 0.011 N, 0.010 Fe, 0.001 Al, 0.005 Mn; 0.2 in. in diameter and 5 in. long.
6	50	Van Zytveld, J.B., Enderby, J.E., and Collings, E.M.	1972		1123-1138		99.9 pure, 0.001 each Al, Fe, 0.02 N_2, 0.001-0.002 each Co, Be, B, 0.001-0.02 Li, 0.01-0.05 Mg; sample was obtained from Atomergic Chemetals Co.
7	27	Meissner, W. and Voigt, B.	1930	-	1.36-273.16	Ca 1	Pure; specimen was enclosed in a glass tube filled with helium gas; specimen dimension 1.2 x 1.2 x 59 mm; electrical resistance was measured by compensation method with a mirror galvanometer; no thermal expansion correction for electrical resistivity data.
8	75	Frank, V. and Jeppesen, O.G.	1953		293.15	Ca	99+ Ca; 0.203 ±0.002 mm thickness, 17 mm width, 48 mm long; density = 1.543 ±0.004 g cm^{-3}, lattice constant = 5.59 ±0.01 x 10^{-8} cm (face-centered cubic).
9	68	Katerberg, J., Niemeyer, S., Penning, D., and Van Zytveld, J.B.	1975	A	308-944		99.5 pure, major metallic impurities were other alkaline earth metals; specimen was supplied by Atomergic Chemetals Co.; the sample was mounted on stainless steel and high purity alumina with their surfaces exposed to the dynamic vacuum; measurements were taken with sample held under an atmosphere pressure of pure intert gas; data was extracted from figure.
10	68	Katerberg, J., et al.	1975	A	300-902		Similar to the above specimen except it was supplied by Hall Co.; data was extracted from the graph.
11	71	Cook, J.G., Laubitz, M.J., and Van der Meer, M.P.	1975	A	4.2-299.3	Ca 2	High purity (99% pure) Ca was sublimed at 1100 K in an Ar atmosphere of 6 mm Hg onto a 304 stainless steel plate kept near 570 K; cylindrical sample was cast from the purified by filling 1.2 cm diameter tubes with dendrites, welding caps onto their ends, heating them above the melting points of Ca in a vacuum furnace and then slowly cooling them; the resistance ratio near 10.
12	71	Cook, J.G., et al.	1975	D	4.2-306.27	Ca 3	Similar to the above specimen; except Ta tubing and caps were used; the resistance ratio was near 70.
13	71	Cook, J.G., et al.	1975	A	324.09-4731	Ca 1	99% pure commercial calcium.
14	70	Swisher, C.L.	1917	B	297-569	O	99.57 pure; specimen was obtained from Kalilbaum; wire specimen 0.23 cm in diameter and 10.4 cm in length; measurements were taken in vacuum.
15	70	Swisher, C.L.	1917	B	295-631	P	Similar to the above specimen; except 0.27 cm in diameter and 10.0 cm in length.

TABLE 10. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence) (Continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	70	Swisher, C. L.	1917	B	295-535	Q	Similar to the above specimen; except 0.275 cm in diameter and 7.5 cm in length.

TABLE 11. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ, 10^{-8} Ωm]

T	ρ
CURVE 1	
4.2	0.035
7.1	0.035
19.3	0.105
22.2	0.115
77.4	0.695
139.7	1.50
191.0	2.14
194.9	2.20
273.5	3.17
301.1	3.53
CURVE 2	
325	5.50
373	6.37
425	7.46
CURVE 3	
289	4.3
CURVE 4	
287	4.0
299	4.1
310	4.5
322	4.7
335	4.9
346	5.1
359	5.3
370	5.6
381	5.8
395	6.2
404	6.4
419	6.7
433	6.9
415	7.1
459	7.3
492	8.0
507	8.7
520	9.2
533	9.7
544	10.4
553	10.6
564	11.0
567	11.5
577	12.1
CURVE 4 (cont.)	
589	13.1
600	14.0
614	15.0
630	16.0
646	16.6
664	17.0
674	17.1
714	17.1
746	17.3
758	17.3
782	17.8
808	18.3
828	18.5
853	18.7
874	19.2
899	19.5
911	19.8
923	19.9
934	20.3
946	20.9
958	21.3
CURVE 5	
287	4.2
317	4.5
338	5.0
360	5.2*
380	5.4
398	5.7
420	5.9
450	6.5
475	6.9
506	7.2
537	7.8
559	8.2
580	8.4
599	8.7
622	9.1
643	9.5
659	9.8
675	10.0
699	10.6
725	11.0
760	11.8
775	12.3
785	12.8
CURVE 5 (cont.)	
800	13.3
818	14.1
834	14.6
856	15.3
874	15.9
886	16.6
913	17.4
934	18.2
964	19.3
986	20.3
1007	21.3
CURVE 6	
1123	33.0 ± 1.4
1136	33.0 ± 1.4
CURVE 7	
1.36	1.131
4.22	1.137
20.45	1.432
77.59	1.781
83.57	1.856
273.16	4.050
CURVE 8	
293.15	3.60 ± 0.03
CURVE 9	
308	4.83
315	4.78*
323	5.26
338	5.53*
354	5.80
369	6.03*
382	6.19*
395	6.34
412	6.76*
428	7.08
443	7.35*
466	8.10
474	8.29*
490	8.80
503	9.11*
CURVE 9 (cont.)	
520	9.34*
534	9.53*
548	9.65
565	9.80*
579	10.03*
591	10.20
604	10.44*
617	10.67*
633	10.83*
645	11.11
660	11.38*
672	11.58*
701	11.75
708	12.02*
721	12.27*
737	12.57*
747	12.75*
757	12.93
775	13.28*
786	13.47*
807	13.85
824	14.15*
837	14.44*
860	14.85
871	15.16*
894	15.46*
898	15.70
913	16.01*
924	16.15*
934	16.39*
944	16.66
CURVE 10	
300	4.78
303	4.90*
316	5.09
336	5.45*
355	5.7[illegible]*
371	6.09
407	6.62
432	7.31*
462	7.96*
476	8.40
492	8.89*
506	9.37
523	9.99*
CURVE 10 (cont.)	
538	10.54
561	11.09*
585	11.38
597	11.56*
623	12.01
642	12.56*
654	12.77
676	13.01*
689	12.93
696	12.90*
701	12.98*
707	13.07*
716	13.16
728	12.87*
738	13.53
753	13.79*
775	14.08
800	14.47*
816	14.70
831	14.97*
853	15.35*
863	15.60
884	15.95*
894	16.19*
902	16.41
CURVE 11	
4.2	0.369
23.0	0.393
35.0	0.468
49.6	0.622
64.6	0.833
94.89	1.261
101.46	1.359
150.68	2.069
200.01	2.734
200.42	2.758*
249.70	3.442
253.62	3.495
299.3	4.139*
CURVE 12	
4.2	0.045
30.43	0.1037
40.34	0.1777
CURVE 12 (cont.)	
50.61	0.2571
60.07	0.3978
70.96	0.5315
87.54	0.758
106.31	1.003
122.07	1.213
137.46	1.408
153.72	1.615
167.70	1.794*
183.43	1.991
198.37	2.179
198.37	2.179*
214.63	2.379
229.00	2.564
253.20	2.856
259.47	2.945
277.46	3.203
291.13	3.325
305.53	3.507*
306.27	3.545
CURVE 13	
324.49	5.501*
373.57	6.378*
427.5	7.321
473.1	8.720
CURVE 14	
297	4.6
356	5.2
437	6.44
517	7.68
569	8.44
657	10.36
753	11.28
797	12.08
841	12.60
881	13.76
CURVE 15	
293	4.76
373	5.66
443	6.97
518	8.07

* Not shown in figure.

TABLE 11. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF CALCIUM Ca (Temperature Dependence) (Continued)

[Temperature, T, K; Resistivity, ρ, $10^{-8}\ \Omega m$]

T	ρ
CURVE 15 (cont.)	
565	8.65
631	9.95
647	10.30
662	10.45
724	11.12
791	12.30
873	13.80
CURVE 16	
295	4.78*
314	5.02
321	5.14
333	5.33
359	5.56
377	5.88
394	6.05
411	6.50
431	7.33
464	7.93
535	8.36
555	8.73
593	9.04
616	9.58
631	9.87
670	10.59
725	11.23
773	12.05
836	13.05
873	13.88
878	14.00

* Not shown in figure.

4.4. Strontium

Strontium, with atomic number 38, is a silvery-white metal, resembling calcium in its properties but softer. It exists in three structural modifications: face-centered cubic α-Sr stable below 488 K, close-packed hexagonal β-Sr stable between 488 and 815 K, and body-centered cubic γ-Sr stable above 815 K. The density of α-Sr is 2.60 g cm^{-3} at 293 K. The metal melts at 1042 K and boils at about 1645 K. At room temperature and a high pressure of 3.5×10^9 Pa, α-Sr undergoes a phase transformation to a body-centered cubic structure similar to γ-Sr. Naturally occuring strontium is composed of four stable isotopes, the most abundant being ^{88}Sr which constitutes 82.56%. Twelve other radioactive isotopes are known to exist, one of which, the longest-lived ^{90}Sr with a half life of 28.1 years, is of great importance. This radioactive isotope is one of the best long-lived high energy beta emitters known and is very useful. But it also is a product of nuclear fallout and presents a health problem. Strontium is the fifteenth most abundant element in the continental crust of the earth (0.0375% by weight).

Temperature Dependence

There are 11 sets of experimental data available for the temperature dependence of the electrical resistivity of strontium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 13. The data are tabulated in Table 14 and shown in Figures 8 and 9. Determinations of the electrical resistivity for both the solid and liquid states cover the temperature range from 1.32 to 1093 K.

The data of Messiner and Voigt [27] (curves 8 and 9), Rinck [76] (curve 11), McWhan, Rice, and Schmidt [77] (curves 1-3), and Rashid and Kayser [78] (curve 4) were not for high-purity specimens. At temperatures below 815 K the recommended values are based on the data of Cook and Van der Meer [73] (curve 6), Rashid and Kayser [78] (curve 5), and Katerberg et al. [68] (curve 10). These three sets of data for 99.5% pure specimens appear to be reasonably consistent. A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the selected data for $\rho-\rho_0$ from 50 to 800 K. The following results were obtained for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$6.015\cdot10^{-8}\Omega$ m	$-0.02743\cdot10^{-8}\Omega$ m	0	142.7 K	0.0108	0

The Debye temperature deduced from specific heat measurements is 147 K which is very close to the present value for θ_R. The resulting values from equation (8) were then corrected for thermal linear expansion to become the final recommended values.

There appears to be no discontinuity in the electrical resistivity at the temperature of 488 K where the transition from α-Sr to β-Sr occurs. However, at the β-Sr to γ-Sr transition around 815 K, there is a sudden jump of about 40% in the resistivity values. Above 815 K the recommended resistivity values are based on the data of Katerberg et al. [68] (curve 10). Their data were fitted with a linear logarithmic equation up to the melting point resulting in the following equation:

$$\log_{10} \rho = -1.6233 + 1.137 \times \log_{10} T \qquad 815\ K \leq T \leq 1042\ K \qquad (13)$$

Only one set of data is available on the electrical resistivity of strontium in the liquid state. Van Zytveld et al. [50] (curve 7) found that the temperature dependence of electrical resistivity is small and weakly negative. At the melting point (1042 K), the electrical resistivity of strontium in the liquid state is about 31% higher than that of solid strontium.

The recommended values for the total and intrinsic electrical resistivities of strontium are listed in Table 12, and those for the total electrical resistivity are also shown in Figures 8 and 9. The recommended values for the total electrical resistivity are for 99.95$^+$% pure strontium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of $0.80 \times 10^{-8}\,\Omega$ m. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.54% at 1 K, -0.42% at 100 K, and -0.21% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within ±10% below 50 K, within ±5% from 50 to 815 K, within ±10% from 815 K to 1042 K and within ±20% above 1042 K. Above 40 K, the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiessan's Rule; below 40 K ρ_i values are very uncertain and are not listed in the table.

TABLE 12. RECOMMENDED ELECTRICAL RESISTIVITY OF STRONTIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, $10^{-8}\ \Omega$ m; Intrinsic Resistivity, ρ_i, $10^{-8}\ \Omega$ m]

Solid

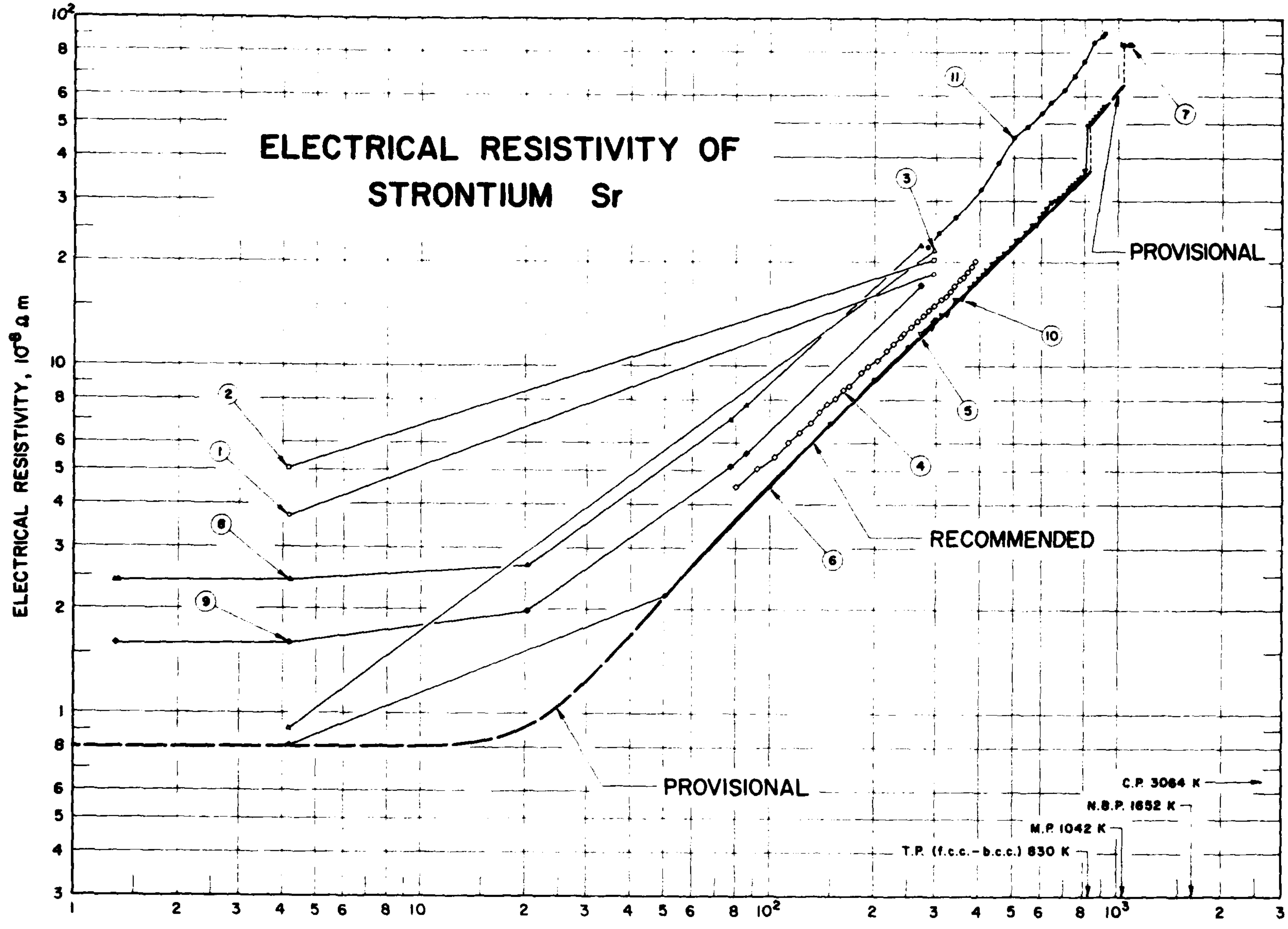
T	ρ	ρ_i	T	ρ	ρ_i
1	0.800*		250	11.3	10.5
4	0.800*		273.15	12.3	11.5
7	0.800*		293	13.2	12.4
10	0.805*		300	13.5	12.7
15	0.835*		350	15.7	14.9
20	0.918*		400	17.8	17.0
25	1.065*		450	20.0	19.2
30	1.257*		500	22.2	21.4
35	1.460*		550	24.5	23.7
40	1.700*		600	26.7	25.9
45	1.94*	1.14*	650	28.9	28.1
50	2.18	1.38	700	31.2	30.4
60	2.68	1.88	750	33.4	32.6
70	3.16	2.36	800	35.6	34.8
80	3.64	2.84	815	36.1	35.3
90	4.12	3.32	815	48.8*	48.0*
100	4.58	3.78	950	54.5*	53.7*
110	5.04	4.24	1000	62.2*	61.4*
120	5.50	4.70	1042	65.6*	64.8*
130	5.94	5.14			
140	6.39	5.59			
150	6.84	6.04			
175	7.95	7.15			
200	9.04	8.24			
225	10.2	9.35			

Liquid

T	ρ
1042	84.8*
1093	84.7*

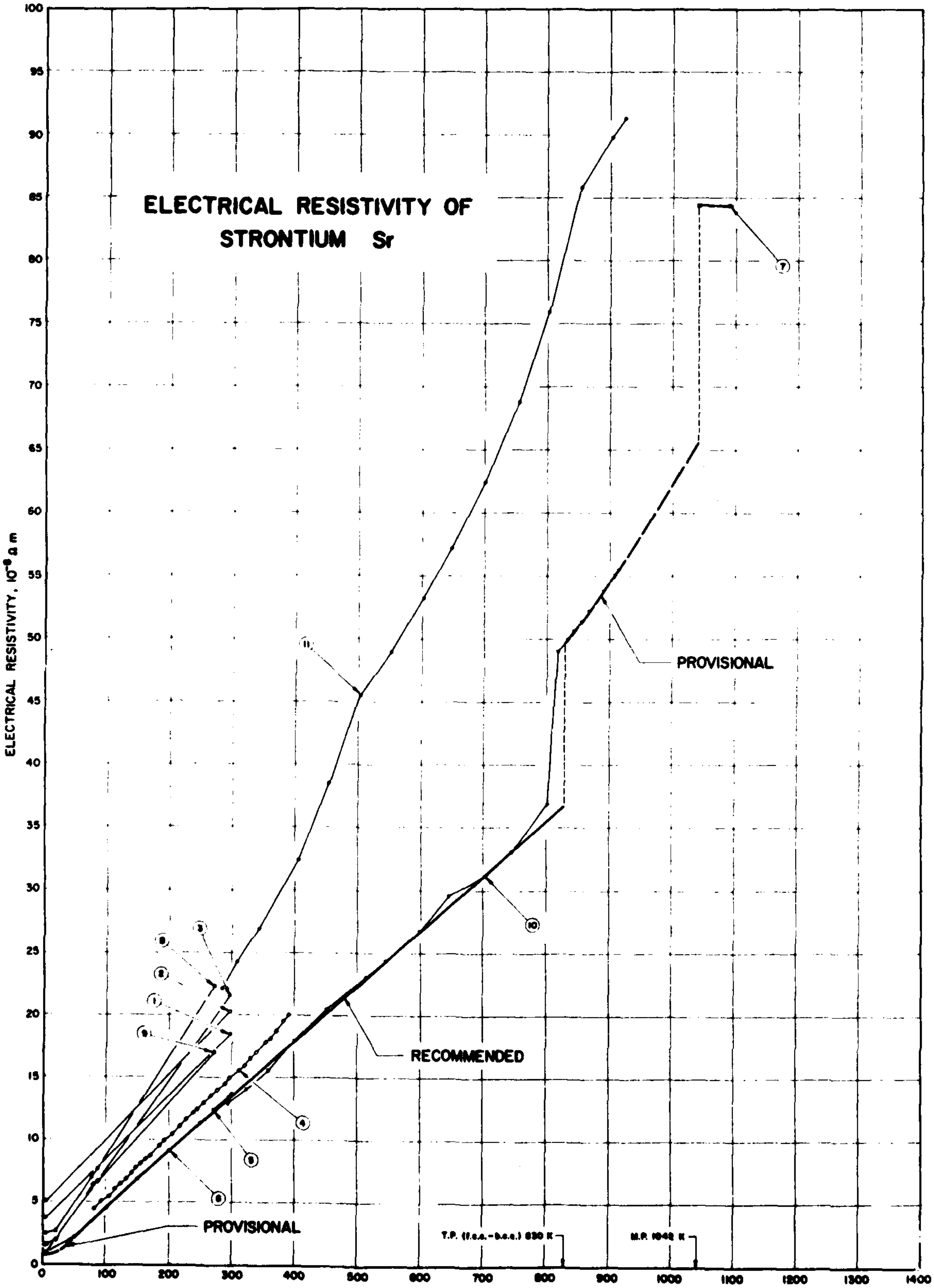
* Provisional values

The recommended values for the total electrical resistivity are for 99.95^{+}% pure strontium and those at temperatures below 30 K are applicable only to a specimen with residual resistivity of 0.80 x $10^{-8}\ \Omega$ m.



ELECTRICAL RESISTIVITY OF
STRONTIUM Sr
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
PROVISIONAL
RECOMMENDED
PROVISIONAL
C.P. 3064 K
N.B.P. 1652 K
M.P. 1042 K
T.P. (f.c.c.–b.c.c.) 830 K
CINDAS

FIGURE 8



CINDAS

FIGURE 9

TABLE 13. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF STRONTIUM Sr (Temperature Dependence)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	77	McWhan, D.B., Rice, T.M., and Schmidt, P.H.	1969	A	4.2, 298	Sr 4	98.1 Sr, 1.9 (Mg, Ca, Ba), 0.04 other; $R_{298}/_{4.2}$ = 5; samples were made from metal purified by fractional distillation.
2	77	McWhan, D.B., et al.	1969	A	4.2, 298	Sr 5	98.8 Sr, 1.2 (Mg, Ca, Ba), 0.05 other; $R_{298/4.2}$ = 4.
3	77	McWhan, D.B., et al.	1969	A	4.2, 298	Sr 6	98.6 Sr, 1.4 (Mg, Ca, Ba), 0.03 other; $R_{298/4.2}$ = 24.
4	78	Rashid, M.S. and Kayser, F.X.	1971		80-400	Sr	98^+ Sr, 0.2 each Ba, Ca, 0.025 Mg, 0.03 each Fe, N_2, 0.015 Al, 0.05 (Li + Na + K); 3.8 mm diameter, 10 mm long wire specimen annealed at 470 K for 16 hr, 3 times.
5	78	Rashid, M.S. and Kayser, F.X.	1971		273, 298	Sr (distilled)	Same as above except the specimen was distilled at 1140 K.
6	73	Cook, J.G. and Van der Meer, M.P.	1973		4.2-300	Sr	99^+ purity; $\rho_{(273.2)}/\rho_{(4.2)}$ = 15.5
7	50	Van Zytveld, J.B., Enderby, J.E., and Collings, E.M.	1972		1043-1093	Sr	99.5 pure, < 0.08 Fe, 0.05 each Al, N_2, Ba, Mg, Ca, 0.01 Cl_2, 0.1 others; specimen was obtained from Atomergic Chemetals Co.
8	27	Meissner, W. and Voigt, B.	1930	-	1.32-273	Sr 1	< 0.1 Fe; specimen was in a glass tube with helium; specimen size was 0.5 x 2.5 x 34 mm; the electrical resistance was measured by compensation method with a mirror galvanometer; no thermal expansion correction for electrical resistivity data.
9	27	Meissner, W. and Voigt, B.	1930	-	1.32-273	Sr 2	Similar to the above specimen except it was heated in vacuo for 3 hr at 160 C.
10	68	Kaзerberg, J., Niemeyer, S., Penning, D., and Van Zytveld, J.B.	1975	A	294-912		99.5-99.7 purity specimen was obtained from Atomergic Chemetals Co.; the measurements were taken with sample held under an atm of pure inert gas; data were extracted from figure.
11	76	Rinck, E.	1952	A			Pure, double distilled specimen was obtained from Pechiney Co.; cylindrical specimen about 10 cm long; melting point 1041 K; data were extracted from graph.

TABLE 14. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF STRONIUM Sr (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ, 10^{-8} Ωm]

CURVE 1

T	ρ
4.2	3.7
298	18.5

CURVE 2

T	ρ
4.2	5.08
298	20.3

CURVE 3

T	ρ
4.2	0.90
298	21.6

CURVE 4

T	ρ
80.2	4.49
92.8	5.07
104.1	5.47
113.9	6.02
122.9	6.42
132.1	6.86
140.1	7.35
147.8	7.76
155.4	8.09
163.1	8.51
170.9	8.76
184.8	9.55
192.2	9.93
198.8	10.13*
205.0	10.47
211.1	10.73*
217.1	11.07
222.8	11.35*
228.9	11.64
234.3	11.89*
239.7	12.15
245.9	12.43
251.2	12.65*
256.3	12.98
262.0	13.25*
267.4	13.49
272.2	13.75*
277.4	13.99
282.9	14.24*
288.0	14.50
292.4	14.69*
297.7	14.93*

CURVE 4 (cont.)

T	ρ
302.6	15.13*
312.2	15.59
317.1	15.77*
321.7	15.92
326.7	16.09*
330.9	16.53
335.6	16.71*
340.1	17.03
344.9	17.22*
349.6	17.35*
353.9	17.82
355.5	17.99*
362.8	18.17
367.3	18.51*
371.6	18.77
377.4	18.96*
379.7	19.24*
383.6	19.53
388.1	19.80*
391.0	20.05

CURVE 5

T	ρ
272.7	12.46
297.9	13.46

CURVE 6

T	ρ
4.2	0.806
50	2.18
100	4.50
150	6.82
200	9.12
250	11.38
273	12.5 *
300	13.65

CURVE 7

T	ρ
1043	84.8 ± 2.0
1093	84.65 ± 2.0

CURVE 8

T	ρ
1.32	2.416
1.35	2.416
4.21	2.416

CURVE 8 (cont.)

T	ρ
20.40	2.662
77.75	7.005
86.32	7.717
273.16	22.31

CURVE 9

T	ρ
1.32	1.586
4.20	1.595
20.40	1.978
77.75	5.143
86.32	5.639
273.16	17.02

CURVE 10

T	ρ
294	12.94
310	13.63
322	14.21
342	15.14
359	15.84
378	16.72
390	17.28
399	17.70
408	18.01*
414	18.26
422	18.62
438	19.38
454	20.12
471	20.84
499	22.00
514	22.75
527	23.42
548	24.33
570	25.26
587	25.92
602	26.80
617	27.60
629	28.20
648	29.00
667	29.76
683	30.39
697	30.96*
706	31.31
724	32.11
737	32.66
747	33.14

CURVE 10 (cont.)

T	ρ
763	33.81
779	34.59
793	35.23
804	36.60
819	49.02
835	49.93
844	50.64
856	51.33
869	52.27
892	53.89
908	55.03
913	55.43

CURVE 11

T	ρ
285	22.1
309	24.3
322	25.2*
343	26.9
365	28.8*
388	30.6*
406	32.4
420	34.1*
431	35.1*
444	36.6*
455	38.5
469	40.7*
479	42.7*
491	44.4*
504	45.6
514	46.9*
526	47.6*
539	48.3*
552	49.0
560	50.2*
570	50.6*
583	51.2*
593	52.0*
604	53.3
624	55.2*
648	57.2
668	58.8*
685	60.4*
702	62.5
716	64.3*
735	66.3*
741	67.2*

CURVE 11 (cont.)

T	ρ
756	68.8
775	70.2*
787	71.0*
794	73.4*
804	76.0
815	79.0*
825	82.6*
834	84.2*
846	85.0*
855	85.9
864	86.4*
876	87.3*
888	88.4*
904	89.9
913	90.6*
926	91.4

*Not shown in figure.

4.5. Barium

Barium, with atomic number 56, is a soft, silver-white metal, resembling calcium chemically. It oxidizes very easily in air, melts at 1002 K, and boils at 2174 K. Its density is 3.5 g cm^{-3} at 293 K. The critical temperature of barium has been estimated to be 3670 K. Barium crystal has a body-centered cubic structure. At a pressure of about 5.9 x 10^9 Pa, the body-centered cubic structure transforms to a close-packed hexagonal form. Naturally occuring barium is composed of seven stable isotopes, the most abundant being ^{138}Ba, which constitutes 71.66%. Thirteen other radioactive isotopes are known to exist. Barium is the fourteenth most abundant element in the continental crust of the earth (0.0524% by weight).

Temperature dependence

There are 21 sets of experimental data available for the electrical resistivity of barium. The information on specimen characterization and measurement condition for each of the data sets is given in Table 16. The data are tabulated in Table 17 and shown in Figures 10 and 11. Determinations of the electrical resistivity for both the solid and liquid states cover continuously the temperature range from 1.26 to 1451 K.

The data for the electrical resistivity of barium show considerable scatter. At low temperatures, the data of Meissner and Voigt [27] (curve 5), Meissner, Franz, and Westerhoff [79] (curve 10), and of Rashid and Kayser [80] (curves 6 and 7) are not for high-purity specimen. Above room temperature, Rinck [81] found a distinct slope change about 650 K (curve 13) which he assumed to be due to phase change at this temperature. The data of Grüntherodt, Hause, and Kunzi [82] (curve 9) are similar to Rinck's. The data of Grube and Dietrich [83] (curve 14) also show a discontinuity near 650 K, which however, exhibits quite a different nature from that indicated by the data of Rinck. The data of Katerberg, Nieneyer, Penning, and Van Zytveld [68] (curves 11 and 12) show no slope change at 650 K, but show a slope change near 530 K. Cook and Laubitz [84] presented data for pure and hydrogen charged Ba from 300 to 750 K (curves 15-21). Their data for pure barium differ from all previous data and show no evidence of transition at any temperature.

A least-mean-square-error fit was made with the modified Bloch-Grüneisen equation (8) to the data of Cook and Laubitz [84] (with correnction for the effect of hydrogen) and of Rashid and Kayser [80] (curve 8) from 30 to 750 K. The following results were obtained for the coefficients in equation (8):

S_1	S_2	S_3	$(\theta_R)_0$	C	P
$5.870\cdot10^{-8}\Omega$ m	$0.3428\cdot10^{-8}\Omega$ m	0	72.8 K	0.0252	0

The Debye temperature deduced from specific heat measurements is 110 K which is almost 40% higher than the present value for θ_R. The resulting values from equation (8) were then corrected for the thermal linear expansion and extrapolated to lower and higher temperatures to become the final recommended values.

There are three data sets available on the electrical resistivity of barium in the liquid state. Van Zytveld, Enderberg, and Collings [50] (curve 3) and Grüntherodt et al. [82] (curve 9) found that the temperature dependence of the electrical resistivity of liquid barium is small and weakly negative. However, Genter and Grosse [85] (curve 2) found a very large positive temperature dependence. On comparison with the electrical resistivity data for other alkaline earth elements in the liquid state, indicated that the electrical resistivity of liquid barium should have a weakly negative dependence on temperature. The data of Van Zytveld et al. and of Grüntherodt et al. were normalized by matching their values at the melting point of 1002 K. The normalized values were then least-mean-square-error fitted with a linear equation to yield the provisional values. At the melting point (1002 K), the electrical resistivity of barium in the liquid state is about 25% higher than that of solid barium.

The recommended values for the total and intrinsic electrical resistivities are listed in Table 15, and those for the total resistivity are also shown in Figures 10 and 11. The recommended values for the total electrical resistivity are for 99.5^{+}% pure barium and those at temperatures below 100 K are applicable only to a specimen with residual resistivity of $0.081 \times 10^{-8}\Omega$ m. The recommended values from 1 to 293 K are corrected for the thermal linear expansion. The correction amounts to -0.5% at 1 K, -0.37% at 100 K, and -0.18% at 200 K. The uncertainty in the recommended values for the total electrical resistivity is believed to be within ±10% below 30 K, within ±5% from 30 to 750 K, and within ±10% from 750 to 1300 K. Above 40 K the uncertainty in the recommended values for the intrinsic resistivity is slightly higher than that in the total electrical resistivity because of the possible deviations from the Matthiesen's Rule; below 40 K, the ρ_i values are very uncertain and are not listed in the table.

TABLE 15. RECOMMENDED ELECTRICAL RESISTIVITY OF BARIUM
(Temperature Dependence)

[Temperature, T, K; Total Resistivity, ρ, $10^{-8}\ \Omega$ m; Intrinsic Resistivity, ρ_i, $10^{-8}\ \Omega$ m]

Solid

T	ρ	ρ_i	T	ρ	ρ_i
1	0.081*		250	26.9	26.8
4	0.082*		273.15	30.2	30.1
7	0.104*		293	33.2	33.1
10	0.189*		300	34.3	34.2
15	0.501*		350	42.4	42.3
20	0.940*		400	51.4	51.3
25	1.42 *		450	61.4	61.3
30	1.92 *		500	72.4	72.3
35	2.41 *		550	84.7	84.6
40	2.91 *		600	98.2	98.1
45	3.39	3.31	650	113.	113.
50	3.88	3.80	700	130.	130.
60	4.86	4.78	750	148.	148.
70	5.84	5.76	800	168. *	168. *
80	6.83	6.75	900	216. *	216. *
90	7.83	7.75	950	244. *	244. *
100	8.85	8.77	1000	275. *	275. *
110	9.89	9.81	1002	276. *	276. *
120	11.0	10.9			
130	12.0	11.9			
140	13.1	13.0			
150	14.3	14.2			
175	17.2	17.1			
200	20.2	20.1			
225	23.5	23.4			

Liquid

T	ρ
1002	306. *
1050	303. *

* Provisional values

The recommended values for the total electrical resistivity are for 99.5+% pure barium and those at temperatures below 100 K are applicable only to a specimen with residual resistivity of $0.081 \times 10^{-8}\ \Omega$ m.

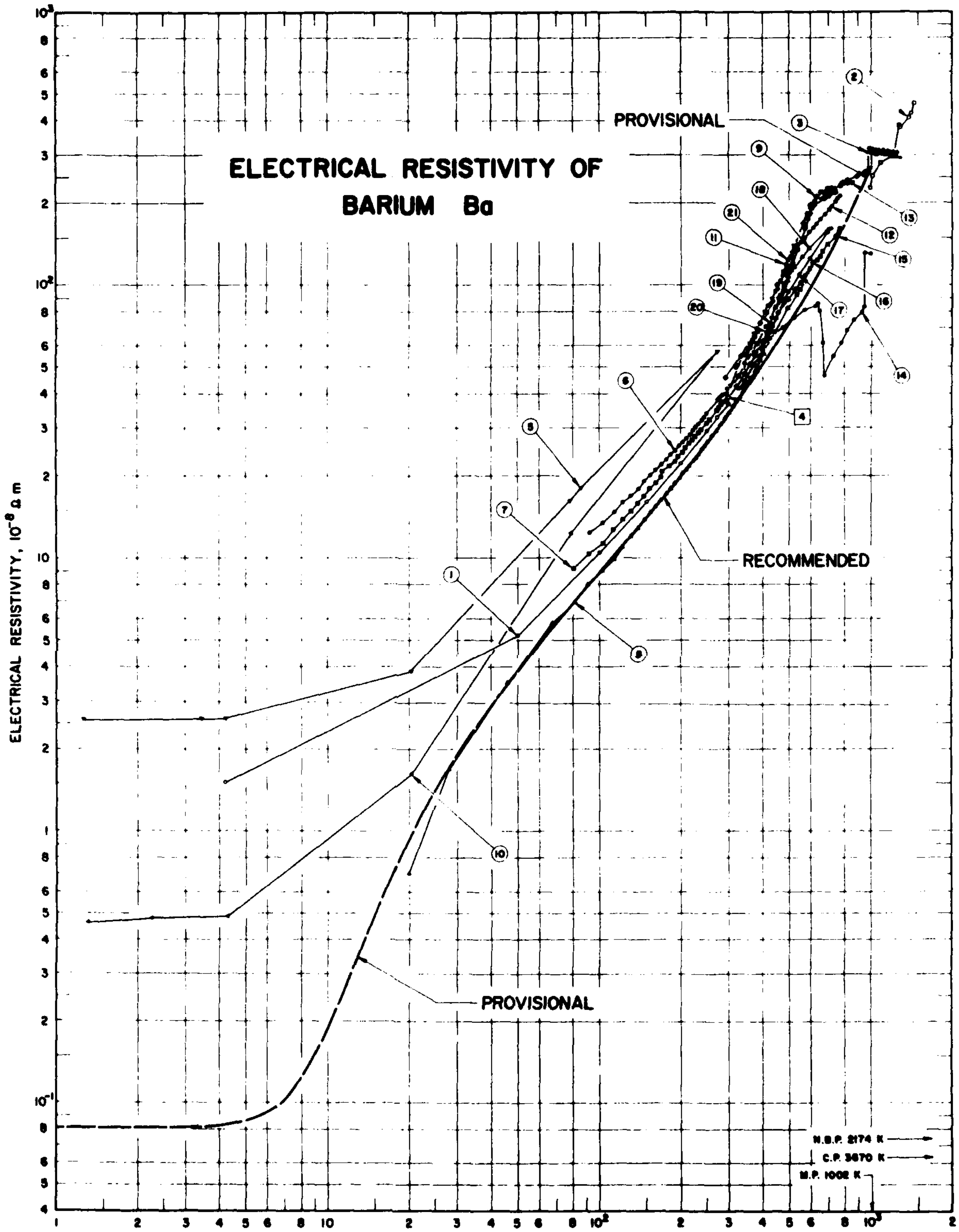


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FIGURE 10

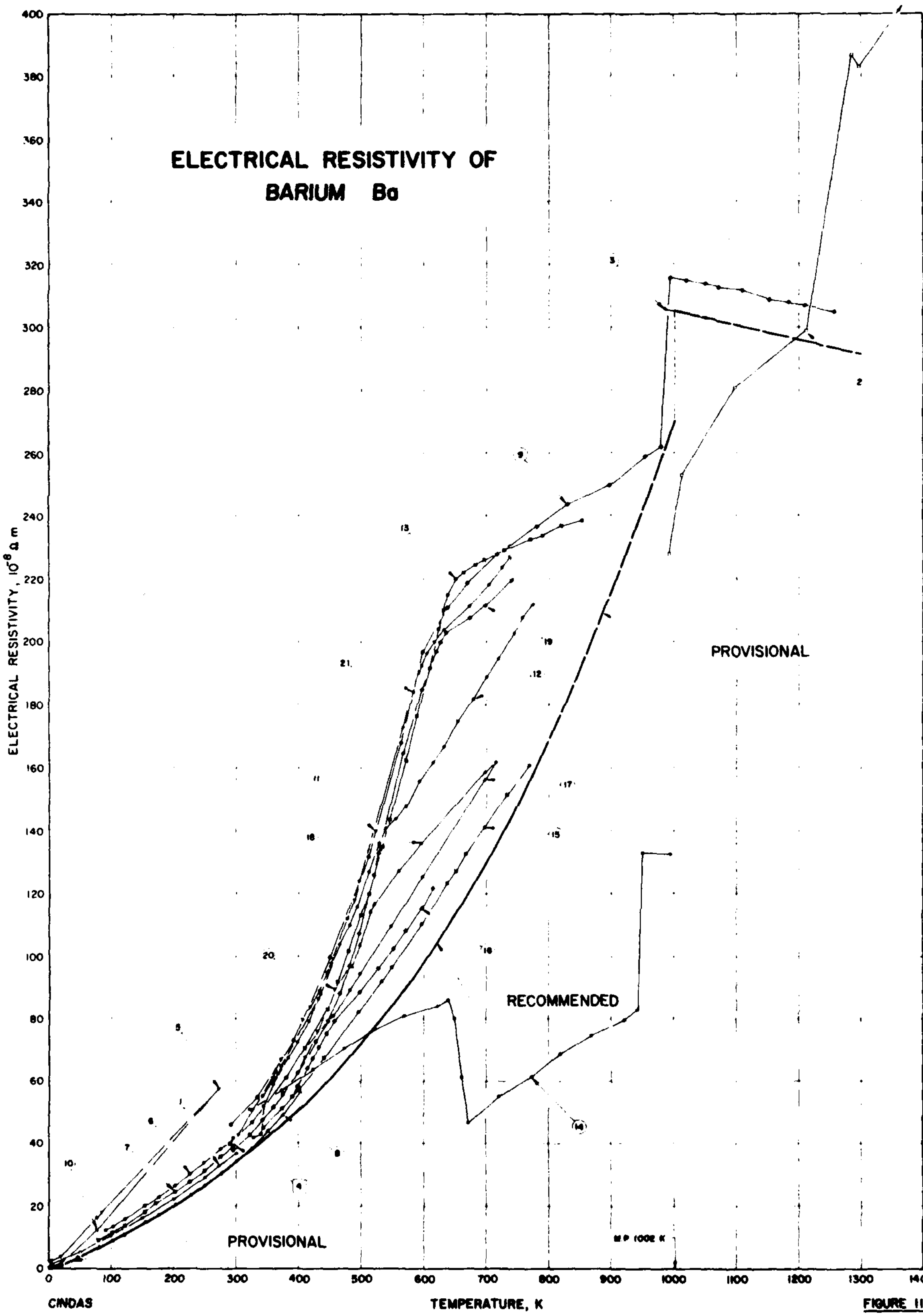
ELECTRICAL RESISTIVITY OF
BARIUM Ba
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
PROVISIONAL
RECOMMENDED
PROVISIONAL
M.P. 1002 K
CINDAS

FIGURE 11

TABLE 16. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	73	Cook, J.G. and Van der Meer, M.P.	1973		4.2-300		99⁺ purity; $\rho_{(273)}/\rho_{(4.2)}$ = 21.8; data were extracted from the smooth table.
2	85	Genter, R.B. and Grosse, A.V.	1971		993-1500		99.97 pure, 0.03 each Ca, Sr; liquid barium was contained in a Type 304 stainless steel tube about 0.5 in O.D., 0.421 in I.D. and 10 in. long; the sample was obtained from Mackay Metals, New York.
3	50	Van Zytveld, J.B., Enderby, J.E., and Collings, E.M.	1972		988, 1053		99.5 Ba, <0.1 each Sr, Na, C, <0.05 each Al, Fe, N_2, Zn; specimen was obtained from Atomergic Chemetals Co.
4	86	Müller, W.E.	1967		300		Pure;
5	27	Meissner, W. and Voigt, B.	1930		1.26-273	Ba 1	Pure; specimen was placed in a glass tube filled with helium; sample size 0.2 x 4 x 40 mm; the electrical resistance was measured by compensation method, a mirror galvanometer was used.
6	80	Rashid, M.S. and Kayser, F.X.	1971	A	80-300	1	99.0 pure Ba bar was obtained from Charles Pfizer Co., Inc.; it was extruded to 0.254 cm diameter wire and 3 cm long specimen; the specimen was in b.c.c. structure.
7	80	Rashid, M.S. and Kayser, F.X.	1971	A	80-300	2	Similar to the above specimen except it was in recrystallized treatment at 470 K for 16 hr.
8	80	Rashid, M.S. and Kayser, F.X.	1971	A	20-400	3	Similar to the above specimen except it was double distilled and annealed at 400 K for 4 days; ρ(300 K)/ρ(4.2 K) = 400 ~900.
9	82	Güntherodt, H.J., Hauser, E., and Künzi, H.V.	1975	C	292-1258		99.5 pure; the specimen was supplied by Fluka; a thin-wall vacuum tight stainless steel crucible was used in measurement; the specimens were etched first in methyl alcohol and then in toluene, then the specimens were transferred to the measuring cell and the open end of the crucible was pressed together; data were extracted from the figure; reported error 4%.
10	79	Meissner, W., Franz, H., and Westerhoff, H.	1932		1.3-273.16		Pure; the specimen was obtained from Dr. Friderich; relative resistance data were reported; resistance at temperature 273.16 K, R_0 = 3.12 x 10⁻³ Ω; the resistivity data were obtained by using $\rho_{273.16K}$ = 37.6 x 10⁻⁸ Ω m.
11	68	Katerberg, J., Niemeyer, S., Penning, D., and Van Zytveld, J.B.	1975	A	295-524		99.5-99.7 purity specimen was obtained from Atomergic Chemetals Co.; the experiment was measured with the sample held under an atm of pure argon; data were extracted from figure.
12	68	Katerberg, J., et al.	1975	A	328-776		Similar to the above specimen.
13	81	Rinck, F.	1931	A			Pure; double distilled specimen was prepared by Prof. Guntz; cylindrical specimen 10 cm long, 1.215 cm in diameter; because of crack only small section of the specimen was used to measure the resistance; melting point 984 K; data were extracted from figure.
14	63	Grube, G. and Dietrich, A.	1938		322-995		98.72 Ba, 0.31 Mg, 0.18 Zn, 0.25 Si, 0.05 Fe + Al, 0.33 Cl, rest N_2 + O_2; melting point 950 ±2 K; the specimen was obtained from I.G. Farbenindustrie Aktiengesellschaft, Bitterfeld.
15	84	Cook, J.G. and Laubitz, M.J.	1976		344-770	Ba3	Pure; specimen was prepared by sublimation at 1173 K in He at 8 mm Hg, a 405 stainless steel pot was used; a Ta tube degassed at 1173 K was filled with Ba dendrites and welded shut at both ends and it was kept at 1173 K in vacuum for three days in order to drive off as much H as possible, finally the Ta was removed from the Ba casting using a lathe in a glove box containing inert gas; the residual resistance ratio of the sample was 55; measurements were taken with increasing temperature; data were extracted from the smooth figure; no thermal expansion correction on data.

TABLE 16. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence) (continued)

Cur. No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	84	Cook, J.G. and Laubitz, M.J.	1976		344-615	Ba3	The above specimen; the sample was first cooled to 620 K and after a 10 hr period measurements were taken with decreasing temperature.
17	84	Cook, J.G. and Laubitz, M.J.	1976		423-716	Ba3	The above specimen was allowed to react with H_2 at 535 K; measurements were taken with increasing temperature.
18	84	Cook, J.G. and Laubitz, M.J.	1976		485-716	Ba3	The above specimen; measurements were taken with decreasing temperature.
19	84	Cook, J.G. and Laubitz, M.J.	1976		295-742	Ba3	The above specimen was allowed for H_2 charging at 620 K; measurements were taken with increasing temperature.
20	84	Cook, J.G. and Laubitz, M.J.	1976		295-742	Ba3	The above specimen; measurements were taken with decreasing temperature.
21	84	Cook, J.G. and Laubitz, M.J.	1976		324-739	Ba2	Commercially pure; residual resistance ratio was 10; data were extracted from the smooth figure and without thermal expansion correction.

TABLE 17. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence)

[Temperature, T, K; Resistivity, ρ, 10^{-8} Ωm]

T	ρ
CURVE 1	
4.2	1.51
50	3.21
100	10.51
150	16.14
200	22.34
250	29.25
273	33.0
300	36.9
CURVE 2	
993	228
1013	253
1093	281
1212	299
1256	387
1298	383
1396	412
1412	420
1451	465
CURVE 3	
989	306.0 ± 11
1053	302.4 ± 11
CURVE 4	
300	39
CURVE 5	
1.26	2.57
3.44	2.59
4.21	2.59
20.45	3.863
78.00	16.38
85.68	18.14
273.16	57.6
CURVE 6	
92	12.4
103	13.5
114	14.7
122	16.0
130	16.9

T	ρ
CURVE 6 (cont.)	
139	17.9
146	19.1
154	20.1
161	21.0
170	22.0
176	23.0
183	24.0
190	24.8
197	25.8
203	26.6
209	27.5
216	28.4
221	29.3
226	30.2
232	31.0
238	32.0
244	32.9
249	34.0
275	38.2
280	39.1
285	40.0
296	41.9
CURVE 7	
80	9.2
92	10.4
103	11.4
113	12.8
122	13.8
131	14.9
139	15.9
146	16.9
154	18.0
162	18.8
170	19.8
171	20.9
183	21.7
190	22.6
196	23.6
203	24.5
209	25.3
215	26.2
220	27.0
226	27.9
233	28.8
238	29.6

T	ρ
CURVE 7 (cont.)	
250	31.4
255	32.2
271	34.8
276	35.8
281	36.7
286	37.7
296	39.3
CURVE 8	
20	0.7
28	1.7
46	3.5
67	5.8
81	6.9
91	8.0
102	9.0
113	9.9
122	11.0
130	12.0
139	12.8
147	13.9
155	14.7
161	15.5
169	16.3
176	17.2
184	18.0
190	18.8
198	19.6
203	20.5
210	21.2
215	21.9
222	22.7
227	23.4
233	24.2
238	25.1
244	25.9
250	26.6
254	27.4*
261	28.2
266	28.7*
271	29.6
276	30.3
281	31.2
287	31.9*
291	32.9
295	33.5*

T	ρ
CURVE 8 (cont.)	
301	34.3
306	35.2*
311	36.2
316	36.9*
320	37.8
325	38.5
331	39.3
333	40.3*
339	41.2*
343	42.2
348	43.2*
352	44.0
356	44.9*
361	46.0
365	47.1*
369	48.0*
376	49.1
377	49.9*
382	51.0
386	52.2*
391	53.4
395	54.5*
399	55.7*
403	56.6
CURVE 9	
292	46
334	55
393	73
451	100
513	132
565	168
599	197
639	211
670	219
719	228
782	237
832	244
898	250
955	259
980	262
995	316
1021	315
1051	314
1073	313
1111	312

T	ρ
CURVE 9 (cont.)	
1154	309
1185	308
1211	307
1258	305
CURVE 10	
1.30	0.459
2.24	0.474
4.26	0.482
20.47	1.61
78.18	12.3
273.16	57.6*
CURVE 11	
295	40.1
306	44.3
326	51.4
342	57.1*
357	62.4
372	67.2
391	73.3*
407	79.2
419	83.3
434	89.3
446	94.7
462	106*
489	118
527	140
CURVE 12	
329	42.4
338	43.3
343	53.7
360	59.6
374	66.0
435	88
451	97
466	104
482	110
494	116
513	127
529	136
540	141
556	144

T	ρ
CURVE 12 (cont.)	
573	148
594	156
616	162
633	167
655	175
680	182
701	189
720	195
746	203
759	208
776	212
CURVE 13	
290	40.0
326	46.9
346	51.7*
380	61.1
410	70.8
446	83.1
463	92.0
480	101.8
500	113.4
513	120.0
521	126.0
535	135.2
546	143.7
573	162.5
590	176.8
610	191.8
624	204.3
[illegible]	210.3
[illegible]	215.2
652	220.1
663	222.3
683	224.7
698	226.2
729	229.2
772	232.7
791	234.1
820	237.0
854	238.7
CURVE 14	
322	50.9
373	57.1

* Not shown in figure.

TABLE 17. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF BARIUM Ba (Temperature Dependence) (continued)

CURVE 14 (cont.)

T	ρ
423	64.0
473	70.7
523	76.7
570	81.0
623	84.1
639	85.9
650	80.3
661	61.4
672	46.9
721	55.2
773	61.5
819	66.9
869	74.7
922	79.8
942	83.0
930	132.9
995	132.7

CURVE 15

T	ρ
344	44.9
374	51.4
390	55.1
400	57.1
441	67.6
497	82.3
534	92.1
550	96.6
598	110.6
638	123.6
652	127.5
668	133.0
698	141.4
734	151.6
770	161.0

CURVE 16

T	ρ
344	44.9*
374	51.4*
390	55.1*
399	58.2
415	64.3
423	67.3
432	70.9
446	75.4
459	79.4
498	88.7
528	96.3

CURVE 16 (cont.)

T	ρ
552	102.5
572	108.3
598	115.6
615	121.9

CURVE 17

T	ρ
423	67.3*
432	70.9*
456	81.1
492	89.2
498	94.6
548	109.7
598	125.5
699	156.6
716	161.9

CURVE 18

T	ρ
495	96.9
498	103.8
516	114.4
521	116.6
560	127.1
597	136.3
699	159.0
716	161.9*

CURVE 19

T	ρ
295	38.0
322	42.8
343	47.5
360	51.5
375	55.8
399	62.7
428	72.7
447	79.4
466	88.3
482	97.0
498	107.6
528	133.0
568	164.6
598	184.9
620	197.1
627	200.1
637	203.1
674	207.8
700	211.9
742	219.9

CURVE 20

T	ρ
295	38.0*
322	42.8*
343	47.5*
360	51.5*
375	55.8*
399	62.7*
411	67.7
431	76.0
458	89.7
479	101.7*
498	113.4*
528	133.0*
568	164.6*
598	184.9*
620	197.1*
627	200.1*
637	203.1*
674	207.8*
700	211.9*
742	219.9*

CURVE 21

T	ρ
324	50.6*
343	55.4
368	62.5
384	67.6
399	72.6
417	79.5
431	86.6
453	97.8
479	112.2
498	124.2
568	172.8
584	184.3
598	192.7
606	196.5
618	200.2
634	204.1
674	211.5
705	218.3
726	223.8
739	227.0

* Not shown in figure.

4.6. RADIUM

Radium, with atomic number 88, is a brilliant white, radioactive metal, and is the last member of Group II A elements. Its density has been estimated to be about 5 g cm^{-3}, which is, however, questionable. The melting and boiling points of radium have been given as about 973 K and 1900 K, respectively. Radium has no stable isotope and has sixteen radioactive isotopes known to exist, with half-lives ranging from less than 1 millisecond (^{216}Ra) to 1620 years (^{226}Ra). One gram of the longest-lived ^{226}Ra undergoes 3.7×10^{10} disintegrations per second; this amount of radioactivity has been defined as one curie. Radium occurs in nature and is present in all uranium minerals in trace quantities.

Temperature Dependence

Although no information appears to have been published regarding the electrical resistivity of radium, a value of 0.186 W cm^{-1} K^{-1} attributed to Chirkin [87] for the room temperature thermal conductivity of radium does appear in the Handbook of the Physico-chemical Properties of the Elements edited by Samsonov [88]. Neither the basis of this value nor its probable reliability is known.

We have roughly estimated the lattice thermal conductivity of radium at 293 K to be 0.013 W cm^{-1} K^{-1} by extrapolation to the atomic number 88 of a curve drawn through the lattice thermal conductivity values of calcium, strontium, and barium in a logarithmic graph of lattice thermal conductivity versus atomic number. The lattice thermal conductivity values of calcium, strontium, and barium are taken from Cook and Van der Meer [73]. Using the Wiedermann-Franz-Lorenz law, the electrical resistivity at 293 K is estimated to be 41×10^{-8} Ω m.

On the basis of the expected similarities between radium and other cubic-structure alkaline earth elements, namely calcium, strontium, and barium, we have roughly estimated the provisional intrinsic electrical resistivity of radium from 200 to 500 K by a least-mean-square-error fitting to the intrinsic electrical resistivity values of calcium, strontium, barium with a logarithmic equation with temperature and atomic number as the independent variables. The resulting equation is as follows:

$$\log_{10} \rho_i = -0.95 \log_{10}T - 1.18 \log_{10}Z + 1.37 \log_{10}T \times \log_{10}Z \qquad (14)$$

where Z is the atomic number and T is the absolute temperature.

The provisional values are listed in Table 18 and shown in Figure 12. The uncertainty in the provisional values is believed to be within ± 80%. The room temperature electrical resistivity value is about two times of the value calculated from Chirkin's thermal conductivity data.

TABLE 18. PROVISIONAL ELECTRICAL RESISTIVITY OF RADIUM (Temperature Dependence)

[Temperature, T, K; Intrinsic Resistivity, ρ_i, $10^{-8}\ \Omega\ m$]

T	ρ_i
200	44
225	54
250	65
273.15	76
293	85
300	88
350	115
400	145
450	177
500	212

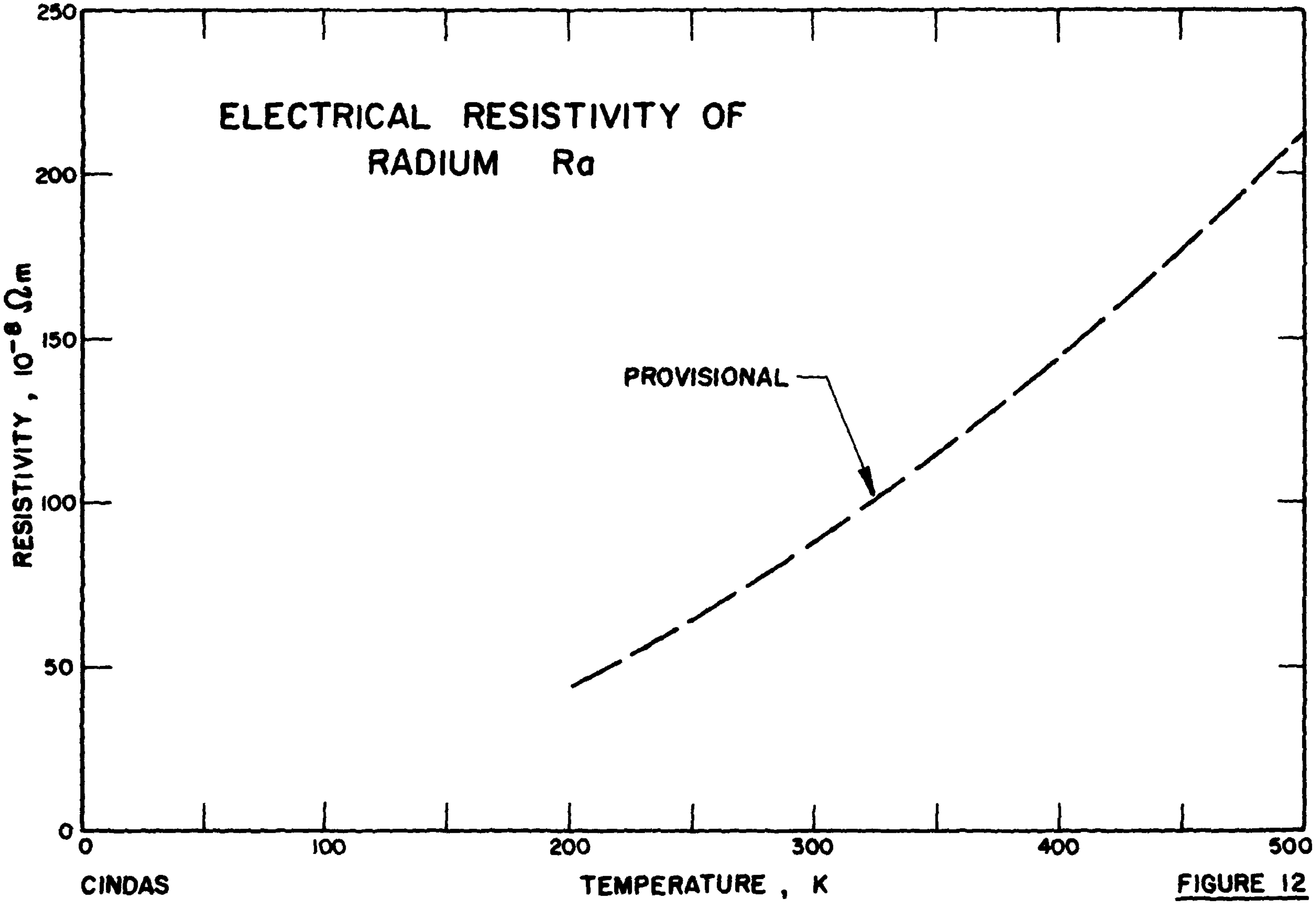

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FIGURE 12

5. SUMMARY AND CONCLUSIONS

The electrical resistivities of alkaline earth elements have been surveyed and studied over the years by a number of investigators, including Meaden [89] and Cook, Laubitz, and Van der Meer [71, 73, 84]. Electrical resistivity data are presented also in a number of handbooks such as those of Kaye and Laby [90], Landolt-Börnstein [91], AIP [92], CRC [93], etc. However, their main concern is to provide a general picture by giving only one or a few particular sets of data, and only a limited temperature range is covered.

The purpose of the present work is quite different from that of the above mentioned works. There are two major aims: (1) to exhaustively search the open literature so that all the available experimental data are comprehensively compiled, and (2) to generate recommended reference values by critical evaluation, analysis, and synthesis of the existing experimental data. These aims are now achieved. This work has presented the most comprehensively compiled experimental data and information on the electrical resistivity of alkaline earth elements and has provided the recommended reference values over a very wide range of temperature. The recommended values were obtained by least squares fitting of the selected experimental data or by correlating the related properties.

A comparison of electrical resistivity data from the literature with the present recommended values are shown in Table 19. Table 19 shows that the recommended electrical resistivity values from the various sources are quite different, up to 100% in some cases, that the more recent values are not necessarily closer to the truth, and that many of the values contained in popular handbooks are much in error. This attests to the need of reliable reference values such as those generated in the present work.

With a view to bring out any similarities or differences between the recommended values for the alkaline elements, the recommended values of the intrinsic resistivities for all the six elements are shown together in Figure 13. It can be seen from Figure 13 that the electrical resistivities of calcium, strontium, barium, and radium which have cubic crystalline structure, form a nice family of curves with systematic variations, those of heavier elements being the higher. The electrical resistivities of beryllium and magnesium, which have hexagonal crystalline structure, vary differently from the above mentioned and from each other. Their cross-over is due to the fact that beryllium has a much higher melting point.

TABLE 19. COMPARISON OF ELECTRICAL RESISTIVITY DATA FROM THE LITERATURE WITH THE PRESENT RECOMMENDED VALUES

Element	Temperature K	Total Resistivity, ρ, $10^{-8}\Omega$ m						
		Present work (1976)	CRC (1974)	AIP† (1972)	Kaye & Laby (1966)	Meaden (1965)	Landolt & Börnstein (1960)	Cook, et al. (1973-6)
Be	20	0.0336	-	0.0054	-	0.0054	-	-
	273.15	3.02	4.0 (293K)	2.72	2.8	2.72	3.2	-
	1000	27.5	-	-	26 (973 K)	-	-	-
	1500	49.9	-	-	-	-	-	-
Mg	20	0.0123	-	0.0125	-	0.0125	-	-
	273.15	4.05	4.45 (293 K)	3.94	3.9	3.94	4.31	-
	922	14.7	-	-	-	-	-	-
	1200	25.6	-	-	-	-	-	-
Ca	20	0.0600	-	-	-	-	-	0.104 (30 K)
	273.15	3.11	3.91	3.61 (293 K)	6.8	3.6 (295 K)	4.06	3.20 (277 K)
	1000	12.8	-	-	-	-	-	-
	1150	33.0	-	-	-	-	-	-
Sr	20	0.918	-	2.48	-	2.48	-	-
	273.15	12.3	23.0 (293 K)	21.8	23	21.8	30.3	12.5
	1000	62.2	-	-	-	-	-	-
	1093	84.7	-	-	-	-	-	-
Ba	20	0.940	-	0.98	-	0.98	-	-
	273.15	30.2	-	36.3	60	36.3	36.0	33
	1000	275	-	-	-	-	-	-
	1050	303	-	-	-	-	-	-
Ra	200	44*	-	-	-	-	-	-
	273.15	76*	-	-	-	-	-	-
	500	212*	-	-	-	-	-	-

* Intrinsic resistivity
† The values in the AIP Handbook are taken from the book by Meaden so that they are identical.

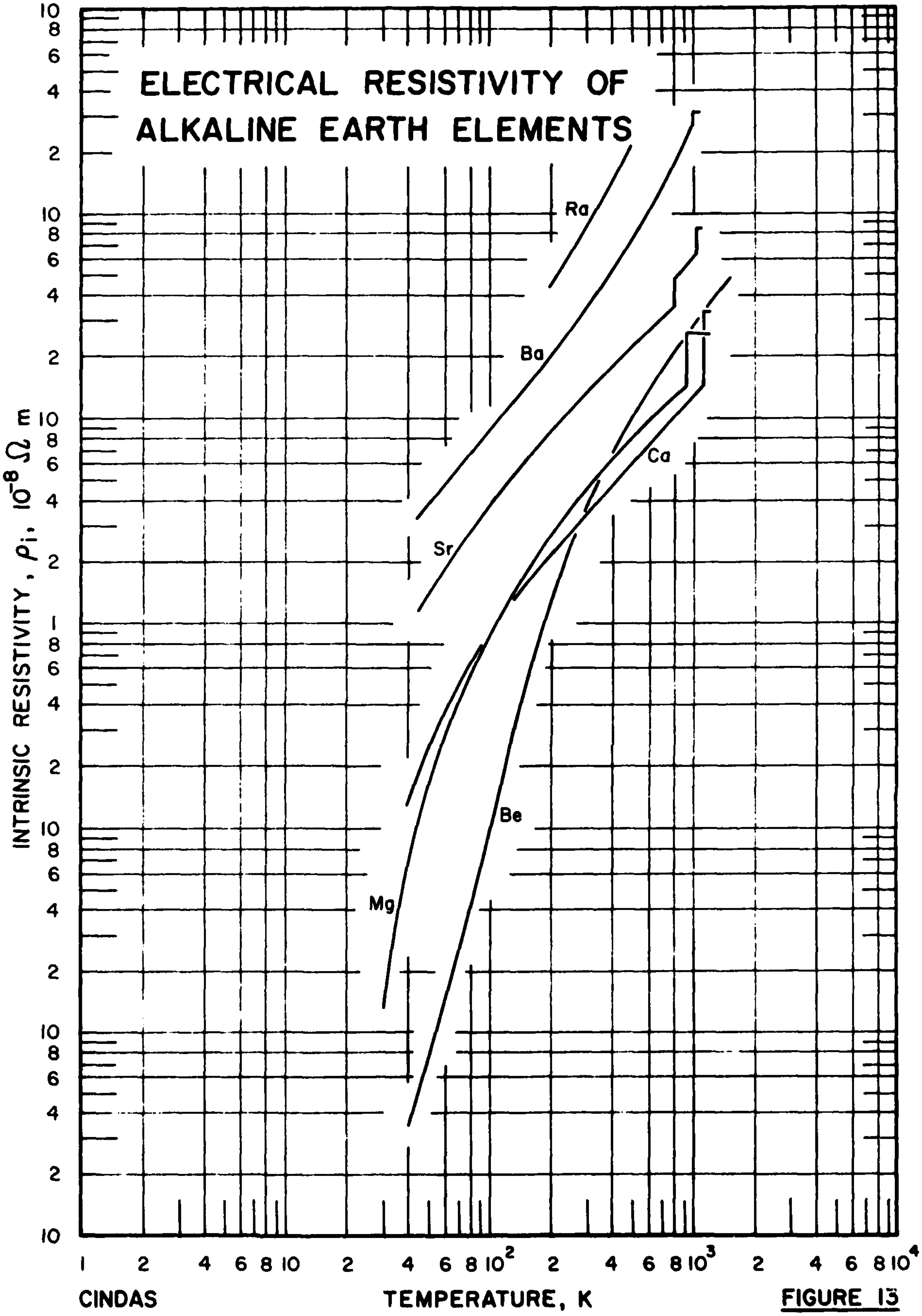
ELECTRICAL RESISTIVITY OF ALKALINE EARTH ELEMENTS
INTRINSIC RESISTIVITY, ρ_i, 10^{-8} Ω m
TEMPERATURE, K
Ra
Ba
Sr
Ca
Mg
Be
1 2 4 6 8 10 2 4 6 8 10^2 2 4 6 8 10^3 2 4 6 8 10^4
CINDAS

FIGURE 13

6. REFERENCES

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7. APPENDIX

7.1. Methods of Measuring Electrical Resistivity

A. Steady State Methods

1. Voltmeter and ammeter direct reading (V) [94*, p. 159, 119, pp. 244-5]
2. DC Potentiometric Method (A) [89*, pp. 151-8]
   a. 4-probe potentiometric method
3. DC Bridge Method (B) [89, pp. 141-51]
   a. Kelvin Double Bridge
   b. Mueller Bridge
   c. Wheatstone Bridge
4. van der Pauw Method (P), [95]*
5. Galvanometer Amplifier Method (G), [96*, pp. 159-62]

B. Non-steady State Methods

1. Periodic currents involved
   a. Direct connection to sample
      (1) AC Potentiometric Method (C) [89, pp. 161-2]
      (2) AC Bridge Method (D) [89, p. 162]
      (3) Q-Meter Method (Q)
   b. No connection to sample
      (1) Mutual Inductance Method (M) [97]*
      (2) Self-inductance Method (S) [98]*
      (3) Rotating Field Method (R) [99]*
2. Non-periodic currents involved
   a. Direct connection to sample
      (1) Transient (subsecond) technique (T) [100]*
   b. No connection to sample
      (1) Eddy current decay method (E) [101, 89, p. 103]

C. General Comments

1. Code "I" means Induction Method

   This is a combination of Items B.1b. and B.2.b. above. Subsumed under I is M, R, S, or E. Used only if author indicates induction method used and does not report which specific one.

2. The symbol "→" is used if method described by the author is not sufficient to assign a specific code presently used. For example, if the author stated that "AC Method"

---

* References are given in Section 6.

was used in his measurement but no specifics were given, the following wording would be used in the column Composition, Specifications, and Remarks: "Experimental method described as an AC method." In the column for Method Used on the Specification Table the following symbol would appear: $\rightarrow$.

FILM

6 —