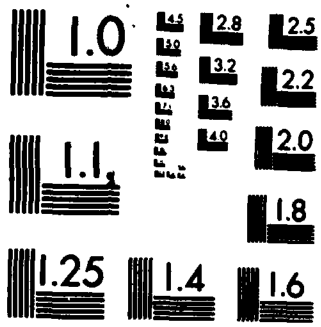
AD-A129 176 ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM(U) 1/1
THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION
ANALYSIS CENTER LAFAYETTE IN P D DESAI ET AL. DEC 82
UNCLASSIFIED CINDAS-63 F/G 7/2 NL

END
DATE
FILMED
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD A129176

CINDAS

THERMOPHYSICAL PROPERTIES RESEARCH CENTER
ELECTRONIC PROPERTIES INFORMATION CENTER
THERMOPHYSICAL AND ELECTRONIC PROPERTIES INFORMATION ANALYSIS CENTER
UNDERGROUND EXCAVATION AND ROCK PROPERTIES INFORMATION CENTER

ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM

By

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

CINDAS Report 63

December 1982

Prepared for

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

This document has been approved for public release and sale; its distribution is unlimited.

DTIC ELECTE JUN 08 1983 S D E

83 06 07 093

DTIC FILE COPY

CENTER FOR INFORMATION AND NUMERICAL DATA ANALYSIS AND SYNTHESIS
PURDUE UNIVERSITY
PURDUE INDUSTRIAL RESEARCH PARK
2595 YEAGER ROAD
WEST LAFAYETTE, INDIANA 47906

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A129 176	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM		5. TYPE OF REPORT & PERIOD COVERED State-of-the-Art Report
		6. PERFORMING ORG. REPORT NUMBER CINDAS Report 63
7. AUTHOR(s) P. D. Desai, H. M. James, and C. Y. Ho		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Thermophysical and Electronic Properties Information Analysis Center, CINDAS/Purdue Univ., 2595 Yeager Rd., W. Lafayette, IN 47906		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Defense Technical Information Center, Defense Logistics Agency, Attn: DTIC-AI, Cameron Station, Alexandria, VA 22314		12. REPORT DATE December 1982
		13. NUMBER OF PAGES 66
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

CINDAS/TEPIAC Publication; (DTIC Source Code 413571); Microfiche copies available from DTIC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

*Electrical Restivity--*Vanadium--*Zirconium--elements--metals

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM

By

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

CINDAS Report 63

December 1982

Prepared for

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

Accession For
NTIS GRA&I [X]
DTIC TAB [ ]
Unannounced [ ]
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A
DTIC COPY INSPECTED 2

CENTER FOR INFORMATION AND NUMERICAL DATA ANALYSIS AND SYNTHESIS
Purdue University
2595 Yeager Road
West Lafayette, Indiana 47906

Copyright © 1982 by the Purdue Research Foundation, West Lafayette, Indiana

All rights reserved. This work or any part thereof may not be reproduced in any form without written permission of the Purdue Research Foundation.

PREFACE

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

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

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

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

ABSTRACT

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

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

CONTENTS

LIST OF TABLES

LIST OF FIGURES

*Figures include the recommended values.

NOMENCLATURE

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

1. INTRODUCTION

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

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

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

The last three sections are for acknowledgments, appendices, and references. There are two appendices given. The first appendix presents a logical organization of the methods for the measurement of electrical resistivity. The methods are designated with respective code letters and the same code letters are used in the 'Method Used' column of the Table of Measurement Information

---

[1]Numbers in brackets indicate literature references listed in Section 6.

for indicating the experimental methods used by the various authors. The second appendix presents conversion factors for the units of electrical resistivity, which may be used to convert easily the electrical resistivity values in the SI units given in this work to values in any of the several other units listed.

2. GENERAL BACKGROUND

2.1. Theoretical Background

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

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

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

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

$$\rho(c,T) = \rho_0(c) + \rho_i(T) + \Delta(c,T), \quad (2)$$

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

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

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

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

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

At low temperatures ($T \lesssim \theta_R/20$), eq (3a) reduces to

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

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

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

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

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

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

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

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

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

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

Substituting eqs (7) and (3b) into eq (6) yields

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

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

2.2. Presentation of Data and Information

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

(1) A discussion text,

(2) A table of recommended values,

(3) A figure presenting experimental data as a function of temperature in a log-log scale,

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

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

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

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

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

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

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

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

where $\Delta L = L - L_0$ and L and L_0 are the lengths of the specimen at any temperature T and at a reference temperature T_0, respectively. The thermal expansion correction amounts roughly to about -0.2% at low temperatures, zero at room temperature, about 0.3% near 500 K, and about 1.5% to 2.5% near the melting point of the element.

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

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

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

A Direct-current potentiometer method

B Direct-current bridge method

C Alternating-current potentiometer method

K Direct heating method

R Rotating magnetic field method

T Transient (subsecond) method

V Voltmeter and ammeter direct reading method

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

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

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

3. ELECTRICAL RESISTIVITY DATA AND INFORMATION

3.1. Vanadium

There are 69 sets of experimental data available for the electrical resistivity of undoped vanadium as a function of temperature. The residual resistivity of the purest sample reported in this investigation is 0.01008 x 10^{-8} Ω m. Information on the specimen characterization and measurement condition for each of the data sets is given in table 2. The data are tabulated in table 3 and shown partially in figure 1.

In the absence of a magnetic field, vanadium is a superconductor below its superconducting transition temperature (5.46 K). The superconducting transition temperature is very sensitive to the magnetic field intensity: the higher the magnetic field intensity, the lower is the superconducting transition temperature. Aleksandrov et al. [19] found that the superconducting transition temperature of vanadium would be lowered to 4.5 K in a magnetic field of ~0.5 kOe. Furthermore, their measurements for the nonsuperconducting state of a high purity vanadium specimen at ~5.4 K in a magnetic field of ~2.2 kOe showed an increase of about 0.45% in the electrical resistivity; thus the influence of the magnetic field on the electrical resistivity of very pure vanadium could be neglected.

The electrical resistivity measurements below room temperature have received considerable attention. This is evident in the extent of the measurements of Pan et al. [13] (data sets 6,7), Courtney [14] (data sets 8-11), Chakal'skii et al. [15] (data set 15), Jung et al. [16-18] (data sets 13-16), Aleksandrov [19] (data sets 17,18), Azhazha et al. [20] (data sets 19,20), Westlake and Alfred [37,38] (data sets 37,38), Amitin et al. [40] (data sets 41,42), Taylor and Smith [45] (data sets 52-55), and White and Woods [48,49] (data set 59). Very recent studies have been made by Gautron et al. [53] (data set 64) on a sample with the highest purity (i.e., lowest ρ_0 = 0.01 x 10^{-8} Ω m) and by Tsai et al. [54] (data sets 65,66) on a sample with ρ_0 = 0.0109 x 10^{-8} Ω m.

The temperature dependent part of the electrical resistivity below 21 K was reported to be proportional to T^3 by White and Woods [48,49]. This was confirmed later by results of Chakalskii et al. [15], Jung et al. [16-18], and by Aleksandrov et al. [19]. The presence of the cubic term is evidently connected with s-d interband scattering. However, studies of Tsai et al. [55] on the sample with ρ_0 = 0.0109 x 10^{-8} Ω m found an additional T^2 term which they attributed to electron-electron scattering (ρ_e). In order to verify these results, Gautron et al. [53] carried out electrical resistivity measurements on an even purer specimen with ρ_0 = 0.01 x 10^{-8} Ω m, and obtained a value of (1.6 ± 0.2) x 10^{-11} Ω cm/K^2 for ρ_e that was compatible with the value of (1.3 ± 0.2) x 10^{-11} Ω cm/K^2 obtained by Tsai et al. [54]. Gautron et al. [53] pointed out that the temperature dependent electrical resistivity above 10 K is dominated by electron-phonon interactions. Below 10 K, the electron-electron term makes a significant contribution, and it begins to dominate below 5 K. Failure to detect the ρ_e term in earlier studies [e.g., 15-18, 48-50] was attributed to the fact that these studies did not involve measurements to low enough temperatures, and also to the fact that below 10 K the electron-electron contribution is of the order of or less than ρ_0, even for relatively pure specimens.

An anomalous behavior of the electrical resistivity between 180 and 300 K has been observed by Burger and Taylor [46], Suzuki et al. [74], Smirnov and Finkel [67], and by Rostoker and Yamamoto [73]. However, Westlake [38] found that hydrogen absorbed in the specimen affects the resistivity anomously near 180 K and that hydrogen-free vanadium did not show such anomalous behavior.

Comparison of the electrical resistivity data below room temperature indicates that the electrical resistivity of vanadium deviates from Matthiessen's rule. The deviations are dependent not only on the concentration of impurities, but also on their type. The deviations are larger for the less pure specimens.

With the discussion given above in mind, the recommended values are based on the data of Courtney [14] (data set 11), Jung et al. [16-18] (data sets 13-16), Gautron et al. [54] (data set 64), and of Tsai [55] (data set 65), who all measured specimens with RRR > 1500. Special weight was given to the data of Gautron et al. [54] on a specimen with RRR = 1970 and ρ_0 = 0.01 x 10^{-8} Ω m. The deviation of the data from the recommended values for somewhat less pure specimens [13,19,20,37,38,40,45,48,49] are shown in figure 1.

At the highest temperatures there is general agreement on the temperature dependence of the electrical resistivity. There are little good data from 300 to 1200 K. The recommended values in this temperature range are based on the data of Neimark et al. [28] (data set 26) and of Taylor and Groot [55] (data set 67). However, Neimark et al. have indicated rather high maximum error for their measurements, and RRR = 400 is reported by Taylor and Groot [55] for their sample. The recommended values from 1200 to the melting point are based on the data of Gathers et al. [10] (data set 2), Cezairliyan et al. [22-24] (data set 22), and of Peletskii et al. [32] (data set 30) [57] (data set 69). A compromise has been made between their somewhat divergent results. The scatter of the data from other investigations reported in table 2 [12,28-30,33,34, 36,43,44,56] is of the order of ±10%. The recommended values above 2202 K, in the liquid region, are based on the compromise between the only two data sets available, due to Seydel and Fucke [9] (data set 1) and to Gathers et al. [10] (data set 2). At 4000 K the divergent in their values approaches 9%. The data of Gathers et al. [10] indicate a lower melting point than the generally accepted value of 2202 K, presumably because their data were taken under pressure.

The recommended values of the electrical resistivity given in table 1 and shown in figures 2 and 3 along with the experimental data, which were used to generate these values, are for vanadium of 99.99% purity or higher, but those below 100 K are applicable specifically to vanadium having a residual resistivity of 0.0100×10^{-8} Ω m. The table gives both values uncorrected and corrected for thermal expansion, while the figures show only the uncorrected recommended values and mostly uncorrected experimental data. The values for the thermal expansion were taken from ref. [121]. The uncertainty in the recommended values is estimated to be within ±10% from 7 to 20 K and ±5% at lower and higher temperatures.

Vanadium is a transition element and its low-temperature electrical resistivity depends on the type as well as on the concentration of impurities. The electrical resistivity of lower-purity vanadium is, therefore, difficult to estimate, especially at low temperatures (<250 K). However, judging from the data reported by Jung et al. [16-18], it appears that for specimens having residual resistivities less than 0.5×10^{-8} Ω m only small uncertainties (<0.01×10^{-8} Ω m at 20 K, and ~0.3×10^{-8} Ω m at 100 K) are introduced by the application of Matthiessen's rule. The data from refs. [16-18] (data set 13) and from ref. [38] (data set 38) with sample residual resistivity of 0.52×10^{-8} Ω m and 0.81×10^{-8} Ω m, respectively, are also shown in one of the figures for illustration.

Additional information on the electrical resistivity is reported in refs. [58-95]. Data of Hensler et al. [35] (data sets 33,34), Gurp [41] (data sets 43,44), and of Wruk and Wert [51] (data sets 61,62) are for films/foils; readers are directed to refs. [96-115] for additional information/data on films. The data of Courtney [14] (data sets 8-10) are hydrogen-doped vanadium and additional information/data on various doped-vanadium samples are reported in refs. [65,72,102,116-119]. Effects of irradiation are discussed in refs. [71,72,120], of annealing temperature in refs. [66,112,116,120], and of pressure in refs. [73,74,122].

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

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
1	0.0100(b)	0.0100	700	47.2	47.4
4	0.0105	0.0105	800	53.1	53.4
7	0.0117	0.0117	900	58.7	59.1
10	0.0145	0.0145	1000	64.1	64.6
15	0.0232	0.0232	1100	69.1	69.7
20	0.0391	0.0391	1200	73.8	74.5
25	0.0661	0.0660	1300	78.5	79.4
30	0.112	0.112	1400	83.2	84.2
40	0.304	0.304	1500	87.8	89.0
50	0.649	0.648	1600	92.3	93.7
60	1.114	1.112	1700	96.7	98.3
70	1.706	1.703	1800	100.9	102.7
80	2.413	2.409	1900	104.9	107.0
90	3.196	3.191	2000	108.7	111.0
100	4.01	4.00	2100	112.2	114.8
150	8.22	8.21	2202	115.6(s)	118.5(s)
200	12.43	12.42	2202		135.1(ℓ)
250	16.37	16.36	2400		137.6
273	18.14	18.14	2600		140.4
293	19.68	19.68	2800		143.3
300	20.21	20.21	3000		146.4
350	24.2	24.2	3200		149.7
400	28.0	28.0	3400		153.3
500	34.8	34.9	3600		157.5
600	41.1	41.2	3800		162.0
			4000		166.8

[a]The values are for vanadium of purity 99.99% or higher, but those below 100 K are applicable specifically to vanadium having a residual resistivity of 0.0100×10^{-8} Ω m. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. Solid line separating tabular values indicates solid to liquid state transformation.

[b]Assuming superconductivity suppressed by magnetic field.

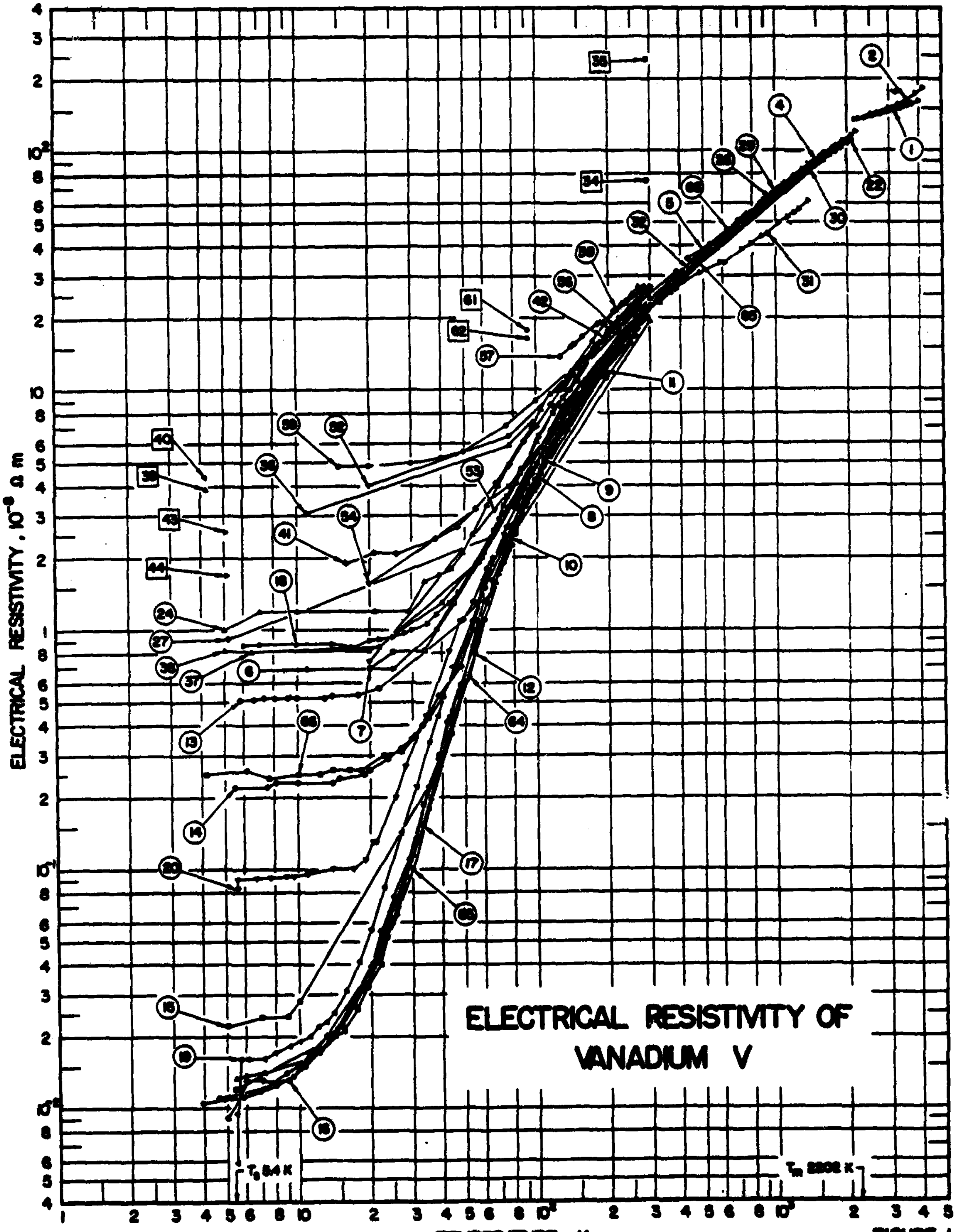

ELECTRICAL RESISTIVITY OF
VANADIUM V
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
T_s 5.4 K
T_m 2208 K
CINDAS

FIGURE 1

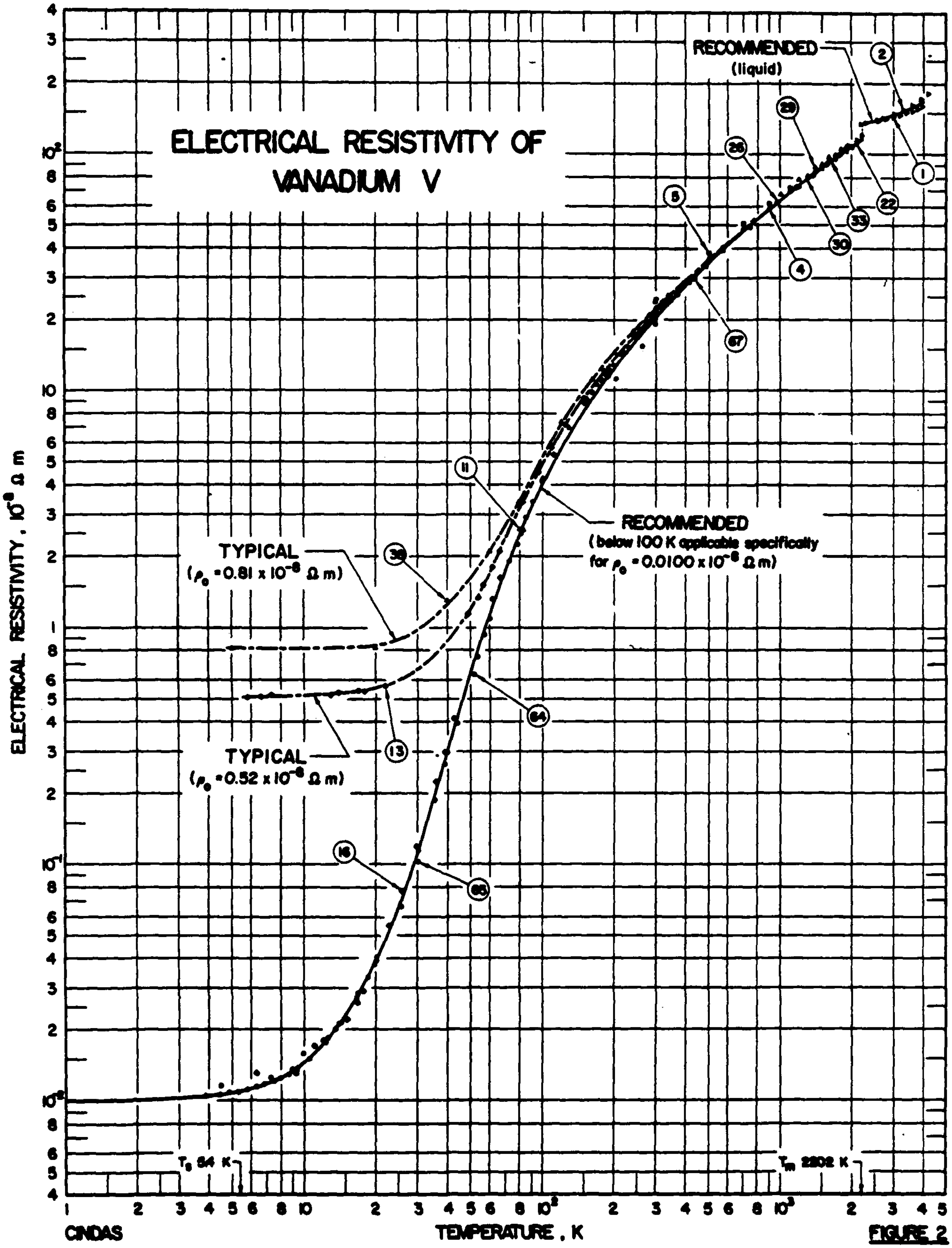
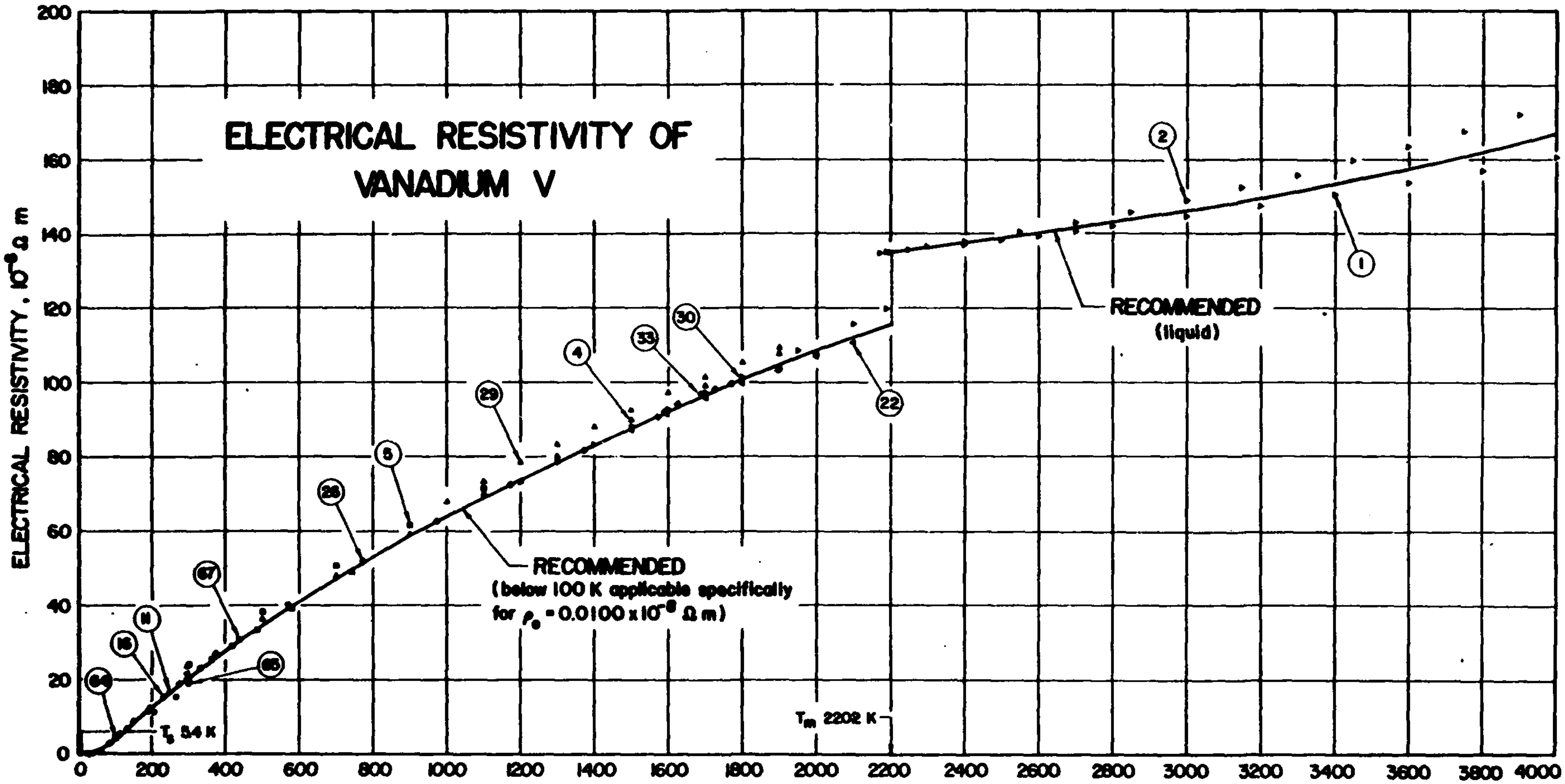

ELECTRICAL RESISTIVITY OF VANADIUM V
RECOMMENDED (liquid)
RECOMMENDED (below 100 K applicable specifically for ρ₀ = 0.0100 x 10⁻⁸ Ω m)
TYPICAL (ρ₀ = 0.81 x 10⁻⁸ Ω m)
TYPICAL (ρ₀ = 0.52 x 10⁻⁸ Ω m)
ELECTRICAL RESISTIVITY, 10⁻⁸ Ω m
TEMPERATURE, K
Tθ 64 K
Tm 2202 K
CINDAS

FIGURE 2



CINDAS

FIGURE 3

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	9	Seydel, U. and Fucks, W.	1980	T	2175-4000		99.9 V; temperature measurements taken on foil samples, length 4.4 cm, cross sections 5×10^{-4} cm^2; heated by means of a capacitor discharge with a heating rate of 10^{10}Ks^{-1}; for the range of Tm (melting temperature) = 2175 K ≤ T ≤ 6600 K, ρ(μΩ cm) = 1.3486 + 1.0219 x 10^{-4}(T-Tm) + 2.1803 x 10^{-8}(T-Tm)^2; error in ρ stated as 5-6%.
2	10	Gathers, G.R., Shaner, J.W., Hixson, R.S., and Young, D.A.	1979		1800-4200		Wire sample 1.0 mm diameter, 25 mm long; phase change from solid to liquid occurs at 2190 K; resihtivity values measured at 0.3 GPa; for the solid, ρ_o(μΩ m) = 0.1077 + 5.3699 x 10^{-4}T - 1.7255 x 10^{-8}T^2, 1800 K ≤ T ≤ 2190 K; least squares fit of data; smoothed value listed.
3*	11	Vedernikov, M.V., Dvunitkin, V.G., and Zhumagulov, A.	1978	A	4.2,293		No details given.
4	12	Peletskii, V.E., Amasovich, E.S., Kostanovskii, A.V., Zaretskii, E.B., Sobol, Ya.G., and Shur, B.A.	1977	A	300-1900	V1	99.8 V, 0.01 C, 0.09 O_2, 0.02 Si, 0.02 Al, 0.02 Fe; density 6.1 g cm^{-3}; crystal orientation [100]; data not corrected for thermal expansion; error does not exceed ±1.5% from 300 to 1600 K and ±2-2.5% from 1600 to 2000 K; data extracted from smooth tabulated values.
5	12	Peletskii, V.E., et al.	1977	A	300-2000	V2	99.9 V, 0.06 C, 0.02 O_2, 0.01 Si, 0.01 Zr, 0.01 Al; density 6.097 g cm^{-3}; crystal orientation 3° [001]; other specifications are same as above.
6	13	Pan, V.M., Prokhorov, V.G., Shevchenko, A.D., and Dovgopol, V.P.	1977	A	11-300		Single crystal specimens; measurements taken with two directions of current flow <100> and <110>; critical temperature for superconductive transition 5.22 K; ρ_{300}/ρ_6 = 43, temperature coefficient of resistivity at 300 K 4.1 x 10^{-3}K^{-1}; application of magnetic field of 40 kOe did not change the temperature dependence of ρ or shift the position of T_c; data extracted from figure reported for measurements in zero magnetic field; values reported at 6 K are 0.5 x 10^{-8} Ω m and 21.5 x 10^{-8} Ω m at 300 K.
7	13	Pan, V.M., et al.	1977	A	20-300		Same as above except magnetic field H = 40 kOe.
8	14	Courtney, D.R.	1977	A	95-288	VH330	Electro-transported rods electropolished in a 94-6% methanol-perchloric acid, then subjected up to 10^{-7} torr in a vacuum furnace and heated to 1000°C for 1 1/4 hr and at 800°C in H_2 for 2 hr; specimen length 4.3 cm and 0.23 cm diam.; 330 ppm H, 140 ppm O, 10 ppm N, 15 ppm C, and 165 ppm O+N+C; data from figure.
9	14	Courtney, D.R.	1977	A	76-296	VH260	Same as above except 260 ppm H, 60 ppm O, 3 ppm N, 18 ppm C, and 81 ppm O+N+C; specimen length 3.92 cm and 0.244 cm diameter.
10	14	Courtney, D.R.	1977	A	72-283	VH54	Same as above except 54 ppm H, 27 ppm O, 1 ppm N, 11 ppm C, and 39 ppm O+N+C; specimen length 2.9 cm and 0.242 cm diameter.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
11	14	Courtney, D.R.	1977	A	81-295	VH1	Same as above except <1 ppm H and 15 ppm (O+N+C); specimen length 3.65 cm and 0.205 cm diam.; data of Jung [16,17].
12	15	Chakal'skii, B.K., Ashasha, V.M., Red'ko, N.A., and Shalyt, S.S.	1976	A	5-155		No details given; specimen same as that reported in data set 17.
13	16 17 18	Jung, W.D. Jung, W.D. Jung, W.D., Schmidt, F.A., and Danielson, G.C.	1975 1975 1977	A A A	6-273 6-273	Sample 1	Specimen prepared by Schmidt of the Ames Laboratory using electrotransport technique from the polycrystalline double-electrorefined vanadium supplied by the U.S. Bureau of Mines; total impurities 100 atm ppm consist of 30 atm ppm Cl, 23 atm ppm W, 22 atm ppm Cu, 10 atm ppm Fe, 5 atm ppm Nb, 4 atm ppm Mg, and 3 atm ppm Si (spark source mass-spectrometry and neglecting 1230 atm ppm O+C+N; $\rho_{273}/\rho_{4.2}$ = 37.6; ρ_{273} = 19.61 x 10^{-8} Ω m; specimen dimension 0.263 cm diameter and 2.5 cm length; data extracted from figure.
14	16 17 18	Jung, W.D. Jung, W.D. Jung, W.D., et al.	1975 1975 1977	A	6-265	Sample 2	Same as above except 570 atm ppm (O+C+N); $\rho_{273}/\rho_{4.2}$ = 81.5 and ρ_{273} = 18.72 x 10^{-8} Ω m; specimen dimension 0.260 cm diameter and 3.47 cm length; data extracted from figure.
15	16 17 18	Jung, W.D. Jung, W.D. Jung, W.D., et al,	1975 1975 1977	A	5-283	Sample 3	Same as above except 55 atm ppm O+C+N, 100 atm ppm Cr+VN, 12 atm ppm W, 13 atm ppm Fe, 14 atm ppm Cl, and 8 atm ppm Mg; no evidence of an impurity gradient; large concentration of Cr+VN likely due to surface hydrocarbon contamination not representative of sample; $\rho_{273}/\rho_{4.2}$ = 785 and ρ_{273} = 18.69 x 10^{-8} Ω m; specimen dimension 0.205 cm diameter and 3.65 cm length; data extracted from figure.
16	16 17 18	Jung, W.D. Jung, W.D. Jung, W.D., et al.	1975 1975 1977	A	5-274	Sample 4	Same as above except 28 atm ppm O+C+N; $\rho_{273}/\rho_{4.2}$ = 1524 and ρ_{273} = 18.90 x 10^{-8} Ω m; specimen dimension 0.241 cm diameter and 4.3 cm length; data extracted from figure.
17	19	Aleksandrov, B.N., Semenova, E.D., Petrova, O.I., Chernyi, B.P., and Ashasha, V.M.	1975	A	5-300	Specimen No. 1	Polycrystalline; purest sample they studied is 1.4 mm diameter and 25-60 mm length; ρ_0 = 0.0129 x 10^{-8} Ω m; data extracted from figure.
18	19	Aleksandrov, B.N., et al.	1975	A	6-47	Specimen No. 4	Similar to above except ρ_0 = 0.867 x 10^{-8} Ω m; least pure sample which studied; data extracted from figure.
19	20	Ashasha, V.M., Volkenshtein, N.V., Startsev, V.Ye., Finkel, V.A., Cherepanov, V.I., and Chernyi, B.P.	1976	A	5-270	V4	High purity sample of ρ_{300}/ρ_0 = 1520 prepared by complex method includes refining by vacuum electron beam melting and electron transfer; total impurities <3 x 10^{-3}%, gas impurities 1%, and <1% hydrogen; superconducting transition temperature T_c = 5.38 K; error of the measurements 0.5% for T < 15 K and 0.01% for T > 70 K; anomaly near 183 K was observed; resistivity contains contribution proportional to fourth power of the temperature; these peculiarities are intensified as the purity of sample increases; data extracted from figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
20	20	Ashasha, V.M., et al.	1976	A	5-272	V6	Same as above except $\rho_{273.2}/\rho_0$ = 220 and T_c = 5.52 K.
21*	21	Alekseevskii, N.E., Mitin, A.V., and Matveeva, N.M.	1975	+	300		99.9 V; resistance measured using electronic amplifier with x-y recorder.
22	22 23 24	Cezairliyan, A., Righini, F., and McClure, J.L. Beckett, C.W.	1974 1974	T	293-2100		99.9 V; polycrystalline; from Materials Research Corp.; 120 ppm C, 20 ppm Fe, 60 ppm Nb, 10 ppm N, 15 ppm O, 15 ppm P, 50 ppm Si, 70 ppm Ta, 10 ppm Ti, 30 ppm W, 15 ppm Zr, other total less than 50 ppm; tube made from rod by electro-erosion, 6.3 mm diameter (outside), 76.26 mm long; density 6.1 g cm^{-3}; heat treated by pulse heating ~30 pulses to 1900 K; 0.5% estimated total error in measurement; experimental vacuum ~10^{-5} torr.
23*	25	Kumagai, K. and Ohtsuka, T.	1974	A	300		99.95 V from Material Research Corp. (V-P grade); method is electron beam furnace at pressures below 10^{-5} torr to outgas sample; T_c = 5.20 K; $\rho_{300}/\rho_{4.2}$ = 20.0
24	26	Prekul, A.F., Rassokhin, V.A., and Volkenshtein, N.V.	1974	A	5-267		No details are given; data extracted from figure.
25*	27	Lang, E. and Bressers, J.	1975	A	77,293	V811	Single crystals of [491] orientation; <10 ppm O_2, <5 ppm of other interstitials and substitutionals; prepared by electron beam melting under UHV conditions, annealed at 1373 K; ρ_{293}/ρ_{77} = 8.59; ideal resistivity ratio 0.116; results of oxygen doping of V crystals indicated a linear increase of resistivity with increasing O_2 content.
26	28	Neimark, B.E., Belyakova, P.E., Brodskii, B.R., Voronin, L.K., Korytina, S.F., and Merkul'ev, A.N.	1973	+	293-1773	VEL2	99.82 V, 0.05 Al, 0.02 Ni, 0.01 Fe, 0.024 C, 0.003 Si, 0.07 O_2; specimen of V fused by electron beam in vacuum from pressed powder; annealed at 900°C in vacuum of 10^{-5} mm Hg and at 1540°C of 10^{-5} mm Hg; resistivity in the range 20-1100°C measured by Jaeger-Disselhorst method and in the range 900-1400°C by Bode method; agreement between these two measurements is ±15% within maximum error of measurements; resistivity value at 293 K increased from 21.3 x 10^{-8} Ω m to 27.3 x 10^{-8} Ω m after heating the specimen to 1100°C; data extracted from smooth tabulated values.
27	29	Chernoplekov, N.A., Panova, G.Kh., Samoilov, B.N., and Shikov, A.A.	1973		5-1032		Pure V (no purity or source mentioned); sample rod 60 mm long with cross section 0.7 x 0.7 mm; values extracted from smooth values from small figure.
28*	30	Arutyunov, A.V., Makarenko, I.N., and Filippov, L.P.	1972		1000-1900		99.72 V, 0.13 Al, 0.09 Si, 0.05 Fe, 0.04 C, 0.055 O, 0.001 H, and 0.01 N; annealed in vacuum at 1600 K for 2 hr; sample 12 mm diameter and 90 mm length; the data reported here appeared to be same as in data set 29.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
29	31	Filippov, L.P. and Yurchak, R.P.	1971	A	1000-1900		99.72 V, 0.13 Al, 0.09 Si, 0.05 Fe, 0.005 O, 0.04 C, 0.01 Ni; polycrystalline; solid and hollow rod; 90 mm length and 12 mm diameter; data extracted from smooth tabulated values; error is 2%.
30	32	Peletskii, V.E., Druzhinin, V.P., and Sobol, Ya.G.	1971	A	293-1800		99.94 V, <0.001 Al, <0.001 Ni, ~0.001 Fe, ~0.046 O_2, ~0.01 N, ~0.001 H; polycrystalline; density 6.099 g cm^{-3}; specimen machined from a rod produced by electron beam melting in vacuum; specimen dimensions 10 mm diameter x 60 mm length; measurements in vacuum of 10^{-6} torr; measurements error 1.8-2.0%; data extracted from smooth tabulated values.
31	33	L'vov, S.N., Mal'ko, P.I., and Nemchenko, V.F.	1971		341-1381		99.9 V.
32	34	Voronin, L.K., Merkul'ev, A.N., and Neimark, B.E.	1970	A	283-1548	VEL2	99.82 V, 0.01 Fe, 0.02 Ni, 0.05 Al, 0.003 Si, 0.07 O_2, 0.001 N_2, <0.001 H, 0.024 C; electron beam melting of pressed powder; annealed at 1173 K; 1 x 10^{-5} mm Hg for 1 hr before measurements; sample size 150 mm x 6 mm diameter; measurements made by Jaeger-Diesselhorst method.
33	34	Voronin, L.K., et al.	1970	A	1591-1727	VEL2	Similar to the above except sample size 70 mm x 2 mm diameter; measurements made at 2 x 10^{-6} mm Hg by Bode method.
34	35	Hensler, D.H., Ross, A.R., and Fuls, E.N.	1970	A	293		Film deposited on sapphire substrate by sputtering from V cathode; substrate held at 673 K during sputtering and for 30 minutes post deposition annealing in vacuum and cooled slowly over several hours; thickness of film 1970 Å; temperature of measurements not reported but assumed to be 293 K.
35	35	Hensler, D.H., et al.	1970	A	293		Film deposited on sapphire substrate by sputtering from V cathode in oxygen 10^{-6} torr; thickness of film 1950 Å; other specifications are same as above.
36	36	Buebner, U.	1969		11-1090		Pure V, 0.08 O, 0.046 N, and 0.044 C; fused by electron beam; sample 80 mm long and 5 mm diameter; data extracted from figure.
37	37	Westlake, D.G. and Alfred, L.C.R.	1968	A	6-350		No details are given.
38	38	Westlake, D.G.	1967	A	5-338		Crystals of electrolytic vanadium from U.S. Bureau of Mines; 230 ppm metallic impurities, 20 ppm C, 100 ppm N, 290 ppm O; crystals electron-beam melted into ingot, rolled to 0.64 mm strips, 60 mm long x 4.2 mm wide cut from sheet, and both rolled surfaces were ground on wet 600-grit SiC paper to produce specimen 0.4 mm thick; specimens were wrapped in Mo foil, vacuum encapsulated in quartz, annealed 4 hr at 1273 K; annealed further in dynamic vacuum 2 x 10^{-6} torr for 30 minutes at 1073 K for dehydrogenation; data extracted from figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
39	39	Wertheimer, M.R. and Gilchrist, J.G.	1967	R	4.2	V1	Specimen from Imphy Kulhmann; 0.3% total impurity; 87% cold drawn.
40	39	Wertheimer, M.R. and Gilchrist, J.G.	1967	R	4.2	V2	Same as above except 97% cold drawn.
41	40	Amitin, E.B., Kovalevskaya, Yu.A., and Kovdrya, Yu.Z.	1967		16-299	Sample 1	99.63 V; polycrystalline; 13.1 x 3.7 x 0.8 mm plate prepared by cutting with corundum disk under emulsion layer subjected to 10^6 atm pressure at 293 K to suppress possible porosity; sample annealed in 10^{-6} mm Hg at 1123 K for 5 hr; density 6.2 g cm^{-3}; ρ_{273}/ρ_0 = 11.5; data obtained from ρ_T/ρ_{273} from figure and ρ_{273} = 24.1 x 10^{-8} Ω m reported by authors.
42	40	Amitin, E.B., et al.	1967		131-277	Sample 2	Sample supplied by Metal Physics Institute of Academy of Sciences of the USSR; ρ_{273}/ρ_0 = 15; data obtained from ρ_T/ρ_{273} from figure and ρ_{273} = 23.6 x 10^{-8} Ω m from Mathiessen's rule.
43	41	Van Gurp, G.J.	1967	R	5.1		99.9 V, 0.05 Si, 0.03 Fe, 0.04 Ti, 0.1 O, 0.06 N; specimen from A. C. Mackay Ltd.; in the form of sheet that was zone melted and cold rolled to 30 μ thickness; resistance measured by Kiethly D.C. Amplifier amplifying voltage output of sample due to varying magnetic fields; $\rho_{298}/\rho_{4.2}$ = 10.
44	41	Van Gurp, G.J.	1967	R	5.2		Same as above except annealed at 10^{-10} torr at 1600°C; $\rho_{298}/\rho_{4.2}$ = 15.
45*	42	Brushinina, J.P., Vladimirskaya, T.M., and Fraktovnikova, A.A.	1966	A	293		0.01-0.05 C, 0.03-0.05 O_2, 0.008-0.01 N_2, 0.2-0.22 Si, 0.27-0.65 Fe, 0.03-0.16 Al; 22 mm x 0.42 mm diameter rod forged from ingots at 1173-1323 K; specimen heated in He atmosphere prior to forging; samples annealed at 1273 K for 30 minutes; measurements in vacuum; measurement temperature not reported, however assumed to be 293 K.
46*	42	Brushinina, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
47*	42	Brushinina, J.P., et al.	1966	A	293		Same as above except diameter 0.96 mm; annealed specimen.
48*	42	Brushinina, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
49*	42	Brushinina, J.P., et al.	1966	A	293		Same as above except diameter 1.33 mm; annealed specimen.
50*	42	Brushinina, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
51*	43 44	Hörz, G., Gebhardt, E., and Dürrschnabel, W. Hörz, G.	1965 1966	K	273-1762		0.06 O_2, 0.01 H_2, 0.04 N_2; fused by electron beam; 0.5 mm diameter wire 16 cm long; annealed at 1500°C for 15 minutes at 1.5 x 10^{-6} torr.

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
52	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V(JM)	99.63 V; ingot from Johnson Matthey Co.; specimen cut to about 10 x 1 x 1 mm; degreased in alcohol; electrolytically polished in dilute H_2SO_4, rinsed, annealed at 1073 K for 5 hr in vacuum at 10^{-6} mm Hg, cooled and process repeated again; this was done to remove strains; accurate to ~1%; error due to irregular cross sectional area.
53	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V(BMI)	99.92 V; specimen from Battelle Memorial Institute; other specifications same as above.
54	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V1(USBM)	99.85 V; specimen from U.S. Bureau of Mines; other specifications same as above.
55*	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V2(USBM)	Similar to the above.
56	46	Burger, J. and Taylor, M.A.	1961	A	224-246		99.9 V from Battelle Memorial Institute, Columbus, OH; 0.005 C, 0.001 Si, 0.001 Cr, 0.04 Fe, 0.005 Al, 0.001 Cu, 0.001 H, 0.008 N, 0.0020 O; ρ_{300} = 23 ± 1 x 10^{-8} Ω m; data extracted from figure.
57	47	Bron, J.A. and Wayman, C.M.	1960	A	126-282		99.7 V, Ca reduced; annealed at 950°C; degassed at 1500°C; 0.025 in. diameter, 8 cm long; heating cycle; no indication of sudden discontinuity but deviation from linearity at 200 K; data extracted from figure.
58	47	Bron, J.A. and Wayman, C.M.	1960	A	140-288		Same as above except cooling cycle; data extracted from figure.
59	48 49	White, G.K. and Wood, S.B.	1959	A	15-390	V4	99.9 V obtained from Electrometallurgical Co.; specimen diameter 3.55 mm; annealed in vacuum at 1573 K; residual resistivity ρ_0 = 4.83 x 10^{-8} Ω m.
60*	50	Samsonov, G.V.	1957	V	295		Unspecified sample of V; thermal coefficient of electrical resistivity +0.28%/degree.
61	51	Wruk, D. and Wert, C.	1955	+	93	V1	Polycrystalline; 0.14 C, 0.12 O_2, 0.11 N_2; bcc structure; foil 0.2 cm wide, 0.008 cm thick, and 4 cm long; IR drop method.
62	51	Wruk, D. and Wert, C.	1955	+	93	V2	Same as above.
63*	52	Potter, H.H.	1941	A	273		Irregular pellets; specimen dimensions of 0.6 mm square and 6 mm in length.
64	53	Goutron, G.J., Zablocki, J.E., Hsiang, T.Y., Weinstock, H., and Schmidt, F.A.	1981	C	3.92-298.0		Sample prepared using electrotransport technique; annealing time 800 hr, cross section was reduced to 0.85 mm square from cylinder 1.6 cm long and 2 mm diam; this was done to remedy too low signal to noise ratio; ρ_{300}/ρ_0 = 1970 and $\rho_{300}/\rho_{4.2}$ = 1770, ρ_0 = 0.01 x 10^{-8} Ω m; superconducting transition temperature, T_c = 5.46 ± 0.02 K which was suppressed by 0.6T field produced by superconducting solenoid;

*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
64 (cont.)	33	Gautreau, G.J., et al.	1981	C	3.92–298.0		additionally electron-electron scattering (ρ_{ee} = 1.6 ± 0.2) x 10^{-13} Ω m K^{-2}, electron-phonon interband scattering ρ_{ed} = (2.6 ± 0.3) x 10^{-14} Ω m K^{5}, and electron-phonon intraband scattering ρ_{es} = (7.3 ± 1.1) x 10^{-18} Ω m K^{-5}.
65	34	Tsai, C.L., Fagaly, R.L., Weinstock, H., and Schmidt, F.A.	1981	C	4.5–298.1	Sample I	Sample purified using electrotransport technique; RRR = 1760; ρ_0 = 0.0109 x 10^{-8} Ω m; superconducting transition temperature 5.43 ± 0.03 K; data extracted from figure.
66	34	Tsai, C.L., et al.	1981	C	4.4–90.5	Sample II	Similar to above except less pure and ρ_0 = 0.261 x 10^{-8} Ω m; superconducting transition temperature 5.37 K; data extracted from figure.
67	35	Taylor, R.E. and Groot, H.	1981	K	298.9–745.0		Sample (RRR ~ 400) received from Dr. J. Cook of National Research Council, Canada; density 6.095 g cm^{-3}.
68	36	L'vov, S.N. and Nemchenko, V.F.	1965	A	292–1470		99.98 V, iodide vanadium; measurement in vacuum furnace 2 x 10^{-6} to 8 x 10^{-5} mm Hg; data extracted from figure.
69*	57	Paletskii, V.E.	1978	+	200–2100		Recommended values for pure V; values based on 1968-IPTS and corrected for thermal expansion; confidence interval of the values varied from -2.8% near room temperature to 1.6–2.0% in the region 1800–2000 K.

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V

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

T	ρ
DATA SET 1	
2175	134.9
2200	135.1
2300	136.7
2400	137.3
2500	138.4
2600	139.6
2700	140.8
2800	142.1
3000	144.8
3200	147.6
3400	150.6
3600	153.9
3800	157.2
4000	160.8
DATA SET 2	
1800	101.7
1950	108.7
2100	115.7
2190(s)	119.9
2190(ℓ)	135.2
2250	136.0
2400	138.2
2550	140.6
2700	143.2
2850	146.0
3000	149.0
3150	152.3
3300	155.8
3450	159.5
3600	163.5
3750	167.7
3900	172.2
4050	176.9
4200	181.9
DATA SET 3*	
4.2	1.75
293	27.8
DATA SET 4	
300	23.9
DATA SET 4 (cont.)	
500	36.4
700	48.2
900	59.35
1100	70.1
1300	80.3
1500	90.1
1700	99.2
1900	107.9
DATA SET 5	
300	24.22
500	38.3
700	50.7
900	61.7
1100	71.5
1300	80.2
1500	88.2
1700	96.0
1900	103.8
2000	107.7
DATA SET 6	
11.4	0.69
25.1	0.69
38.9	1.04
52.6	1.74
57.1	1.98
66.2	2.67
73.1	3.37
75.3	3.83
82.2	4.18
86.7	4.76
95.8	5.45
100.4	6.15
107.2	6.85
114.0	7.66
120.8	8.58
130.0	9.05
136.8	9.98
139.0	10.7
143.6	11.1
148.1	11.2
152.7	12.2
DATA SET 6 (cont.)	
157.2	12.8
161.8	13.4
168.6	14.1
170.9	14.7
177.7	15.2
184.5	15.9
182.2	16.2
191.3	16.6
191.4	17.0
200.4	17.7
209.6	18.4
214.1	18.9
220.9	19.7
227.8	20.4
236.9	21.2
243.7	21.2
248.2	22.2
252.8	23.1
259.6	23.4
268.7	24.3
275.6	25.2
282.4	25.8
291.5	26.8
300.6	27.7
DATA SET 7	
20.5	0.69
25.1	0.81
34.3	0.81
45.7	1.40
59.4	2.09
70.8	2.90
75.3	3.60
79.9	4.06
84.5	4.53
86.7	4.53
91.3	5.11
98.1	5.80
102.7	6.50
109.5	7.19
118.6	8.00
123.1	8.93
130.0	9.40
132.2	9.63
DATA SET 7 (cont.)	
136.8	10.3
141.3	10.8
145.9	11.4
150.4	11.9
155.0	12.6
159.5	13.3
164.0	13.5
175.4	14.9
180.0	15.5
184.5	16.2
191.4	16.3
193.6	17.4
202.7	18.11
214.1	19.4
225.5	20.1
230.0	20.9
239.1	21.6
252.8	22.5
252.8	22.8
261.9	24.0
268.7	24.7
277.8	25.5
286.9	26.2
296.0	27.1
300.6	27.4
DATA SET 8	
95.8	3.9
101.2	4.4
112.5	5.4
116.2	5.8
132.4	7.2
141.0	8.1
177.1	11.2
179.8	11.4
188.9	12.2
193.8	12.7
203.5	13.6
229.3	16.1
237.4	16.9
257.3	19.5
263.2	19.4
271.9	20.4
276.2	20.7
288.5	21.8
DATA SET 9	
76.9	2.3
82.3	2.7
97.4	4.0
103.3	4.5
108.7	5.1
117.3	5.9
126.5	6.7
134.5	7.4
149.6	8.8
156.1	9.4
174.4	11.0
184.6	11.9
195.9	13.0
199.2	13.2
211.0	14.2
213.2	14.4
223.4	15.4
230.4	15.9
246.0	17.6
248.7	17.8
251.4	18.2
257.9	18.7
260.5	18.9
262.7	19.2
270.2	20.0
273.5	20.2
277.2	20.6
287.5	21.3
290.7	21.6
296.1	22.0
DATA SET 10	
78	2.49
84	2.90
86	3.05
91	3.54
113	5.49
124	6.59
136	7.60
157	9.56
164	10.16
205	13.78
208	14.08
215	14.72
DATA SET 10 (cont.)	
218	14.87
225	15.51
228	15.77
239	16.60
242	16.79
246	17.13
254	17.73
257	17.99
262	18.40
268	18.82
269	19.01
279	20.76
283	20.02
DATA SET 11	
81	2.60
100	4.26
130	6.96
154	9.19
170	10.62
191	12.35
199	12.91
215	14.34
218	14.57
229	15.39
247	16.79
250	17.12
260	17.82
275	18.97
283	19.61
295	20.55
DATA SET 12	
5.4	0.012
15.4	0.021
17.5	0.026
19.3	0.032
22.0	0.040
23.4	0.052
26.6	0.076
31.2	0.136
33.3	0.187
40.3	0.294

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	ρ
DATA SET 12 (cont.)	
44.4	0.432
55.6	0.796
76.5	2.16
81.6	2.53
87.0	3.06
92.8	3.48
98.9	3.84
105	4.51
112	5.29
120	6.02
136	6.85
145	8.05
155	8.86
DATA SET 13	
5.8	0.51
6.6	0.51
7.3	0.52
8.1	0.52
9.2	0.52
10	0.52
11	0.52
12	0.52
13	0.52
14	0.53
17	0.54
18	0.54
22	0.57
49	1.14
54	1.33
57	1.51
62	1.80
66	2.10
83	3.30
96	4.51
109	5.72
125	7.18
148	9.27
182	12.1
242	17.1
245	17.2
273	19.5
DATA SET 14	
5.5	0.226

T	ρ
DATA SET 14 (cont.)	
5.9	0.228
6.2	0.228
7.0	0.228
7.5	0.228
8.1	0.230
8.5	0.230
9.2	0.230
10.0	0.232
10.9	0.234
11.9	0.236
12.9	0.236
14.1	0.239
15.8	0.247
17.8	0.250
19.1	0.259
20.9	0.269
22.8	0.280
24.9	0.296
27.9	0.322
30.4	0.354
33.8	0.407
36.2	0.460
39.4	0.533
48.3	0.778
54.3	1.06
61.7	1.51
73.2	2.24
79.9	2.72
86.2	3.27
88.1	3.38
93.3	3.82
107.0	5.03
111.1	5.36
126.7	6.78
139.3	7.84
140.8	7.99
166.8	10.2
177.5	11.2
186.8	12.9
196.5	12.8
203.5	13.3
213.9	14.2
231.4	15.6
265.9	18.2

T	ρ
DATA SET 15	
5.8	0.022
6.7	0.024
8.0	0.024
9.3	0.024
10.9	0.028
36.2	0.236
39.2	0.309
43.1	0.431
48.7	0.596
54.7	0.853
58.4	1.07
77.7	2.39
82.1	2.61
90.3	3.38
100.7	4.30
113.3	5.50
130.8	7.08
154.5	9.27
170.9	10.7
191.3	12.5
217.6	14.6
250.7	17.1
283.4	19.7
DATA SET 16	
5.4	0.009
5.8	0.009
6.3	0.013
7.9	0.013
8.0	0.013
9.3	0.013
11.2	0.017
12.1	0.018
13.6	0.020
15.2	0.022
16.2	0.026
17.9	0.029
20.1	0.039
22.9	0.055
25.8	0.077
29.7	0.119
35.9	0.225
39.2	0.298
42.7	0.417
62.1	1.33
66.6	1.62

T	ρ
DATA SET 16 (cont.)	
80.3	2.57
99.9	4.22
112.2	5.39
130.4	6.97
150.4	8.83
161.9	9.89
176.4	11.1
184.2	11.8
197.9	12.9
215.4	14.3
229.5	15.5
247.3	16.8
260.3	17.9
261.8	18.0
274.8	19.0
DATA SET 17	
5.49	0.0133
5.95	0.0136
7.11	0.0140
10.10	0.0162
13.08	0.0200
15.99	0.0255
19.56	0.0365
22.00	0.0473
24.34	0.0605
26.03	0.0734
28.38	0.0933
29.99	0.112
31.56	0.131
33.35	0.154
35.98	0.198
37.00	0.226
38.01	0.244
39.23	0.272
40.09	0.294
41.92	0.346
42.88	0.370
44.00	0.400
44.90	0.431
46.12	0.471
46.92	0.503
47.58	0.529
60.15	1.33
64.20	1.40
67.40	1.58

T	ρ
DATA SET 17 (cont.)	
69.60	1.72
77.30	2.31
300	19.6
DATA SET 18	
6	0.861
7	0.873
10	0.879
13	0.879
14	0.879
17	0.845
20	0.902
22	0.914
25	0.932
27	0.949
28	0.967
30	0.991
32	1.020
35	1.068
37	1.115
38	1.162
39	1.186
42	1.245
43	1.293
45	1.346
46	1.388
46	1.405
47	1.441
DATA SET 19	
5.5	0.00959
5.5	0.00589
5.7	0.0163
6.1	0.0163
6.5	0.0168
7.2	0.0168
7.9	0.0174
9.1	0.0182
10.7	0.0193
11.9	0.0206
12.9	0.0223
13.8	0.0239
14.7	0.0255
15.8	0.0311
17.9	0.0412

T	ρ
DATA SET 19 (cont.)	
20.2	0.0561
22.9	0.0844
27.2	0.143
31.4	0.223
35.7	0.340
38.6	0.438
45.6	0.708
54.1	1.13
59.8	1.48
65.4	1.90
69.7	2.18
73.9	2.39
75.3	2.74
82.4	3.23
86.6	3.65
92.3	4.14
95.1	4.56
100.7	5.06
106.4	5.48
113.4	6.11
117.7	6.53
120.5	6.95
129.0	7.58
133.2	8.07
144.5	8.63
150.1	9.61
158.6	10.2
165.7	10.9
174.1	11.8
181.2	12.4
185.4	12.8
192.5	13.5
198.1	13.7
206.6	14.6
215.1	15.3
227.8	16.2
233.4	16.8
240.5	17.3
246.1	17.9
256.0	18.7
270.2	19.6
DATA SET 20	
5.65	0.083
5.67	0.088
5.68	0.091

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

DATA SET 20 (cont.)

T	ρ
6.72	0.091
7.76	0.092
8.94	0.093
9.69	0.093
10.7	0.094
11.8	0.096
12.4	0.096
13.6	0.098
14.8	0.10
15.8	0.10
16.7	0.10
17.8	0.10
18.8	0.11
19.9	0.11
20.6	0.13
21.0	0.13
25.5	0.20
28.4	0.27
34.3	0.44
43.1	0.81
48.9	1.1
57.8	1.3
60.7	1.6
73.9	2.5
81.1	3.2
86.9	3.7
98.6	4.7
101.5	5.1
107.3	5.6
116.1	6.4
121.9	6.8
124.8	7.2
130.7	7.6
136.5	8.2
140.8	8.7
146.6	9.2
152.5	9.8
159.7	10.3
165.6	10.9
172.9	11.5
178.7	11.9
183.1	12.4
187.4	13.0
196.2	13.5
203.4	14.3
212.2	14.9
218.0	15.4

DATA SET 20 (cont.)

T	ρ
220.9	15.7
223.8	16.0
234.1	16.6
239.9	17.2
244.3	17.5
251.6	18.0
254.5	18.4
272.0	19.6

DATA SET 21*

T	ρ
300	23

DATA SET 22

T	ρ
293	21.72
1500	87.66
1550	89.81
1600	91.93
1650	94.03
1700	95.83
1750	97.86
1800	99.87
1850	101.69
1900	103.56
1950	105.40
2000	107.20
2050	109.01
2100	110.70

DATA SET 23*

T	ρ
300	22.6

DATA SET 24

T	ρ
5.2	1.07
7.2	1.28
10.3	1.28
15.5	1.28
17.6	1.27
21.7	1.27
24.8	1.27
29.9	1.26
34.1	1.69
39.2	1.68
44.4	1.89

DATA SET 24 (cont.)

T	ρ
49.5	2.10
54.7	2.53
62.9	3.38
69.2	4.02
76.4	4.87
96.0	7.00
105.4	8.50
115.7	9.78
125.0	10.8
140.5	12.8
157.0	14.9
172.5	16.6
183.9	18.3
195.3	19.6
208.7	21.3
228.4	23.6
243.9	25.1
251.1	26.0
257.3	26.8
267.7	27.9

DATA SET 25*

T	ρ
77	2.283
293.2	19.62

DATA SET 26

T	ρ
293	21.4
373	27.0
573	40.2
773	52.1
973	62.8
1173	72.6
1373	81.8
1573	90.8
1773	99.8

DATA SET 27

T	ρ
5.2	0.92
65	2.44
129	8.47
229	17.14
337	25.4
409	30.0
530	39.0

DATA SET 27 (cont.)

T	ρ
659	46.9
789	54.5
875	60.5
975	65.4
1032	69.2

DATA SET 28*

T	ρ
1000	68.0
1100	73.4
1200	78.5
1300	83.5
1400	88.2
1500	92.8
1700	101.5
1800	105.6
1900	109.5

DATA SET 29

T	ρ
1000	68.0
1100	73.4
1200	78.5
1300	83.5
1400	88.2
1500	92.8
1600	97.5
1700	101.5
1800	105.6
1900	109.5

DATA SET 30

T	ρ
293	21.02
1200	73.3
1300	78.8
1400	83.7
1500	88.5
1600	93.0
1700	97.4
1800	101.6

DATA SET 31

T	ρ
341.2	25.1
386.9	26.2
417.2	28.4

DATA SET 31 (cont.)

T	ρ
485.6	30.6
591.8	33.9
614.6	33.9
720.9	38.3
796.8	40.5
880.4	43.8
933.4	44.9
1047.4	49.2
1130.9	52.5
1206.8	54.7
1267.8	56.9
1381.2	61.3

DATA SET 32

T	ρ
283	20.9
301	22.5
320	23.5
337	25.0
359	26.4
381	27.7
402	28.9
419	30.4
442	31.7
465	33.5
482	34.4
500	35.8
520	36.9
541	38.4
565	40.0
590	41.3
600	42.1
617	43.2
651	45.1
684	46.9
730	50.2
770	52.1
796	53.9
822	55.3
849	56.9
876	58.3
907	59.9
932	61.1
962	62.7
999	64.6
1051	67.6
1087	69.5

DATA SET 32 (cont.)

T	ρ
1177	74.0
1218	75.6
1275	78.1
1317	80.1
1455	87.1
1507	89.2
1548	90.8

DATA SET 33

T	ρ
1591	92.3
1626	94.5
1690	97.1
1727	98.4

DATA SET 34

T	ρ
293	75.5

DATA SET 35

T	ρ
293	241

DATA SET 36

T	ρ
11	3.1
77	5.9
273	22.0
293	23.8
410	31.4
468	35.1
575	41.4
680	46.6
773	53.5
779	52.2
875	57.7
925	61.4
979	62.1
1090	68.7

DATA SET 37

T	ρ
6.5	0.81
22	0.85
56	1.89
59	2.05
115.6	6.85

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

DATA SET 37 (cont.)

T	ρ
134.4	8.56
169.8	11.72
191.0	13.55
198.3	14.21
213.5	15.48
233.6	17.16
242.6	17.89
260.8	19.33
270.0	20.08
291.0	21.69
309.6	23.10
333.6	24.90
349.6	26.13

DATA SET 38

T	ρ
5	0.82
20	0.82
40	1.3
60	2.1
80	3.4
121	7.4
161	11.2
201	14.5
241	17.8
280	20.9
300	22.5
320	23.8
338	25.3

DATA SET 39

T	ρ
4.2	3.9

DATA SET 40

T	ρ
4.2	4.4

DATA SET 41

T	ρ
16	1.9
21	2.1
26	2.1
38	2.4
47	2.7
56	3.2
68	4.1

DATA SET 41 (cont.)

T	ρ
77	4.9
89	6.1
100	7.1
108	8.1
116	8.7
123	9.5
126	9.8
134	10.7
141	11.6
144	11.8
151	12.5
155	12.8
160	13.3
163	13.7
168	14.1
171	14.4
175	14.8
179	15.2
183	15.5
186	15.9
192	16.5
199	17.2
206	17.8
212	18.4
220	19.1
226	19.6
229	20.0
234	20.4
239	20.8
244	21.3
249	21.7
256	22.3
262	22.9
265	23.2
275	24.0
287	25.0
299	26.0

DATA SET 42

T	ρ
131	10.1
144	11.7
155	12.7
161	13.3
168	13.9
173	14.3
178	14.9

DATA SET 42 (cont.)

T	ρ
184	15.3
187	15.8
190	16.0
195	16.4
198	16.6
201	16.8
204	17.2
207	17.4
210	17.8
214	18.1
216	18.2
222	18.8
223	19.0
225	19.1
227	19.4
231	19.6
234	19.9
236	20.3
245	21.1
249	21.5
253	21.8
258	22.2
261	22.6
266	23.0
269	23.3
277	24.1

DATA SET 43

T	ρ
5.07	2.6

DATA SET 44

T	ρ
5.15	1.7

DATA SET 45*

T	ρ
293	23.6

DATA SET 46*

T	ρ
293	28.9

DATA SET 47*

T	ρ
293	23.8

DATA SET 48*

T	ρ
293	28.0

DATA SET 49*

T	ρ
293	24.6

DATA SET 50*

T	ρ
293	28.6

DATA SET 51*

T	ρ
273	20.5
283	22.0
1187	73.7
1302	80.0
1317	80.0
1378	83.3
1433	85.8
1437	86.2
1446	86.2
1493	88.7
1537	91.2
1542	90.6
1584	93.2
1632	95.4
1643	95.2
1683	97.1
1724	98.8
1752	101.0
1762	100.8

DATA SET 52

T	ρ
20	4.0
77	6.48
273	22.67

DATA SET 53

T	ρ
20	0.74
77	3.18
273	19.54

DATA SET 54

T	ρ
20	1.56
77	3.98
273	20.34

DATA SET 55*

T	ρ
20	1.54
77	3.96
273	20.39

DATA SET 56

T	ρ
224	18.4
225	18.5
226	18.7
228	18.8
229	19.0
230	19.1
232	19.2
233	19.4
234	19.5
236	19.7
237	19.8
238	19.9
239	20.0
241	20.1
242	20.2
243	20.3
244	20.5
245	20.5
246	20.6
246	20.6

DATA SET 57

T	ρ
126	13.8
132	14.5
138	14.9
145	15.6
151	16.2
161	17.0
167	17.5
174	18.2
182	18.9
192	19.7
203	20.5
213	21.3

DATA SET 57 (cont.)

T	ρ
220	22.0
232	22.9
242	23.6
253	24.5
261	25.0
282	26.7

DATA SET 58

T	ρ
140	15.1
148	15.9
156	16.7
165	17.3
170	17.8
178	18.5
187	19.3
190	19.4
197	20.0
207	20.9
216	21.6
224	22.3
227	22.5
238	23.2
247	24.1
256	24.8
267	25.5
273	25.9
288	27.1

DATA SET 59

T	ρ
15	4.84
20	4.87
30	4.97
40	5.21
50	5.57
75	7.13
100	9.08
150	13.5
200	17.5
250	21.5
273	23.1
295	24.7
390	31.4

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	ρ
DATA SET 60*	
293	26.0
DATA SET 61	
93	17.96
DATA SET 62	
93	16.49
DATA SET 63*	
273	18.2
DATA SET 64	
3.923	0.0105
4.145	0.0106
4.175	0.0105
4.216	0.0106
4.218	0.0105
4.270	0.0106
4.289	0.0106
4.456	0.0106
4.516	0.0107
4.577	0.0107
4.793	0.0107
4.849	0.0108
4.873	0.0107
4.993	0.0108
4.998	0.0108
5.004	0.0108
5.185	0.0109
5.282	0.0109
5.294	0.0109
5.347	0.0109
5.414	0.0110
5.487	0.0110
5.618	0.0111
5.680	0.0110
5.705	0.0110
5.802	0.0111
6.172	0.0112
6.190	0.0113
6.269	0.0114
6.275	0.0113
6.456	0.0114
DATA SET 64 (cont.)	
6.348	0.0114
6.518	0.0114
6.758	0.0116
6.842	0.0117
6.963	0.0117
7.066	0.0118
7.140	0.0119
7.185	0.0118
7.203	0.0118
7.229	0.0119
7.582	0.0121
7.607	0.0122
7.723	0.0122
7.925	0.0122
7.946	0.0124
7.994	0.0124
8.208	0.0125
8.331	0.0127
8.433	0.0128
8.628	0.0129
8.768	0.0131
8.776	0.0130
9.241	0.0135
9.318	0.0136
9.441	0.0137
9.728	0.0139
9.393	0.0137
10.066	0.0144
10.156	0.0144
10.338	0.0147
10.371	0.0146
10.571	0.0150
10.792	0.0153
10.828	0.0153
10.863	0.0153
11.295	0.0160
11.585	0.0164
11.833	0.0167
11.885	0.0167
12.085	0.0170
12.216	0.0172
12.448	0.0176
12.725	0.0181
12.903	0.0184
12.957	0.0185
13.160	0.0189
13.416	0.0194
DATA SET 64 (cont.)	
13.494	0.0195
13.678	0.0200
14.306	0.0212
14.395	0.0215
14.550	0.0218
14.874	0.0225
15.033	0.0228
15.188	0.0231
15.207	0.0233
15.702	0.0247
16.273	0.0260
16.350	0.0264
16.406	0.0263
16.664	0.0273
17.032	0.0282
17.155	0.0285
17.158	0.0286
17.309	0.0291
17.989	0.0315
18.128	0.0319
18.647	0.0338
18.541	0.0332
18.577	0.0335
19.782	0.0381
20.133	0.0396
20.320	0.0406
30.024	0.115
39.950	0.298
52.012	0.635
60.523	1.10
73.034	1.91
79.067	2.24
91.667	3.40
100.03	4.13
189.09	11.50
298.0	19.90
DATA SET 65	
4.49	0.0116
4.86	0.0116
5.47	0.0116
5.69	0.0121
6.41	0.0125
7.22	0.0125
7.81	0.0128
8.13	0.0136
DATA SET 65 (cont.)	
8.97	0.0135
8.98	0.0147
9.72	0.0147
9.91	0.0159
10.73	0.0158
11.17	0.0178
11.62	0.0171
12.58	0.0185
12.58	0.0197
13.62	0.0197
14.17	0.0213
14.45	0.0230
14.46	0.0249
15.34	0.0239
15.65	0.0254
16.94	0.0285
16.95	0.0309
17.63	0.0328
19.08	0.0315
19.09	0.0347
19.86	0.0376
20.67	0.0406
21.51	0.0440
22.38	0.0466
22.83	0.0494
23.30	0.0567
23.77	0.0602
23.77	0.0614
25.73	0.0664
25.74	0.0718
26.25	0.0746
27.32	0.0823
27.87	0.0891
28.44	0.0982
30.18	0.102
30.20	0.119
31.43	0.134
32.70	0.139
33.36	0.160
34.72	0.173
35.42	0.187
36.87	0.215
37.61	0.237
39.15	0.267
40.74	0.306
41.57	0.338
42.41	0.365
DATA SET 65 (cont.)	
44.13	0.395
53.89	0.755
57.22	0.936
81.93	2.49
85.28	2.92
204.4	11.2
264.5	15.4
298.1	19.1
DATA SET 66	
4.36	0.263
4.45	0.248
5.21	0.258
5.64	0.279
5.98	0.268
6.35	0.279
6.87	0.279
7.74	0.268
8.37	0.273
8.71	0.273
10.21	0.268
11.05	0.273
12.44	0.273
13.20	0.278
14.57	0.284
14.87	0.289
15.77	0.278
17.41	0.289
18.85	0.289
19.61	0.295
22.52	0.313
24.86	0.319
26.39	0.345
28.56	0.366
30.31	0.388
33.47	0.411
33.47	0.428
35.52	0.453
36.24	0.481
38.46	0.520
40.02	0.563
41.64	0.585
44.20	0.645
46.92	0.712
48.83	0.816
57.27	1.18
DATA SET 66 (cont.)	
83.60	2.75
90.52	3.22
DATA SET 67	
298.9	21.80
330.0	23.32
347.1	24.10
362.0	25.56
368.4	25.57
415.3	28.82
419.5	29.12
439.5	30.91
484.5	33.48
487.2	33.65
573.8	39.12
580.9	39.55
745.0	49.19
DATA SET 68	
292	26.4
407	31.5
434	35.2
536	40.0
637	46.8
759	53.7
834	53.8
847	57.1
1023	69.0
1037	64.1
1051	69.1
1260	79.4
1342	81.2
1470	88.0
DATA SET 69*	
200	12.70
300	20.11
400	27.13
500	33.81
600	40.15
700	46.19
800	51.96
900	57.47
1000	62.76

*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	ρ
DATA SET 69 (cont.)*	
1100	67.84
1200	72.76
1300	77.52
1400	82.16
1500	86.70
1600	91.17
1700	95.59
1800	99.99
1900	104.84
2000	108.84
2100	113.35

*Not shown in figure.

3.2. Zirconium

There are 43 data sets available from 23 references [33,49,123-144] for the electrical resistivity of zirconium specimens with purity 99.8-99.99%. The temperature range covered by these data sets is from 1.7 to 2127 K. The information on specimen characterization and measurement condition for each of the data sets is given in table 5. The data sets are tabulated in table 6 and shown partially in figure 4.

From liquid-helium temperature to room temperature the only set of data for high-purity zirconium is that of White and Woods [49] (data set 27) on a specimen with RRR = 168. Above 100 K these data appear to be trustworthy, but their reliability below 100 K is not sufficient to permit reliable interpretation in terms of any low-temperature conduction mechanism. However, White and Woods pointed out a $T^{4.5}$ dependence of the temperature-dependent resistivity above 13 K as indicating rather strong electron-phonon s-s interband scattering. This and earlier work of Kemp et al. [141] (data set 31) on a specimen with RRR = 25 was supported fifteen years later by Volkenshtein et al. [131] (data set 12) using a specimen with RRR = 34. Furthermore, the data of Volkenshtein et al. [131] suggested the existence of a T^2 term below 13 K which was undoubtedly *related to electron-electron* scattering. T^3 dependence indicative of s-d electron-phonon scattering was neither explored nor reported by these or other low-temperature studies [131-137,140]. Careful low-temperature studies on a very pure specimen is required to detect such dependence.

The recommended values below 293 K are based on the data of White and Woods [49] (data set 27), who studied the purest specimen ($\rho_o = 0.25 \times 10^{-8}$ Ω m).

In the temperature range up to $T_{\alpha-\beta}$ = 1137 K there appears to be fairly good agreement (±10%) among the data of Bykov et al. [127] (data set 7), L'vov et al. [33] (data set 13), Peletskii et al. [133] (data set 15), Powell and Tye [138] (data sets 22-24), Bing et al. [143] (data set 37), and of Cook et al. [144] (data set 38). The recommended values up to 800 K are based on the data of Peletskii et al. [133] (data set 15). In the temperature range from 800 to 1137 K the recommendations were guided by the data of Cezairliyan and Righini [123,124] (data set 2), Peletskii et al. [133] (data set 15) and those of Kiselev [139] (data sets 25,26). Data of Cezairliyan and Righini [123-125] (data sets 2-5) and those of Peletskii et al. [133] (data sets 15,16) were used to generate the recommended values for β-Zr between 1137 to 2127 K. The value of 141.3 x 10^{-8} Ω m for liquid Zr at 212 Γ follows the only available data of Martynyuk and Tsapkov [129] (data set 10).

The recommended values of the electrical resistivity given in table 4 and shown in figures 5 and 6 are for zirconium of 99.95% purity or higher, but those below 100 K are applicable specifically to samples with ρ_0 = 0.250 x 10^{-8} Ω m. The table gives both values uncorrected and corrected for thermal expansion, while figures 5 and 6 show only the uncorrected values along with experimental data which were used to generate these values. Thermal expansion values needed to carry out thermal expansion correction were taken from ref. [190]. The uncertainty in the recommended values is estimated to be within ±2% below 1137 K, ±3% up to the melting point, and ±4% for the liquid value at 2127 K.

Zirconium is a transition element, and its low-temperature electrical resistivity depends upon the type as well as on the concentration of impurities. The low-temperature electrical resistivity of low purity zirconium is rather difficult to estimate. Data so far available does not permit one to establish the upper limit of ρ_0 for which Matthiessen's rule can be applied to estimate electrical resistivity.

The data available in the literature for the temperature dependence of a bulk sample is reviewed in this report. However, additional information on the electrical resistivity is available in refs. [50,52,82,90,145-183]. Attention is directed to refs. [163,179,184-186] for data on irradiated samples, refs. [106,111,187,188] for data on films, ref. [188] for data on doped zirconium and ref. [189] for data on pressure dependence of resistivity.

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

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
1	0.250	0.250	700	104.2	104.5
4	0.250	0.250	800	114.9	115.3
7	0.250	0.250	900	123.1	123.6
10	0.253	0.253	1000	128.8	129.4
15	0.283	0.283	1100	132.0	132.8
20	0.357	0.357	1137	132.6(α)	133.4(α)
25	0.491	0.490	1137	110.8(β)	111.3(β)
30	0.712	0.711	1150	111.1	111.7
40	1.443	1.441	1200	112.2	112.8
50	2.495	2.492	1300	114.5	115.2
60	3.75	3.75	1400	116.5	117.3
70	5.15	5.14	1500	118.6	119.6
80	6.64	6.63	1600	120.4	121.5
90	8.18	8.17	1700	122.3	123.5
100	9.79	9.78	1800	124.0	125.4
150	17.85	17.84	1900	125.8	127.4
200	26.35	26.33	2000	127.5	129.3
250	34.9	34.9	2100	129.1	131.0
273	38.8	38.8	2127	129.5(s)	131.4(s)
293	42.1	42.1	2127		141.3(ℓ)
300	43.3	43.3			
350	51.9	51.9			
400	60.3	60.3			
500	76.5	76.6			
600	91.5	91.7			

[a]The values are for polycrystalline zirconium of purity 99.95% or higher, but those below 200 K are applicable specifically to zirconium having a residual resistivity of 0.250 x 10^{-8} Ω m. the columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. Solid line separating tabular values indicates solid to liquid state transformation, while dotted line indicates solid phase transition.

α: cph; β: bcc.

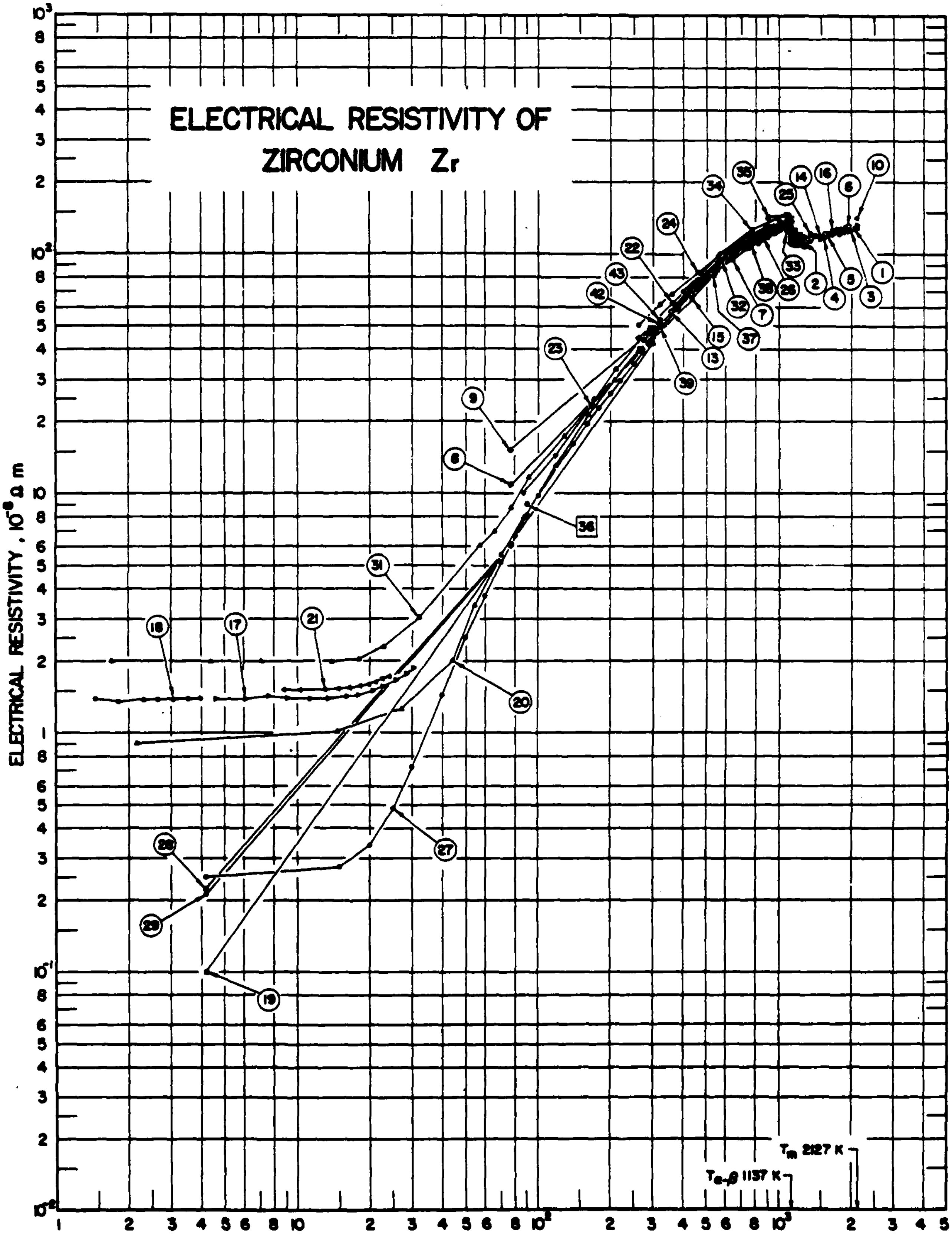

ELECTRICAL RESISTIVITY OF
ZIRCONIUM Zr
ELECTRICAL RESISTIVITY, 10⁻⁸ Ω m
TEMPERATURE, K
T_m 2127 K
$T_{\alpha-\beta}$ 1137 K
CINDAS

FIGURE 4

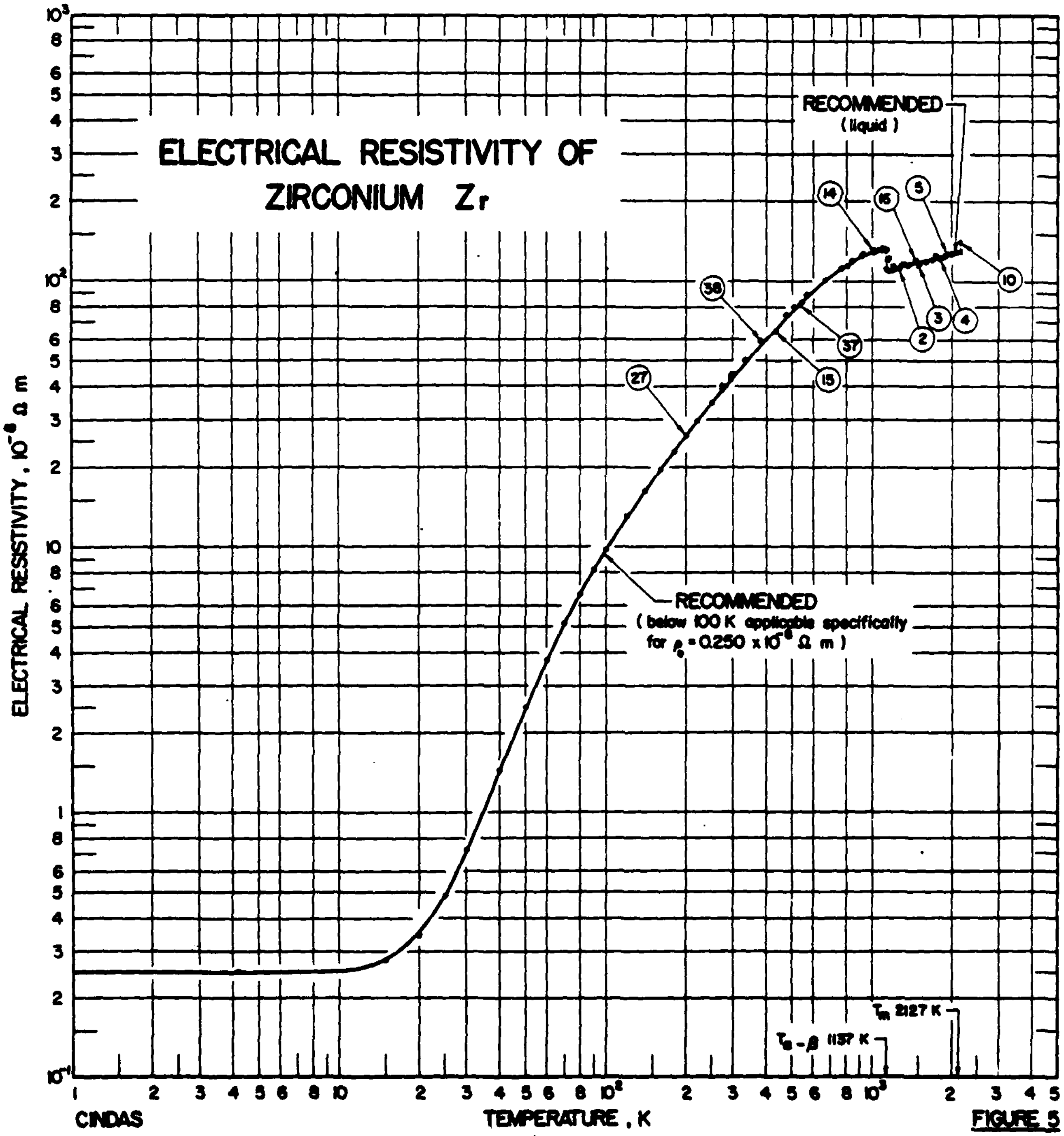

ELECTRICAL RESISTIVITY OF
ZIRCONIUM Zr
RECOMMENDED
(liquid)
RECOMMENDED
(below 100 K applicable specifically
for ρ₀ = 0.250 x 10⁻⁸ Ω m)
14
16
5
10
38
37
15
27
2
3
4
Tm 2127 K
Tα-β 1137 K
ELECTRICAL RESISTIVITY, 10⁻⁸ Ω m
TEMPERATURE, K
CINDAS

FIGURE 5

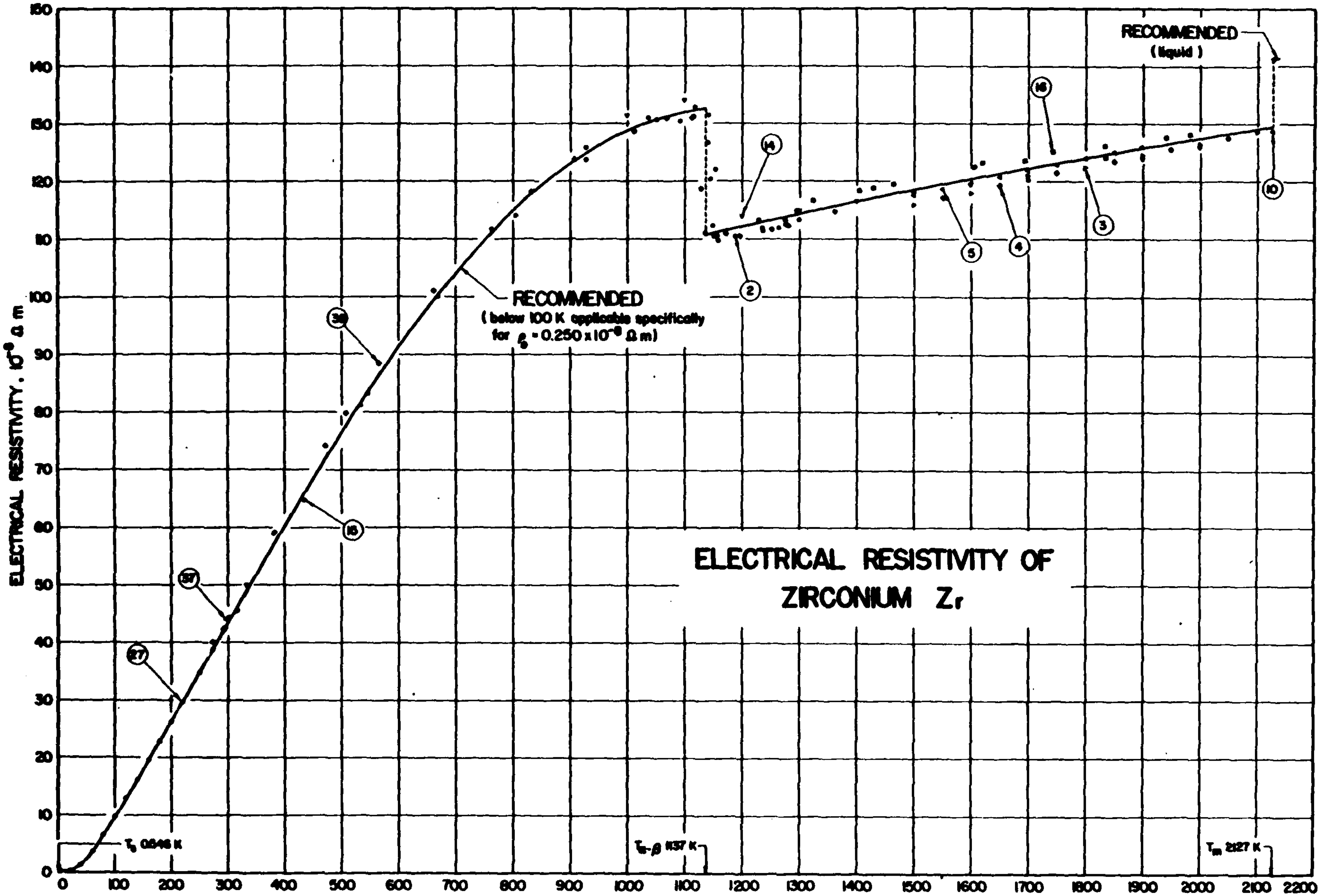

ELECTRICAL RESISTIVITY OF
ZIRCONIUM Zr
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 100 K applicable specifically for ρ_0 = 0.250 x 10^{-8} Ω m)
RECOMMENDED
(liquid)
T_c 0.546 K
$T_{\alpha-\beta}$ 1137 K
T_m 2127 K
CINDAS

FIGURE 6

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	123	Cezairliyan, A. and Righini, F.	1974	T	2097-2128	Specimen II	99.98 Zr, 125 ppm O, 40 ppm Hf, 30 ppm Fe, 6 ppm C, 3.3 ppm H, 3 ppm Al, 2.1 ppm N, 1.5 ppm Ni, 1.5 ppm Si, 1.0 ppm Ti, less than 6 ppm other elements; specimen 76.2 mm long, 6.3 mm O.D., 0.25 mm thickness; small rectangular hole (0.5 x 1 mm) fabricated in the wall at middle of the specimen; approximated blackbody conditions; T_m = 2128 K; data extracted from figure; estimated inaccuracy in the measurement is ±3% (imprecision ±0.05%).
2	123, 124	Cezairliyan, A. and Righini, F.	1974	T	1092-1265	Specimen 3	99.98 Zr, 125 ppm O, 40 ppm Hf, 30 ppm Fe, 6 ppm C, 3.3 ppm H, 3 ppm Al, 2.1 ppm N, 1.5 ppm Ni, 1.5 ppm Si, and 1.0 ppm Ti; specimen tube fabricated from rods by removing center portion using an electro-erosion technique; nominal dimensions of specimen were 76.2 mm long, 6.3 mm O.D., and wall thickness 0.5 mm; outer surfaces of the specimen were polished to reduce heat loss due to thermal radiation; α-β transformation temperature 1147 ± 10 K; data extracted from figure; estimated inaccuracy of the measurement is ±2%.
3	125	Cezairliyan, A. and Righini, F.	1974	T	1500-2100	Specimen 1	99.98 Zr, polycrystalline from Materials Research Corp., 6 ppm C, 3.3 ppm H, 125 ppm O, 2.1 ppm N, 3.0 ppm Al, 30 ppm Fe, 40 ppm Hf, 1.5 ppm Ni, 1.5 ppm Si, 1.0 ppm Ti; nominal dimensions are 76.2 mm length, 25.4 mm (effective length), 6.3 mm O.D., 0.5 mm wall thickness, and 0.5 x 1 mm rectangular blackbody hold; inaccuracy in measured value is ±2%.
4	125	Cezairliyan, A. and Righini, F.	1974	T	1500-2100	Specimen 2	Similar to the above except different specimen.
5	125	Cezairliyan, A. and Righini, F.	1974	T	1500-1900	Specimen 3	Similar to the above except different specimen.
6	126	Mörs, G., Hemmel, M., and Kambach, H.	1974	B	1173-1973	β-Zr	Drawn Zr wire of 0.5 mm diameter of Marzgrade (produced by electron beam zone melting) from Materials Research Corp., Orangeburg, NY; <10 ppm O, 40 ppm C, 15 ppm Al, 50 ppm Fe, 100 ppm Hf, and <75 ppm other; surface impurities were removed by polishing mechanically and electrolytically; wire was heated by D.C. for 30 minutes at 1650 C in high vacuum of 5 x 10^{-7} torr for recrystallization; data extracted from figure.
7	127	Bykov, V.N., Rudnev, I.I., and Solov'ev, V.A.	1972	A	288-1282	Iodide Zirconium	0.056 Fe, <0.001 V, 0.0065 Mn, 0.0074 Mo, 0.012 Cu, 0.0041 Cr, 0.0041 Ni; measurements in 10^{-5} mm Hg vacuum; data extracted from figure.
8	128	Bychkov, Yu.F., Likhanin, Yu, N., and Mal'tsev, V.A.	1973	A	77,295	α-Zr	99.8 Zr (iodide); remelted in arc furnace.
9	128	Bychkov, Yu.F., et al.	1973	A	77,295	ω-Zr	Similar to above except subjected to hydrostatic pressure of 100 Kbars at room temperature to get metastable ω-Zr phase.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
10	129	Martynyuk, M.M. and Tsaphov, V.I.	1973	T	2127		99.76 Zr; values are reported for solid and for liquid at melting point; accuracy of measurements ±4%.
11*	130	Beale, C.	1973		4.2,293		Polycrystalline zirconium 180-250 Å thick vacuum deposited films onto very smooth, optically polished, square-shaped alkalizine borosilicate substrates at room temp.; prior to the film condensation, the substrates had been degassed by baking in vacuo at 350°C for 6 hr and cleaned afterwards by both ultrasonic agitation at 50 kHz and ionic bombardment using a glow discharge of 5 KV; zirconium was evaporated from a copper liquid-nitrogen-cooled crucible employing a 270° beam deflection electron gun under pressure of the order of 10^{-10} torr; both the film thickness and the condensation rate were accurately controlled with a piezoelectric quartz crystal monitor maintained at the substrate temperature; the films were annealed for 3 hr at 300°C to remove frozen-in structural defects and subsequently cooled down to 4.2 K (tetragonal crystal structure characteristic of the β phase as shown by electron-diffraction analysis) using liquid helium as the refrigerant; the specimens were always kept under vacuum at the condensation pressure; to minimize the deformation arising from differential thermal expansion between metal and glass, both heating and cooling rates were lower than 1°C/sec; after the annealing process, measurements were taken; to avoid oxidation or adsorption of some other gases, all the experiments were performed in the vacuum conditions utilized for film preparation.
12*	131	Volkenshtein, N.V., Novoselov, V.A., and Startsev, V.E.	1971	A	0.6-71.0		99.9 Zr, polycrystal; tabulated values calculated from ρ_T/ρ_{273} values reported graphically assuming 38.8 $10^{-8}\Omega$ m for ρ_{273}; $\rho_{300}/\rho_{4.2}$ = 34.
13	33	L'vov, S.N., Mal'ko, P.I., and Nemchenko, V.F.	1971		309-1331		99.9 Zr; sample was prepared from bars (rods) obtained by iodide process; $\rho_{300}/\rho_{4.2}$ = 26; data extracted from figure.
14	132	Zhorov, G.A.	1970		1000-2000	MRTU 95-67-66	99.56 Zr, 0.23 Nb, 0.02 Fe, 0.04 Hf, 0.005 Cu, 0.01 Ni, 0.03 Ti, 0.005 Mo, 0.005 Al, 0.01 Sn, iodide zirconium; density 6.59 g cm^{-3}; rod specimen 58.6 mm length and 9.84 mm diameter; measurements in 5 x 10^{-6} mm Hg; greatest relative error in determination 2.8%; average values of several heating and cooling experiments.
15	133	Peletskii, V.E., Druzhinin, V.P., and Sobol, Ya.G.	1970	A	302-1363		99.9 Zr, 0.01 C, 0.005 N_2, 0.01 O_2, 0.009 Fe, 0.03 Nb, 0.002 Al, 0.005 Cu, 0.003 Ti, 0.005 Si; compact samples obtained by electron-beam melting in vacuum; specimen dimensions are cylinder 60 mm long and 9 mm diameter; sample heated in resistance furnace with a molybdenum heater; measurements in 10^{-5} mm Hg; experimental error ±1.5 to 2%.
16	133	Peletskii, V.E., et al.	1970	A	1229-1983		Same as above except sample heated by electron bombardment.

*Not shown in figure.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
17	134	Elliott, R.O. and Hill, H.H.	1970		4.6-30.6		105 ppm O_2, 8 ppm N_2, 33 ppm C, and 27 ppm Fe; heating cycle; data extracted from figure.
18	134	Elliott, R.O. and Hill, H.H.	1970		1.5-4.0		Same as above except cooling cycle; data extracted from figure.
19	135	Betterton, J.O. and Easton, D.S.	1968		4.2,300		No details given.
20	136	Clinard, F.W., Jr. and Kempter, C.P.	1968	A	2.1-295		Commercial specimen 95-175 ppm O_2, 40 ppm N_2, <40 ppm H_2, <1000 ppm Hf, <1000 ppm Nb, 200 ppm Fe, 100 ppm Ni, <100 ppm each Ti, V, Zn, Mo, and Pb; $\rho_4 = 0.8 \times 10^{-8}\ \Omega$ m; annealed condition; cylindrical specimen 0.25 in. diameter and 1 in. long; data extracted from figure; average of heating and cooling.
21	137	Cape, J.A. and Nako, R.R.	1965		8.8-24.1		Specimen cut from a button arc-cast in an inert atmosphere; finished sample was then measured as machined without annealing; specimen was 1 x 0.1 x 0.01 in.; estimated absolute values of the resistivities are accurate to approximately ±2%; values calculated from graphically reported values of $\rho_T - \rho_{4.2}$ and tabulated values of $1.522 \times 10^{-8}\ \Omega$ m for $\rho_{4.2}$.
22	138	Powell, R.W. and Tye, R.P.	1961	A	264-1196	No. 715	Graphite-melted Zr, 0.018 Fe, 0.043 C, 0.007 Al, 0.007 Nb, 0.0075 N_2, 0.1-0.6 O_2; extruded; average of heating and cooling; data extracted from figure.
23	138	Powell, R.W. and Tye, R.P.	1961	A	87-1230	Van Arkel Zr	Van Arkel zirconium, 0.012 Fe, 0.016 C, 0.0025 N_2, and 0.3-0.6 O_2; cold swaged; average of heating and cooling; data extracted from figure.
24	138	Powell, R.W. and Tye, R.P.	1961	A	264-886	No. 050	Arc melted low-carbon Zr; 0.045 Fe, 0.01 C, 0.008 N_2, 0.11 O_2; extruded; average of heating and cooling; data extracted from figure.
25	139	Kiselev, N.A.	1961		738-1353		Specimen prepared from iodide metal; average of heating thermocouple and optical pyrometer measurements; $T_{\alpha-\beta} = 1138$ K; data extracted from figure.
26	139	Kiselev, N.A.	1961		855-1356		Same as above; average values of cooling thermocouple and optical pyrometer measurements; data extracted from figure.
27	49	White, G.K. and Woods, S.B.	1959	A	4.2-295	Zr3	99.95 Zr, 132 ppm Hf, 79 ppm C, 24 ppm Fe, 11 ppm Ni, 21-50 ppm O_2, 3-50 ppm N_2, <100 ppm Zn, 2-7 ppm each Ca, Cr, Mo, Si, H_2, and <10 ppm other elements; arc cast annealed 4 hr at 1100°C, swaged at room temp.; annealed for 15 min. at 1000°C and finally for 15 min. at 800°C in a vacuum 1-2 x 10^{-6} mm Hg; values calculated from tabulated values of ideal resistivity (ρ_i), $\rho_{295} = 42.4 \times 10^{-8}\ \Omega$ m and $\rho_0/\rho_{295} = 5.96 \times 10^{-3}$.
28	140	Berlincourt, T.G.	1958		4.2-298	Zr1	Crystal bar from Westinghouse, 0.001 Ca, 0.016 Cu, 0.075 Fe, 0.002 H, 0.001 N, 0.016 O_2, 0.013 Si; $\rho_{273}/\rho_{4.2} = 170$.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
29	140	Berlincourt, T.G.	1958		4.2-300	Zr2	Same as above except $\rho_{273}/\rho_{4.2}$ = 179.
30*	140	Berlincourt, T.G.	1958		4.2-300	Zr2'	Same as above except $\rho_{273}/\rho_{4.2}$ = 176.
31	141	Kemp, W.R.G., Klemens, P.G., and White, G.K.	1956	A	1.7-293	JM5000	99.99 Zr from Messrs. Johnson, Matthey and Co., Ltd.; 3 mm diam. rod; annealed for 5 hr. at 950°C in vacuo; data extracted from figure; ρ_0 = 1.98 x $10^{-8}\Omega$ m.
32	142	Adenstedt, H.K.	1952	B	276-1213	Zr660	99.9 Zr, 0.1 Hf, 0.02 Fe, <0.005 Ti, <0.005 Al, <0.005 Si, hafnium free from Foote Mineral Co.; samples prepared from as-deposited iodide crystal bars; cold-swaged condition; Rockwell hardness A-36; first heating run; values obtained by multiplying 43.2 x $10^{-8}\Omega$ m (resistivity at 0°C) by resistivity ratio as function of temperature reported graphically.
33	142	Adenstedt, H.K.	1952	B	924-1299	Zr660	Same as above except second heating run.
34	142	Adenstedt, H.K.	1952	B	404-1189	Zr681	Similar to the above except as deposited iodide crystal bar, 0.036 Hf, <0.005 Fe, <0.005 Ti, <0.005 Al, <0.005 Si; Rockwell hardness A-22; first heating run.
35	142	Adenstedt, H.K.	1952	B	902-1127	Zr681	Same as above except first cooling run.
36	142	Adenstedt, H.K.	1952	B	90	Zr757	Similar to the above except 0.032 Hf, 0.044 O_2, 0.005 N_2, 0.005 Si, and <0.003 each Al, Si, and Ti; cold-swaged, machined and annealed at 973 K from iodide crystal bar; 0.22 in. diam. and 10 in. length; ρ_0 = 39.6 x $10^{-8}\Omega$ m.
37	143	Bing, G., Fink, F.W., and Thompson, H.B.	1951		273-533	Westinghouse Ingot D-216	Pure Zr, 0.04 Hf, 0.04 Fe, 0.02 Ni, 0.007 Ti, 0.003 Sn, 0.001 Al; arc-melted ingot of WBM crystal bar produced from lot CB-37; ingot forged at 1650 to a 1 in. square bar; measurements made at Battelle.
38	144	Cook, L.A., Castleman, L.S., and Johnson, W.E.	1950	B	277-1277	Low-Hf	Foote crystal bar, 0.04 Hf, 0.08 Si, 0.04 Fe, 0.004 Al, 0.005 each Cu, Ca, 0.001 each Ti, Mn, Pb, Mo, 0.01 Mg, 0.003 each Ni, Cr; machined to smooth cylinder 0.358 in. diam.; annealed above recrystallization temp.; data extracted from figure.
39	144	Cook, C.L., et al.	1950	B	303-323	Sample A	Same as above except machined to 0.306 in. diam. cylinder.
40*	144	Cook, C.L., et al.	1950	B	302-315	Sample B	Same as above except swaged from 0.306 in. diam. to 0.125 in. diam. (84% reduction in area).
41*	144	Cook, C.L., et al.	1950	B	302-322	Sample C	Same as sample B except annealed for 1 hr. at 500°C.
42	144	Cook, C.L., et al.	1950	B	303-320	Sample D	Same as sample C, except swaged from 0.125 in. diam. to 0.048 in. diam. (85% reduction in area).
43	144	Cook, C.L., et al.	1950	B	301-321	Sample E	Same as sample D except annealed for 1 hr. at 500°C.

*Not shown in figure.

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr

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

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
DATA SET 1		DATA SET 2 (cont.)		DATA SET 4 (cont.)		DATA SET 7 (cont.)		DATA SET 10		DATA SET 13 (cont.)	
2097.0	128.52	1145	120.5	1850	123.61	556.6	85.3	2127	128.8	468	75.00
2099.1	128.56	1146	127.5	1900	124.60	576.1	88.4	2127	141.3	526	82.14
2101.6	128.61	1146	117.4	1950	125.59	595.5	91.5			577	91.07
2104.3	128.68	1147	119.1	2000	126.58	618.8	93.0	DATA SET 11[a]		621	98.21
2106.6	128.74	1148	118.0	2050	127.62	646.0	94.6			708	107.1
2108.5	128.81	1148	111.0	2100	128.59	661.5	97.6	4.2	0.14	766	114.3
2111.0	128.85	1149	128.8			677.0	99.2	293	0.10	823	121.4
2113.5	128.89	1149	112.4	DATA SET 5		700.3	101.5			852	125.0
2115.9	128.94	1150	125.9			723.6	104.6	DATA SET 12[a]		903	128.6
2118.5	129.01	1151	131.5	1500	117.65	746.9	106.1			976	132.1
2120.3	129.08	1151	124.0	1550	118.62	762.5	109.2	0.58	1.27	997	135.7
2121.5	129.13	1153	110.2	1600	119.75	785.8	110.0	0.95	1.28	1020	137.5
2123.2	129.19	1158	109.8	1650	120.87	805.2	111.5	1.9	1.28	1034	135.7
2124.3	129.23	1171	110.0	1700	122.00	820.7	113.0	3.0	1.28	1063	133.9
2125.1	129.27	1188	110.5	1750	123.06	847.9	114.6	4.2	1.28	1092	133.9
2126.4	129.30	1203	110.9	1800	124.10	863.4	116.1	6.0	1.28	1106	128.6
2126.6	129.29	1219	111.2	1850	125.13	882.8	117.6	8.9	1.29	1135	117.9
2126.7	130.80	1237	111.5	1900	126.14	894.5	117.6	9.6	1.29	1143	114.3
2126.9	130.91	1248	111.7			902.3	118.4	10.4	1.29	1172	114.3
2127.1	129.71	1260	111.9	DATA SET 6		910.0	120.0	11.7	1.30	1208	112.5
2127.2	131.06	1265	112.0			933.3	121.5	14.2	1.31	1230	114.3
2127.4	129.51			1173	111.9	960.5	122.3	14.7	1.31	1280	114.3
2127.4	130.14	DATA SET 3		1272	114.6	979.9	124.6	16.4	1.33	1331	116.1
2127.5	129.62			1370	116.7	991.6	123.8	17.2	1.34		
2127.5	129.88	1500	115.97	1472	119.4	1007.1	126.1	19.7	1.38	DATA SET 14	
2127.6	130.23	1550	117.06	1570	121.3	1034.3	125.3	24.3	1.54		
2127.7	130.80	1600	118.14	1668	124.0	1046.0	126.1	28.3	1.75	1000	131.5
2127.7	131.05	1650	119.25	1770	126.0	1069.3	126.9	32.9	2.05	1100	134
2128.1	130.35	1700	120.36	1868	128.8	1084.8	127.6	36.8	2.40	1200	114
		1750	121.41	1964	130.8	1115.9	128.4	41.4	2.84	1300	115
DATA SET 2		1800	122.50	1973	131.0	1135.3	127.6	43.4	3.08	1400	116.5
		1850	123.60			1146.9	125.3	46.7	3.30	1500	118
1092	130.5	1900	124.62	DATA SET 7		1166.4	109.2	50.7	3.78	1600	119.5
1097	130.9	1950	125.65			1181.9	110.0	52.0	4.06	1700	121
1103	131.3	2000	126.68	288.7	46.1	1185.8	109.2	53.9	4.24	1800	122.5
1111	131.1	2050	127.71	304.2	46.9	1189.7	107.6	55.3	4.42	1900	124
1117	131.3	2100	128.61	323.6	50.0	1282.9	107.6	63.2	5.27	2000	126
1126	131.5			370.2	58.4			71.0	6.21		
1139	125.0	DATA SET 4		389.6	60.0	DATA SET 8				DATA SET 15	
1141	131.7			405.2	60.7			DATA SET 13			
1141	126.9	1500	116.07	420.7	63.8	77	10.9			302.0	44.48
1141	123.0	1550	117.16	436.3	66.9	295	43.6	309	48.21	316.1	45.56
1141	112.0	1600	118.30	459.6	71.5			345	50.00	434.7	64.84
1142	113.1	1650	119.39	475.1	73.0	DATA SET 9		360	57.14	546.4	83.41
1143	118.6	1700	120.50	498.4	76.9			374	60.71	668.7	100.2
1144	129.9	1750	121.56	517.8	81.5	77	14.2	403	60.71	805.4	114.2
1144	114.7	1800	122.57	537.2	83.0	295	47.0	439	67.86	928.3	123.9

[a]Not shown in figure.

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

T	ρ
DATA SET 15 (cont.)	
928.1	126.0
1037	131.1
1051	130.7
1118	132.9
1154	122.2
1152	110.5
1236	112.0
1282	112.4
1300	113.5
1363	114.9
DATA SET 16	
1229	113.4
1275	113.4
1296	114.9
1324	116.7
1405	118.5
1430	118.9
1465	119.6
1606	122.6
1620	123.3
1694	123.7
1743	125.2
1835	124.2
1835	126.3
1941	127.8
1983	128.2
DATA SET 17	
4.6	1.39
4.9	1.40
6.1	1.39
7.6	1.43
9.1	1.40
10.4	1.40
11.4	1.39
13.6	1.40
16.2	1.42
18.0	1.45
20.7	1.50
22.8	1.57
25.9	1.67
28.6	1.77
30.6	1.88

T	ρ
DATA SET 18	
1.5	1.39
1.8	1.36
2.3	1.38
2.6	1.39
3.0	1.38
3.5	1.39
3.9	1.39
4.0	1.40
DATA SET 19	
4.2	0.1
300	42.3
DATA SET 20	
2.1	0.91
14.7	1.02
27.3	1.2
44.1	2.0
54.7	3.4
70.6	5.5
87.5	7.9
105	10.8
118	13.1
132	15.5
149	18.6
163	21.4
180	24.7
190	26.5
208	29.9
233	32.7
246	35.2
261	37.2
271	39.3
278	40.3
285	41.2
295	43.2
DATA SET 21	
8.8	1.52
10.2	1.52
13.0	1.52
14.0	1.52
14.9	1.53
15.8	1.53
16.6	1.54
18.3	1.57

T	ρ
DATA SET 21 (cont.)	
19.9	1.60
21.3	1.64
22.7	1.68
24.1	1.73
DATA SET 22	
264	44.7
364	62.2
461	78.0
524	86.3
564	92.1
621	99.2
664	104
709	109
764	115
812	119
863	123
912	128
957	131
1006	134
1057	135
1111	136
1131	136
1139	131
1142	127
1148	121
1150	116
1153	116
1162	115
1176	115
1196	116
DATA SET 23	
87	10.0
118	14.3
167	23.2
267	40.1
367	57.6
464	73.7
564	90.1
618	99.8
664	105
712	111
764	116
815	120
863	123
909	127

T	ρ
DATA SET 23 (cont.)	
957	130
1009	133
1060	136
1108	139
1145	142
1159	139
1179	126
1190	120
1205	121
1213	122
1230	121
DATA SET 24	
264	50.2
324	60.8
364	67.7
421	76.9
461	83.5
521	91.2
564	97.2
615	103
664	109
712	114
769	119
789	123
861	127
886	128
DATA SET 25	
738	111.3
770	113.9
867	121.7
927	126.1
949	127.4
971	128.7
1002	130.4
1031	131.1
1049	131.8
1068	131.8
1099	132.2
1102	132.2
1115	132.2
1121	129.9
1126	123.4
1132	118.7
1131	116.0
1131	115.2

T	ρ
DATA SET 25 (cont.)	
1138	114.6
1159	114.8
1175	115.2
1278	117.2
1297	117.9
1318	118.7
1334	119.8
1340	120.1
1353	122.0
DATA SET 26	
855	117.2
971	127.0
1043	133.1
1068	133.5
1096	133.5
1102	132.9
1108	129.9
1132	120.0
1138	118.9
1147	118.4
1172	118.0
1234	117.6
1278	117.2
1312	117.4
1331	118.1
1340	119.6
1356	122.2
DATA SET 27	
4.2	0.251
15	0.276
20	0.341
25	0.486
30	0.721
40	1.451
50	2.501
60	3.751
70	5.151
80	6.651
90	8.151
100	9.801
120	13.051
140	16.251
160	19.551
180	22.851
200	26.351

T	ρ
DATA SET 27 (cont.)	
220	29.651
250	34.851
273	38.851
295	42.651
DATA SET 28	
4.2	0.224
77	6.11
298.6	42.6
DATA SET 29	
4.2	0.213
77	6.08
300.1	42.6
DATA SET 30*	
4.2	0.216
77	6.08
300	42.6
DATA SET 31	
1.7	2.00
4.4	2.00
7.1	2.00
14	2.00
18	2.05
23	2.30
32	3.04
57	6.10
66	6.97
77	8.72
91	11.7
129	17.4
172	24.8
212	33.1
292	47.1
293	48.9
DATA SET 32	
276	43.6
461	76.2
580	94.0
689	108
915	130

*Not shown in figure.

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

T	ρ	T	ρ	T	ρ
DATA SET 32 (cont.)		DATA SET 37		DATA SET 41*	
1019	136	273	40.2	302.9	46.7
1137	117	298	44.1	306.2	47.3
1164	117	533	81.3	311.4	48.2
1213	118	DATA SET 38		317.0	49.4
DATA SET 33		277	39.9	322.4	50.4
924	130	293	42.4	DATA SET 42	
1028	133	334	50.1	303.1	47.8
1073	130	382	59.1	305.4	48.1
1085	126	471	74.2	309.8	49.0
1096	124	508	79.9	315.3	50.1
1110	120	563	88.5	319.7	50.8
1122	117	662	101.1	320.8	51.0
1152	115	763	111.7	DATA SET 43	
1176	115	832	118.2	301.1	49.0
1253	114	908	123.9	303.2	49.4
1299	116	1013	128.7	305.5	49.8
DATA SET 34		1069	131.1	310.4	50.6
404	69.2	1113	131.1	315.6	51.6
570	99.8	1129	118.8	321.6	52.8
779	127	1136	111.1		
931	139	1156	110.6		
993	142	1172	111.0		
1026	144	1197	110.6		
1050	144	1253	111.8		
1078	145	1277	112.6		
1107	145	DATA SET 39			
1127	131	303.5	45.9		
1142	122	304.4	46.2		
1159	121	306.0	46.5		
1189	122	307.4	46.6		
DATA SET 35		308.0	46.8		
982	141	309.3	47.1		
1088	145	310.8	47.2		
1098	138	313.8	47.8		
1114	126	323.0	49.6		
1127	124	DATA SET 40*			
DATA SET 36		302.1	46.5		
90	9.03	305.0	47.0		
		309.9	48.0		
		315.9	49.2		

*Not shown in figure.

4. ACKNOWLEDGMENTS

This work was supported by the Office of Standard Reference Data (OSRD) of the National Bureau of Standards (NBS), U.S. Department of Commerce. The extensive documentary activity essential to this work was supported by the Defense Logistics Agency (DLA) of the U.S. Department of Defense.

The authors wish to express their appreciation and gratitude to Dr. H. J. White, Jr. of the NBS Office of Standard Reference Data for his guidance, cooperation, and sympathetic understanding during the course of this work.

5. APPENDICES

5.1. Methods for the Measurement of Electrical Resistivity

At the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) of Purdue University, the experimental methods for the measurement of electrical resistivity have been classified into various categories according to a similar scheme used by CINDAS for the classification of methods for the measurement of thermal conductivity [191, pp. 13a-25a]. This classification scheme of CINDAS is presented below. Note that the letters in parentheses following the respective methods are the code letter used in the 'Method Used' column of the Table of Measurement Information for indicating the experimental methods used by the various authors.

Methods for the Measurement of Electrical Resistivity

A. Steady-State Methods

1. Voltmeter and ammeter direct reading method (V) [192, p. 159; 193, pp. 244-5]
2. Direct-current potentiometer method (A) [194, pp. 151-8]
   a. 4-probe potentiometer method
3. Direct-current bridge methods (B) [194, pp. 144-51]
   a. Kelvin double bridge method
   b. Mueller bridge method
   c. Wheatstone bridge method
4. Direct-heating method (K) [195,196]

B. Non-Steady-State Methods

1. Periodic current method
   a. Direct connection to sample
      (1) Alternating-current potentiometer method (C) [194, pp. 161-2]
   b. No connection to sample
      (1) Rotating magnetic field method (R) [197]
2. Non-periodic current method
   a. Direct connection to sample
      (1) Transient (subsecond) method (T) [198]

5.2. Conversion Factors for the Units of Electrical Resistivity

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

Conversion Factors for the Units of Electrical Resistivity

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

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

6. REFERENCES

1. Chi, T.C., 'Electrical Resistivity of Alkali Elements,' J. Phys. Chem. Ref. Data, 8(2), 339-438 (1979).

2. Chi, T.C., 'Electrical Resistivity of Alkaline Earth Elements,' J. Phys. Chem. Ref. Data, 8(2), 439-97 (1979).

3. Matula, R.A., 'Electrical Resistivity of Copper, Gold, Palladium, and Silver,' J. Phys. Chem. Ref. Data, 8(4), 1147-298 (1979).

4. Ho, C.Y., Powell, R.W., and Liley, P.E., 'Thermal Conductivity of the Elements: A Comprehensive Review,' J. Phys. Chem. Ref. Data, Vol. 3, Suppl. 1, 796 pp. (1974).

5. Matthiessen, A., 'Electrical Resistivity of Alloys,' Ann. Physik, 110, 190-221 (1860).

6. Matthiessen, A. and Vogt, C., 'The Influence of Temperature on the Electrical Conductivity of Alloys,' Ann. Physik, 122, 19-78 (1864).

7. Bloch, F., 'On the Quantum Mechanics of Electrons in a Crystalline Lattice,' Z. Phys., 52, 555-600 (1928).

8. Bloch, F., 'The Electrical Resistance Law at Low Temperatures,' Z. Phys., 59, 208-14 (1930).

9. Seydel, U. and Fucke, W., 'Electrical Resistivity of Liquid Titanium, Vanadium, Molybdenum, and Tungsten,' J. Phys. F, 10(8), L203-6 (1980).

10. Gathers, G.R., Shaner, J.W., Hixson, R.S., and Young, D.A., 'Very High Temperature Thermophysical Properties of Solid and Liquid Vanadium and Iridium,' High Temp.-High Pressures, 11(6), 653-68 (1979).

11. Vedernikov, M.V., Dvunitkin, V.G., and Zhumagulov, A., 'Rules Governing the Behavior of the Electrical Resistivity and Thermoelectric Power of Systems of Binary Continuous Solid Solutions of Metals,' Fiz. Tverd. Tela, 20(11), 3302-5 (1978); Engl. transl.: Sov. Phys.-Solid State, 20(11), 1904-6 (1978).

12. Peletskii, V.E. Amasovich, E.S., Kostanovskii, A.V., Zaretskii, E.B., Sobol, Ya.G., and Shur, B.A., 'Thermal Conductivity of Vanadium,' Teplofiz. Vys. Temp., 15(6), 1202-7 (1977); Engl. transl.: High Temp., 15(6), 1028-33 (1977).

13. Pan, V.M., Prokhorov, V.G., Shevchenko, A.D., and Dovgopol, V.P., 'The Physical Properties of Vanadium in the Temperature Range 4.2-300 K,' Fiz. Nizk. Temp., 3(10), 1266-71 (1977); Engl. transl.: Sov. J. Low Temp. Phys., 3(10), 609-12 (1977).

14. Courtney, D.R., 'Thermal Conductivity of Hydrogen Doped High Purity Vanadium,' Iowa State Univ., M.S. Thesis, 40 pp. (1977).

15. Chakal'skii, B.K., Azhazha, V.M., Red'ko, N.A., and Shalyt, S.S., 'Thermal Conductivity of Vanadium at Low Temperatures,' Pisma Zh. Eksp. Teor. Fiz., 23(9), 513-15 (1976); Engl. transl.: JETP Lett., 23(9), 468-70 (1976).

16. Jung, W.D., 'Thermal Conductivity of High Purity Vanadium,' Ames Lab. Rept. IS-T-693, 110 pp. (1975).

17. Jung, W.D., 'The Thermal Conductivity of High Purity Vanadium,' Iowa State Univ. of Science and Technology, Ph.D. Theses, 109 pp. (1975). [Univ. Microfilm No. 76-1850]

18. Jung, W.D., Schmidt, F.A., and Danielson, G.C., 'Thermal Conductivity of High-Purity Vanadium,' Phys. Rev., 15B(2), 659-65 (1977).

19. Aleksandrov, B.N., Semenova, E.D., Petrova, O.I., Chernyi, B.P., and Azhazha, V.M., 'The Electrical Resistivity of Vanadium of Various Purities in the 4.2 to 47 K Temperature Range,' Fiz. Nizk. Temp., 1(3), 388-99 (1975).

20. Azhazha, V.M., Volkenshtein, N.V., Startsev, V.Ye., Finkel, V.A., Cherepanov, V.I., and Chernyi, B.P., 'Resistivity of High Purity Vanadium. Investigation of Critical Temperature and Anomalies in the Temperature Dependence,' Fiz. Met. Metalloved., 41(6), 1188-95 (1976); Engl. transl.: Phys. Met. Metallogr., 41(6), 54-60 (1976).

21. Alekseevskii, N.E., Mitin, A.V., and Matveeva, N.M., 'Investigation of the Superconducting Properties of Vanadium - Aluminum and Vanadium Tin Solid Solutions,' Zh. Eksp. Teor. Fiz., 69(6), 2124-31 (1975); Engl. transl.: Sov. Phys.-JETP, 42(6), 1080-3 (1976).

22. Cezairliyan, A., Righini, F., and McClure, J.L., 'Simultaneous Measurements of Heat Capacity, Electrical Resistivity and Hemispherical Total Emittance by a Pulse Heating Technique: Vanadium, 1500 to 2100 K,' National Bureau of Standards, Inst. for Materials Research, Rept. NBSIR-74-600, 30-46 (1974).

23. Cezairliyan, A., Righini, F., and McClure, J.L., 'Simultaneous Measurements of Heat Capacity, Electrical Resistivity, and Hemispherical Total Emittance by a Pulse Heating Technique. Vanadium, 1500 to 2100 K,' J. Res. Natl. Bur. Stand., 78A(2), 143-7 (1974).

24. Beckett, C.W., 'Thermodynamics of Chemical Species Important to Rocket Technology,' U.S. Air Force Rept. AFOSR-TR-75-0596, 200 pp. (1974). [AD A008 935]

25. Kumagai, K. and Ohtsuka, T., 'The Superconductivity of Alloys of a Transition Metal with Non-Transition Elements (and Normal State Properties),' J. Phys. Soc. Jpn., 37(2), 384-407 (1974).

26. Prekul, A.F., Rassokhin, V.A., and Volkenshtein, N.V., 'Effect of Spin Fluctuations on the Superconducting and Normal Properties of Alloys of Titanium Containing Vanadium, Niobium, or Tantalum,' Zh. Eksp. Teor. Fiz. 67(6), 2286-92 (1974); Engl. transl.: Sov. Phys.-JETP, 40(6), 1134-6, (1975.)

27. Lang, E. and Bressers, J., 'Effect of Oxygen Doping on the Electrical Resistivity of Vanadium,' Z. Metallkd., 66(10), 619-22 (1975).

28. Neimark, B.E., Belyakova, P.E., Brodskii, B.R., Voronin, L.K., Korytina, S.F., and Merkul'ev, A.N., 'Physical Properties of Vanadium,' Heat Transfer-Sov. Res., 5(2), 141-5 (1973).

29. Chernoplekov, N.A., Panova, G.Kh., Samoilov, B.N., and Shikov, A.A., 'Alteration of the Superconducting Properties of Vanadium by Introduction of Tantalum Impurity Atoms,' Zh. Eksp. Teor. Fiz., 64(1), 195-203 (1973); Engl. transl.: Sov. Phys.-JETP, 37(1), 102-6 (1973).

30. Arutyunov, A.V., Makarenko, I.N., and Filippov, L.P., 'Thermal Properties of Vanadium at High Temperatures,' Teplofiz. Svoistva Veshchestv Mater., 5, 105-8 (1972).

31. Filippov, L.P. and Yurchak, R.P., 'High Temperature Investigations of the Thermal Properties of Solids,' Inzh. Fiz. Zh., 21(3), 561-77 (1971); Engl. transl.: J. Eng. Phys., 21(3), 1209-20 (1971).

32. Peletskii, V.E., Druzhinin, V.P., and Sobol, Ya.G., 'Thermophysical Properties of Vanadium at High Temperatures,' High Temp.-High Pressures, 3(2), 153-9 (1971).

33. L'vov, S.N., Mal'ko, P.I., and Nemchenko, V.F., 'Electrical Conductivity and Thermal Conductivity of Group IV-VI Transition Metals in the 20-1200 C Range,' Metallofizika, 37, 22-9 (1971).

34. Voronin, L.K., Merkul'ev, A.N., and Neimark, B.E., 'Some Physical Properties of Vanadium,' High Temp., 8(4), 737-40 (1970).

35. Hensler, D.H., Ross, A.R., and Fuls, E.N., 'Reactively Sputtered Thin Films in the Vanadium-Oxygen System Using Triode Sputtering,' J. Electrochem. Soc., 116(6), 887-9 (1969).

36. Heubner, U., 'Thermal and Electrical Conductivity of Vanadium Alloys Between 20 and 650°,' J. Nucl. Mater., 32(1), 88-100 (1969).

37. Westlake, D.G. and Alfred, L.C.R., 'Determination of the Debye Characteristic Temperature of Vanadium from the Bloch-Grueneisen Relation,' J. Phys. Chem. Solids, 29(11), 1931-4 (1968).

38. Westlake, D.G., 'A Resistometric Study of Phase Equilibria at Low Temperatures in the Vanadium-Hydrogen System,' Trans. Met. Soc. AIME, 239, 1341-4 (1967).

39. Wertheimer, M.R. and Gilchrist, J.G., 'Flux Jumps in Type II Superconductors,' J. Phys. Chem. Solids, 28(12), 2509-24 (1967).

40. Amitin, E.B., Kovalevskaya, Yu.A., and Kovdrya, Yu.Z., 'Hall Effect and Electrical Resistivity of Vanadium at 20-300 K,' Sov. Phys.-Solid State, 9(3), 704-6 (1967).

41. Van Gurp, G.J., 'The Effect of Structure on the Superconducting Properties of Vanadium and Niobium Foils,' Philips Res. Rep., 22(1), 10-35 (1967).

42. Druzhinina, I.P., Vladimirskaya, T.M., and Fraktovnikova, A.A., 'Thermoelectric Properties of Vanadium,' Meas. Tech., 8, 1032-4 (1966).

43. Hörz, G., Gebhardt, E., and Durrschnabel, W., 'Emissivity and Electrical Resistivity of Vanadium, Vanadium Nitride and Vanadium Oxide Mixed Crystals,' Z. Metallkd., 56(8), Pt. 2, 554-60 (1965).

44. Hörz, G., 'Emissivity and Electrical Resistivity of Tantalum at High Temperatures,' Z. Metallkd., 57, 871-3 (1966).

45. Taylor, M.A. and Smith, C.H.L., 'The Electrical Resistivity of Vanadium and Vanadium-Chromium Solid Solutions,' Physica, 28(4), 453-60 (1962).

46. Burger, J.P. and Taylor, M.A., 'Anomalies in the Magnetic Susceptibility and Electrical Resistivity of Vanadium,' Phys. Rev. Lett., 6(4), 185-7 (1961).

47. Hren, J.A. and Wayman, C.M., 'Some Properties of Vanadium at Subatmospheric Temperatures,' Trans. Met. Soc. AIME, 218, 377-9 (1960).

48. White, G.K. and Woods, S.B., 'Low Temperature Resistivity of Transition Elements. Vanadium, Niobium, and Hafnium,' Can. J. Phys., 35(3), 892-900 (1957).

49. White, G.K. and Woods, S.B., 'Electrical and Thermal Resistivity of the Transition Elements at Low Temperatures,' Philos. Trans. R. Soc. London, A251, 273-302 (1959).

50. Samsonov, G.V., 'The Electrical Conductivity of Certain Compounds of the Transitional Metals with Boron, Carbon and Nitrogen, and the Electrical Conductivity of Alloys of these Compounds,' Sov. Phys.-Tech. Phys., 1(4), 695-701 (1957).

51. Wruck, D. and Wert, C., 'The Role of Crystal Structure on Irradiation Effects in Metals,' Acta Metall., 3(2), 115-20 (1955).

52. Potter, H.H., 'Electrical Resistance and Thermoelectric Power of the Transition Metals,' Proc. Phys. Soc. London, 53(6), 695-705 (1941).

53. Gautron, G.J., Zablocki, J.E., Hsiang, T.Y., and Weinstock, H., 'Electron-Electron Scattering in Vanadium,' J. Low Temp. Phys., 49(1/2), 185-91 (1982).

54. Tsai, C.L., Fagaly, R.L., Weinstock, H., and Schmidt, F.A., 'Electrical and Thermal Transport Coefficients of Pure Vanadium,' Phys. Rev. B, 23(12), 6430-40 (1981).

55. Taylor, R.E. and Groot, H., 'Thermal Conductivity of Vanadium,' Thermophysical Properties Research Lab. Rept. TPRL 265, 5 pp. (1982).

56. L'vov, S.N. and Nemchenko, V.F., 'Temperature Relation of Thermal Electromotive Force and Specific Electric Resistance of Titanium, Vanadium and Chromium and Their Borides, Carbides, and Nitrides,' Vysokotemp. Neorg. Soedin., 100-7 (1965); Engl. transl.: Los Alamos Scientific Lab. Rept. LA-TR-67-17, 14 pp. (1967).

57. Peletskii, V.E., 'Electrical Resistivity of Vanadium in the Temperature Range 200-2100 K,' Teplofiz. Vys. Temp., 16(1), 72-6 (1978); Engl. transl.: High Temp., 16(1), 57-60 (1978).

58. Altshuler, B.L. and Aronov, A.G., 'Influence of Electron-Electron Correlations on the Resistivity of Dirty Metals,' Pisma Zh. Eksp. Teor. Fiz., 27(12), 700-12 (1978); Engl. transl.: JETP Lett., 27(12), 662-4 (1978).

59. Roberts, B.W., 'Properties of Selected Superconductive Materials,' Natl. Bur. Stand. Rept. NBS-TN-983, 103 pp. (1978).

60. Kulikov, N.I., 'McMillan-Hopfield Factor and Ideal Resistivity of Transition Metals,' J. Phys. F, 8(6), L137-40 (1978).

61. Khanna, S.N. and Jain, A., 'Calculations on Electrical Resistivity and the Thermoelectric Power of Nonsimple Metals,' J. Phys. F, 7(12), 2523-30 (1977).

62. Jaffee, R.I., 'Refractory Metals,' Proc. Int. Symp. High Temp. Technol., 61-75 (1960).

63. Moraga, L.A. and Vilche, A., 'The Electrical Conductivity of Inhomogeneous Thin Metallic Films,' Thin Solid Films, 38(2), 117-30 (1976).

64. Khanna, S.N. and Jain, A., 'Electrical Resistivity of Noble and Transition Metals Using Animalu's Model Potential,' J. Phys. Chem. Solids, 38, 447-50 (1977).

65. McIntire, W.R. and Cohen, J.B., 'Static Distortions and Resistivity Due to Interstitials,' Acta Metall., 23(8), 953-6 (1975).

66. Grigsby, D.L., 'Vanadium Silicide. Data Sheet,' Hughes Aircraft Co. Rept. EPIC-DS-154, 49 pp. (1967). [AD 810 374]

67. Smirnov, Yu.M. and Finkel, V.A., 'Crystal Structure of Tantalum, Niobium, and Vanadium at 110-400 K,' J. Exptl. Theoret. Phys., USSR, 49, 1077-82 (1965); Engl. transl.: Sov. Phys.-JETP, 22(4), 750-53 (1966).

68. Grigsby, D.L., 'A Compilation on the Transition Regions of Element Superconductors,' Hughes Aircraft Co. Rept. EPIC-IR-28, 35 pp. (1966).

69. Biget, M., Rizk, R., Vajda, P., and Bessis, A., 'On the Spontaneous Recombination Volume of Frenkel Defects in Irradiated b.c.c. Metals,' Solid State Commun., 16(7), 949-52 (1975).

70. Smith, T.F., 'Pressure Dependence of the Superconducting Transition Temperature for Vanadium,' J. Phys. F, 2(5), 946-56 (1972). [AD 754 662]

71. Vajda, P. and Biget, M., 'Low-Temperature Fission Neutron Damage in Vanadium and Molybdenum,' Phys. Status Solidi, 23(1), 251-60 (1974).

72. McLlwain, J.F., Chen, C.W., Bajaj, R., and Wechsler, M.S., 'Effect of Neutron Irradiation on Vanadium,' Iowa State Univ. of Science and Technology, Dept. of Metallurgy, Rept. IS-2833, 21 pp. (1972).

73. Rostoker, W. and Yamamoto, A.S., 'A Contribution to the Oxygen Vanadium Phase Diagram,' Trans. Am. Soc. Met., 67, 1002-17 (1955).

74. Suzuki, H., Minomura, S., and Miyahara, S., 'Effect of Pressure on the Anomaly of Vanadium,' J. Phys. Soc. Jpn., 21(10), 2089 (1966).

75. Carlson, O.N. and Stevens, E.R., 'Vanadium and Vanadium Alloys,' Encycl. Chem. Technol., 21, 157-67 (1970).

76. Weiss, V., Jelinek, R.V., Sessler, J.G., Latorre, A.V., and Ziemer, R.D., 'Air Weapons Materials Application Handbook Metals and Alloys,' U.S. Air Force Rept. ARDC-TR-59-66 (1962). [AD 287 184]

77. Druzhinina, I.P., Fraktovnikova, A.A., and Vladimirskaya, T.M., 'Effect of Group VI Elements on Thermoelectric Properties of Vanadium,' Teplofiz. Vys. Temp., 14(1), 221-3 (1976); Engl. transl.: High Temp., 14(1), 200-2 (1976).

78. Westlake, D.G. and Miller, J.F., 'Resistivity Due to Hydrogen in Transition Metal Alloys,' J. Phys. F, 10(5), 859-63 (1980).

79. Weinstock, H., Tsai, C.L., and Schmidt, F.A., 'Thermal and Electrical Conductivity of Pure Vanadium at Low Temperatures,' J. Phys. (Paris), Colloq., 2(6), 1026-7 (1978).

80. Dunleavy, H.N. and Jones, W., 'Multiple Scattering Calculations of the Resistivity of Liquid Transition Metals,' J. Phys. F, 8(7), 1477-82 (1978).

81. L'vov, S.N., Mal'ko, P.I., and Nemchenko, V.F., 'Effect of Temperature on the Thermal and Electrical Conductivity and the Wiedemann-Franz Relation for D-Transition Metals,' Metallofizika, 64, 63-8 (1976).

82. Hirata, K., Waseda, Y., Jain, A., and Srivastava, R., 'Resistivity of Liquid Transition Metals and Their Alloys Using the T Matrix,' J. Phys. F, 7(3), 419-25 (1977).

83. Vasileva, E.V., Gorbova, A.S., and Prokoshkin, D.A., 'Effect of Heat Treatment on Properties of Alloy NT25A5,' Metalloved. Term. Obrab. Met., 5, 51 (1976); Engl. transl.: Met. Sci. Heat Treat. Met., 18(5-6), 453-4 (1976).

84. Kharoo, H.L., Gupta, O.P., and Hemkar, M.P., 'Phonon-Limited Electrical and Thermal Resistivities of Noble Metals,' Phys. Rev. B, 18(10), 5419-26 (1978).

85. Belousov, O.K. and Kornilov, I.I., 'Density of States and Some Physical Properties of Vanadium-Chromium Alloys,' Dokl. Akad. Nauk SSSR, 210(2), 374-6 (1973).

86. Allen, P.B., 'Superconductivity and Phonon Softening,' Phys. Rev. Lett., 29(24), 1593-6 (1972).

87. Collings, E.W., 'Anomalous Electrical Resistivity, Body-Centered-Cubic Phase Stability, and Superconductivity in Titanium-Vanadium Alloys,' Phys. Rev. B, 9(10), 3989-99 (1974).

88. Parker, R.D. and Halloran, M.H., 'Experimental Study of the Fermi Surface of Vanadium,' Phys. Rev. B, 9(10), 4130-7 (1974). [AD 785 941]

89. Postnikov, V.S., Miloshenko, V.E., Shunin, G.E., and Shukhalov, E.I., 'Effect of the Normal-Superconducting Transition on the Internal Friction of Vanadium,' (Savitskii, E.M., Editor), Strukt. Svoistva Sverkhprovodyashchikh Mater., 105-8 (1974).

90. L'vov, S.N., Mal'ko, P.I., and Nemchenko, V.F., 'High Temperature Resistivity of D-Transition Metals,' Fiz. Met. Metalloved., 32(3), 485-91 (1971); Engl. transl.: Phys. Met. Metallogr., 32(3), 35-40 (1971).

91. Chernoplekov, N.A., Panova, G.Kh., Samoylov, B.N., Zhernov, A.P., and Shikov, A.A., 'The Resistivity of Vanadium Alloyed with Tantalum,' Fiz. Met. Metalloved., 36(5), 978-82 (1973); Engl. transl.: Phys. Met. Metallogr., 36(5), 72-5 (1973).

92. Kerker, G. and Bennemann, K.H., 'Theory for Superconductivity in Amorphous Transition Metals,' Z. Phys., 264(1), 15-20 (1973).

93. Savitskii, E.M. and Polyakova, V.P., 'Phase Diagrams and Properties of Noble Metals and Their Alloys,' Tr. Inst. Fiz. Metal. Ural. Nauch. Tsent. Akad. Nauk SSSR, 28, 44-57 (1971).

94. Grechko, O.G., L'vov, S.N., and Bondarev, V.N., 'Physical Properties of Group IV-VI Transition Metal Germanides,' Metallidy-Str., Svoistva, Primen., 142-9 (1971).

95. Chiu, J.C.H., 'Deviations from Linear Temperature Dependence of the Electrical Resistivity of Vanadium-Chromium and Tantalum-Tungsten Alloys,' Phys. Rev. B, 13(4), 1507-14 (1976).

96. Teplov, A.A., Mikheeva, M.N., Golyanov, V.M., and Gusev, A.N., 'Superconducting Transition Temperature, Critical Magnetic Fields, and the Structure of Vanadium Films,' Zh. Eksp. Teor. Fiz., 71(3), 1122-8 (1976); Engl. transl.: Sov. Phys.-JETP, 44(3), 587-91 (1976).

97. Osipov, K.A., Orlov, A.F., and Ivanovskaya, G.F., 'The Electrical Properties of Vanadium and Tantalum Films Produced and Annealed in Super-High Vacuum,' Izv. Akad. Nauk SSSR, Met., 1, 178-81 (1974); Engl. transl.: Russ. Metall., 1, 108-10 (1974).

98. Chander, R., Howard, R.E., and Jain, S.C., 'Electrical Conductivity and Hall Effect in Thin Vanadium Films,' J. Appl. Phys., 38, 4092-3 (1967).

99. Hoffman, D.W. and Thornton, J.A., 'The Compressive Stress Transition in Aluminum, Vanadium, Zirconium, Niobium and Tungsten Metal Films Sputtered at Low Working Pressures,' Thin Solid Films, 45(2), 387-96 (1977).

100. Alekseevskii, N.E. and Sakosarenko, V.M., 'Superconducting Properties of Vanadium Films,' Phys. Status Solidi, 34A(2), 541-6 (1976).

101. Borodziuk-Kulpa, A., Stolecki, B., and Wesolowska, C., 'Electrical Properties of Vanadium Films,' Thin Solid Films, 67(1), 21-8 (1980).

102. Lang, E. and Bressers, J., 'On the Effect of Some Sample Preparation Techniques on the Electrical and Caloric Properties of Vanadium,' Z. Metallkd., 67(1), 66-71 (1976).

103. Chaplin, R.L., Sonnenberg, K., and Coltman, R.R., Jr., 'A Measurement of the Frenkel Defect Resistivity in Vanadium and Its Implications,' Radiat. Eff., 27(1-2), 119-20 (1975).

104. Lakh, K.I. and Stasyuk, Z.V., 'Effect of Adsorption on the Electrical Conductivity of Vanadium Thin Films,' Fiz. Elektron. (Lvov), 5, 102-4 (1972).

105. Reale, C., 'Determination of Charge-Transport Parameters for Metals with Cubic Symmetry by a Study of Size Effects on Thin Films,' Phys. Status Solidi, 58B(1), K5-7 (1973).

106. Schmidt, P.H., 'Superconductivity of Transition Metal Thin Films Deposited by Noble Gas Ion Beam Sputtering,' J. Vac. Sci. Technol., 10(5), 611-15 (1973).

107. Linker, G., Meyer, O., and Gettings, M., 'Back-Scattering Energy Loss Parameter Measurements in Thin Metal Films,' Thin Solid Films, 19(2), 177-85 (1973).

108. Felsch, W., 'Effect of Surface Charge on the Superconductivity of Vanadium Films,' *Low Temp. Phys.-LT 13, Proc. Int. Conf. Low Temp. Phys.*, 13th (Timmerhaus, K.D., O'Sullivan, W.J., and Hammel, E.F., Editors), 3, 543-6 (1974).

109. Linker, G., 'Influence of Ion Bombardment on the Superconducting Transition Temperature of Evaporated Vanadium Layers,' J. Nucl. Mater., 72(1-2), 275-81 (1978).

110. Kreinina, G.S., 'Current-Voltage Characteristics of Palladium and Vanadium Films,' Radiotekh. Elektron., 17(6), 1269-72 (1972).

111. Schmidt, P.H., Castellano, R.N., Barz, H., Cooper, A.S., and Spencer, E.G., 'Variation of Superconducting Transition Temperatures of Transition-Metal Thin Films Deposited with the Noble Gases,' J. Appl. Phys., 44(4), 1833-6 (1973).

112. Korshunov, V.D. and Tarakanov, V.I., 'Action of Gamma-Rays on Metal Thin Films,' Izv. Vyssh. Ucheb. Zaved., Fiz., 15(11), 143-5 (1972); Engl. transl.: Sov. Phys. J., 15(11), 1674-6 (1972).

113. Korshunov, V.D. and Tarakanov, V.I., 'Influence of Gamma Rays on the Structure and Properties of Thin Films,' Fiz. Khim. Obrab. Mater., 5, 46-9 (1974).

114. Noer, R.J., 'Superconductive Tunneling in Vanadium with Gaseous Impurities,' Phys. Rev. B, 12(11), 4882-5 (1975).

115. Nestell, J.E., Jr., 'Optical Properties and Structure of Vanadium, Niobium, Tantalum, Chromium, Molybdenum, and Tungsten Films,' Dartmouth College, Ph.D. Thesis, 233 pp. (1979). [Univ. Microfilm No. 80-01173]

116. Eto, M. and Narutani, T., 'Contribution of Dissolved or Precipitated Oxygen to the Electrical Resistivity of Vanadium,' J. Mater. Sci., 9(11), 1902-4 (1974).

117. Peterson, D.T. and Jensen, C.L., 'Electromigration of Hydrogen and Deuterium in Vanadium and Niobium by a Resistance Method,' Metall. Trans., 9A(11), 1673-7 (1978).

118. Watanabe, K. and Fukai, Y., 'Electrical Resistivity Due to Interstitial Hydrogen and Deuterium in Vanadium, Niobium, Tantalum, and Palladium,' J. Phys. F, 10(8), 1795-801 (1980).

119. Druzhinina, I.P., Fraktovnikova, A.A., and Vladimirskaya, T.M., 'Influence of Rhenium on the Thermoelectric Properties of Vanadium,' Teplofiz. Vys. Temp., 14(3), 652-4 (1976); Engl. transl.: High Temp., 14(3), 579-81 (1976).

120. Stanley, J.T., Williams, J.M., Brundage, W.E., and Wechsler, M.S., 'Effect of Interstitial Impurities on the Annealing of Neutron-Irradiated Vanadium,' Acta Metall., 20(2), 191-8 (1972).

121. Touloukian, Y.S. and Ho, C.Y., Editors, Properties of Selected Ferrous Alloying Elements, Vol. III-1 of McGraw-Hill/CINDAS Data Series on Material Properties, McGraw-Hill Book Co., New York, 269 pp. (1981).

122. Brandt, N.B. and Zarubina, O.A., 'Superconductivity of Vanadium at Pressures Up to 250 Kbar,' Fiz. Tverd. Tela, 15(11), 3423-5 (1973); Engl. transl.: Sov. Phys.-Solid State, 15(11), 2281-2 (1974).

123. Cezairliyan, A. and Righini, F., 'Measurement of Melting Point, Radiance Temperature (at Melting Point), and Electrical Resistivity (above 2100 K) of Zirconium,' Rev. Int. Hautes Temp. Refract., 12(3), 201-7 (1975).

124. Cezairliyan, A. and Righini, F., 'Thermodynamic Studies of the Alpha-Beta Phase Transformation in Zirconium Using a Subsecond Pulse Heating Technique,' J. Res. Natl. Bur. Stand., 79A(1), 81-4 (1975). [AD A013 906]

125. Cezairliyan, A. and Righini, F., 'Simultaneous Measurements of Heat Capacity, Electrical Resistivity and Hemispherical Total Emittance by a Pulse Heating Technique: Zirconium, 1500 to 2100 K,' J. Res. Natl. Bur. Stand., 78A(4), 509-14 (1974).

126. Hörz, G., Hammel, M., and Kanbach, H., 'Electrical Resistivity of Beta-Zirconium-Oxygen Solid Solutions as a Function of Oxygen Concentration and Temperature,' J. Nucl. Mater., 55(3), 291-8 (1975).

127. Bykov, V.N., Rudnev, I.I., and Solov'ev, V.A., 'Anomalies of the Physical Properties of Alpha-Titanium and Alpha-Zirconium,' Elektron. Str. Fiz. Svoistva Tverd. Tela, 1, 42-7 (1972).

128. Mal'tsev, V.A., 'Physical Properties of the Omega Phase of Zirconium,' Fiz. Met. Metalloved., 36(2), 413-14 (1973); Engl. transl.: Phys. Met. Metallogr., 36(2), 174-6 (1973).

129. Martynyuk, M.M. and Tsapkov, V.I., 'The Applicability of Mott's Formula to the Fusion of Transition Metals,' Zh. Fiz. Khim., 47(5), 1308-98 (1973); Engl. transl.: Russ. J. Phys. Chem., 47(5), 741-2 (1973).

130. Reale, C., 'Determination of Charge-Transport Parameters for the Group IV Metals,' Rev. Bras. Fis., 3(3), 431-9 (1973).

131. Volkenshtein, N.V., Novoselov, V.A., and Startsev, V.E., 'Role of Interelectron Collisions in the Electric Resistance of Transition Metals,' Zh. Eksp. Teor. Fiz., 60(3), 1078-85 (1971); Engl. transl.: Sov. Phys.-JETP, 33(3), 584-7 (1971).

132. Zhorov, G.A., 'Emissivity of Metals of the IVb Subgroup at High Temperatures,' High Temp., 8(3), 501-4 (1970).

133. Peletskii, V.E., Druzhinin, V.P., and Sobol, Ya.G., 'Emissivity, Thermal Conductivity, and Electrical Conductivity of Remelted Zirconium at High Temperatures,' High Temp., 8(4), 732-6 (1970).

134. Elliott, R.O. and Hill, H.H., 'Resistance Minimums in Zirconium-Plutonium Alloys,' J. Less-Common Met., 22(1), 123-6 (1970).

135. Betterton, J.O., Jr. and Easton, D.S., 'Electrical Resistivity of Zirconium Alloys,' USAEC Rept. ORNL-4370, 23-4 (1968).

136. Clinard, F.W., Jr. and Kempter, C.P., 'Low-Temperature Electrical Properties of Some Transition Metals and Transition-Metal Carbides,' J. Less-Common Met., 15(1), 59-73 (1968).

137. Cape, J.A. and Hake, R.R., 'Localized Magnetic Impurity States in Titanium, Zirconium, and Hafnium,' Phys. Rev. A, 139(1), 142-9 (1965).

138. Powell, R.W. and Tye, R.P., 'The Thermal and Electrical Conductivities of Zirconium and of Some Zirconium Alloys,' J. Less-Common Met., 3, 202-15 (1963).

139. Kiselev, N.A., 'Device for Determining the Electrical Resistance and the Melting Point of Metals and Alloys,' Metallurgiya, Metallovedenie, Fiziko-Khimicheskie Metody Issledovaniya, 3, 1 (1958); Engl. transl.: OTS-60-51087, 3, 280-7 (1961).

140. Berlincourt, T.G., 'Hall Effect, Resistivity, and Magnetoresistivity of Thorium, Uranium, Zirconium, Titanium and Niobium,' Phys. Rev., 114(4), 969-78 (1959).

141. Kemp, W.R.G., Klemens, P.G., and White, G.K., 'Thermal and Electrical Conductivities of Iron, Nickel, Titanium, and Zirconium at Low Temperatures,' Aust. J. Phys., 9, 180-8 (1956).

142. Adenstedt, H.K., 'Physical, Thermal and Electrical Properties of Hafnium and High Purity Zirconium,' Trans. Am. Soc. Metals, 44, 949-73 (1952).

143. Bing, G., Fink, F.W., and Thompson, H.B., 'The Thermal and Electrical Conductivities of Zirconium and Its Alloys,' USAEC Rept. BMI-65, 19 pp. (1951).

144. Cook, L.A., Castleman, L.S., and Johnson, W.E., 'Preliminary Report on the Electrical Resistivity of Zirconium,' Westinghouse Electric Corp. Rept. WAPD-25, Dec. 20 (1950).

145. Nakagawa, M., Mansel, W., Boening, K., Rosner, P., and Vogl, G., 'Spontaneous Recombination Volumes of Frenkel Defects in Neutron-Irradiated Non-Face-Centered Cubic Metals,' Phys. Rev. B, 19(2), 742-8 (1979).

146. Azhazha, V.M., V'yugov, P.N., Reshetova, L.N., San'kov, A.A., and Tarasova, M.I., 'Purification of Zirconium by Vacuum Zone Refining,' Izv. Akad. Nauk SSSR, Met., 1, 41-4 (1975); Engl. transl.: Russ. Metall., 1, 36-9 (1975).

147. Hörz, G. and Hammel, M., 'Kinetics and Mechanism of the Reaction of Beta-Zirconium with Oxygen at Low Pressures,' *J. Nucl. Mater.*, 55(3), 284-90 (1975).

148. Baranov, I.A., Bychkov, Yu.F., Korzhov, V.P., Mal'tsev, V.A., Slavgorodskii, M.P., and Shmalevich, R.S., 'Effect of Rhodium on Superconductivity of Zirconium and Some of Its Alloys,' Sverkhprovodyashchie Splavy Soedin., 140-7 (1972).

149. Fedorov, G.B., Zuev, M.T., Smirnov, E.A., and Kissil, A.E., 'Physical Properties of Uranium Zirconium Alloys at Low Temperatures,' At. Energ., 34(2), 85-8 (1972).

150. Pande, B.M., Anand, M.S., and Argarwala, R.P., 'Recovery of Deformed Zirconium Above Room Temperature,' Phys. Status Solidi, 10A(2), K137-9 (1972).

151. Claisse, F., Cormier, M., and Frigout, C., 'The Exponential Temperature Dependence of the Electrical Resistivity of Hexagonal Close-Packed Hafnium, Titanium and Zirconium Alloys,' High Temp.-High Pressures, 4(4), 395-9 (1972).

152. Hall, L.A. and Germann, F.E.E., 'Survey of Electrical Resistivity Measurements on 8 Additional Pure Metals in the Temperature Range 0 to 273 K,' Natl. Bur. Stand. Tech. Note 365-1, 85 pp. (1970).

153. Blumenthal, W.B. and Roach, J.D., 'Zirconium Metal and Its Metal-Like Compounds,' Encycl. Chem. Technol., 22, 614-29 (1970).

154. Golutvin, Yu.M. and Maslennikova, E.G., 'The Heat Capacity of Metallic Hafnium,' Izv. Akad. Nauk SSSR, Met., 5, 174-83 (1970); Engl. transl.: Russ. Metall., 5, 129-35 (1970).

155. Parker, E.R., Materials Data Book for Engineers and Scientists, McGraw-Hill Book Co., New York, 398 pp. (1967).

156. Bridgman, P.W., 'The Resistance of 72 Elements, Alloys and Compounds to 100,000 kg/cm,' Proc. Amer. Acad. Arts Sci., 81(4), 165-251 (1952).

157. Squire, C.F. and Kaufmann, A.R., 'The Magnetic Susceptibility of Titanium and Zirconium,' J. Chem. Phys., 9(9), 673-7 (1941).

158. Fast, J.D., 'The Manufacturing of the Pure Metal of the Titanium Group by Thermal Replacements of Their Iodide. IV. The Occurrence of the Lower Zirconium Iodide During the Manufacturing of Ductile Zirconium,' Z. Anorg. Allgem. Chem., 239, 145-54 (1938).

159. McLennan, J.C., Howlett, L.E., and Wilhelm, J.O., 'On the Electrical Conductivity of Certain Metals at Low Temperatures,' Trans. Roy. Soc. Can., 23, Sect. III, 287-306 (1929).

160. Clausing, P. and Moubis, G., 'Electrical Resistance of Titanium at Low Temperature,' Physica, 7, 245-50 (1927).

161. Bridgman, P.W., 'The Compressibiity and Pressure Coefficient of Resistance of Zirconium and Hafnium,' Proc. Amer. Acad. Arts Sci., 63, 347-50 (1928).

162. Meissner, W. and Voigt, B., 'Measurements with the Aid of Liquid Helium. XI. Resistance of Pure Metals at Low Temperatures,' Ann. Physik, 7(7), Pt. 5, 761-97, 892-936 (1930).

163. Akatsu, E., 'Chemistry of the Fission Products,' Japan Atomic Energy Research Inst., Tokyo, Rept. JAERI-M-7873, 78 pp. (1978).

164. Volkenshtein, N.V., Galoshina, E.V., and Panikovskaya, T.N., 'Temperature Dependence of Magnetic Susceptibility Anisotropy of Transition Metal Crystals with a Hexagonal Close Packed Structure,' Zh. Eksp. Teor. Fiz., 67(4), 1468-73 (1974); Engl. transl.: Sov. Phys.-JETP, 40(4), 730-2 (1975).

165. Touloukian, Y.S., Editor, Thermophysical Properties of High Temperature Solid Materials. Volume 1: Elements, MacMillan Co., New York, 1152 pp. (1967).

166. Vaynshteyn, A.A., Rusinov, P.S., and Papina, N.V., 'The Heterogeneous Properties of Polycrystals with an Axial Texture,' Fiz. Met. Metalloved., 48(5), 957-61 (1979); Engl. transl.: Phys. Met. Metallogr., 48(5), 49-53 (1979).

167. Moers, K., 'Conductivity Measurements on High Melting Carbides, Nitrides and Borides at Room, Low and High Temperatures,' Z. Anorg. Allgem. Chem., 198, 262-75 (1931).

168. Martyniuk, V.M. and Tsapkov, V.I., 'Electrical Resistance, Enthalpy, and Phase Transitions of Titanium, Zirconium, and Hafnium During Pulsed Heating,' Izv. Akad. Nauk SSSR, Met., 181-8 (1974); Engl. transl.: Russ. Metall., 108-12 (1974).

169. Rassmann, G. and Merz, A., 'Developments in the Field of High Temperature Materials,' Technik, 17(2), 74-9 (1962).

170. Grigsby, D.L., 'Electrical Resistivity of Selected Materials,' Hughes Aircraft Co. Rept. EPIC-IR-44, 15 pp. (1966).

171. Antler, M. and Krumbein, S.J., 'Contact Properties of Conductive Hard-metals and of Tin Nickel Plate,' in Electrical Contacts-1965, Proc. Eng. Seminar on Electrical Contacts, Univ. of Maine, 103-37 (1965).

172. Fuschillo, N. and Lindberg, R.A., 'Electrical Conductors at Elevated Temperatures,' U.S. Air Force Rept. ASD-TRD-62-481 (1962). [AD 299 020]

173. Dayton, R.W., 'Zirconium and Its Alloys,' in Reactor Handbook: Materials, Vol. 4, 459-504 (1955).

174. Lustman, B. and Kerze, F., Jr., The Metallurgy of Zirconium, McGraw-Hill Book Co., New York, 776 pp. (1955).

175. Rosenberg, H.M., 'The Thermal Conductivity of Metals at Low Temperatures,' Philos. Trans. R. Soc. London, A247, 441-97 (1955).

176. DeBoer, J.H. and Clausing, P., 'Electrical Resistance of Titanium, Zirconium, and Solid Solutions,' Physica, 10, 267-9 (1930).

177. DeBoer, J.H. and Fast, J.D., 'The Production of the Pure Metals of the Titanium Group by Thermal Replacement of Their Iodides. III. Hafnium,' Z. Anorg. Allgem. Chem., 187, 193-208 (1930).

178. Huett, R., 'The Physical Ordering Principle of Crystals in Nature,' Wissenschaftlicher Bericht, Gesmthochschule Siegen, Abteilung Gummersbach, 1-2 (1978).

179. Brehm, C. and Lehr, P., 'Plastic Deformation of Titanium and Zirconium,' Melaux, 46(551-2), 253-71; (553), 325-34; (554), 359-81 (1971).

180. Stewart, R.B. and Johnson, V.J., 'A Compendium of the Properties of Materials at Low Temperature (Phase),' U.S. Air Force Rept. WADD-TR-60-56, Part IV, 501 pp. (1961).

181. Greig, D. and Morgan. G.J., 'The Electrical Resistivity of Transition Metals at High Temperatures,' Philos. Mag., 27(8), 929-40 (1973).

182. Pav, T. and Saxl, I., 'Physical Properties of Zirconium and Its Alloys,' Ustav Jaderneho Vyzkumu, Ceskoslovenska, Akademie Ved. Rez. Rept. UJV-2708-M, 119 pp. (1971).

183. Degtyareva, V.F., Karimov, Yu.S., and Rabin'kin, A.G., 'Superconductivity and Magnetic Susceptibility of the Alpha and Omega Modifications of Titanium and Zirconium,' Fiz. Tverd. Tela, 15(11), 3436-8 (1973); Engl. transl: Sov. Phys.-Solid State, 15(11), 2293-4 (1974).

184. Rosenbaum, M., Bisogni, E.A., and Blewitt, T.H., 'Resistivity Changes in Neutron-Irradiated Zirconium at 77 K,' J. Nucl. Mater., 48(2), 201-3 (1973).

185. Omar, A.M., Robinson, J.E., and Thompson, D.A., 'The 10-16 MeV Proton Irradiation of Iron, Zirconium and Copper: Resistivity-Dose Measurements,' J. Nucl. Mater., 84(1-2), 173-82 (1979).

186. Filippov, V.F., 'Study of Some Properties of Zirconium with Additions of Transition Metals,' Joint Publications Research Service Rept. JPRS-59873, 75-83 (1973).

187. Reale, C., 'Results of Combined Measurements of Resistivity and Thermopower of Transition and Noble Metal Films,' Phys. Lett. A, 50(1), 53-4 (1974).

188. Bastl, Z., 'Influence of Interstitial Hydrogen on Hall Voltage and on Electric Resistance of Thin Zirconium Films,' Collect. Czech. Chem. Commun., 40(7), 1987-96 (1975).

189. Eichler, A. and Gey, W., 'Superconductivity in Alpha- and Omega-Zirconium Under High Pressure,' Z. Phys., 251(4), 321-3 (1972).

190. Touloukian, Y.S., Kirby, R.K., Taylor, R.E., and Desai, P.D., Thermal Expansion, Metallic Elements and Alloys, Vol. 12 of Thermophysical Properties of Matter - The TPRC Data Series, IFI/Plenum Data Corp., New York, 1348 pp. (1975).

191. Touloukian, Y.S., Powell, R.W., Ho, C.Y., and Klemens, P.G., Thermal Conductivity - Metallic Elements and Alloys, Vol. 1 of Thermophysical Properties of Matter - The TPRC Data Series, IFI/Plenum Data Corp., New York, 1595 pp. (1970).

192. Laws, F.A., Electrical Measurements, 2nd Edition, McGraw-Hill Book Co., Inc., New York, 739 pp. (1938).

193. Harris, F.K., Electrical Measurements, John Wiley and Sons, Inc., New York, 784 pp. (1952).

194. Meaden, G.T., Electrical Resistance of Metals, Plenum Press, New York, 218 pp. (1965).

195. Taylor, R.E. and Groot, H., 'Operating Manual for Kohlrausch Apparatus,' Thermophysical Properties Research Laboratory Rept. TPRL 291, 11 pp., 1978.

196. Taylor, R.E., 'A Description of the Thermophysical Properties Research Laboratory,' Thermophysical Properties Research Laboratory Rept. TPRL 181 (Revised), 72 pp., 1982.

197. Radenac, A., Lacoste, M., and Roux, C., 'Apparatus Meant for the Measurement of the Electrical Resistivity of Metals and Alloys by the Method of the Rotating Field Up to About 2000 K,' Rev. Int. Hautes Temp. Refract., 7(4), 389-96 (1970).

198. Cezairliyan, A., Morse, M.S., Burman, H.A., and Beckett, C.W., 'High-Speed (Subsecond) Measurement of Heat Capacity, Electrical Resistivity, and Thermal Radiative Properties of Molybdenum in the Range 1900-2800 K,' J. Res. Natl. Bur. Stand., Sect. A, 74A(1), 65-92 (1970).