Electrical Resistivity of Selected Elements

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This work compiles, reviews, and discusses the available data and information on the electrical resistivity of hafnium, molybdenum, tantalum, tungsten, and zinc and presents the recommended values resulting from critical evaluation, correlation, analysis, and synthesis of the available data and information. The recommended values presented are both 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 $\pm 2\%$ to $\pm 10\%$.

Key words: conductivity; critical evaluation; electrical conductivity; electrical resistivity; hafnium; metals; molybdenum; recommended values; resistivity; tantalum; tungsten; zinc.

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[a] See AIP document no. PAPS JPCRD-13-1069-71 for 71 pages of data tables. Order by PAPS number and journal reference from the American Institute of Physics, Physics Auxiliary Publication Service, 335 East 45th Street, New York, N.Y. 10017. The price is $1.50 for a microfiche or $5.00 for a photocopy. Airmail is additional. Make checks payable to the American Institute of Physics.

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 hafnium, tantalum, molybdenum, zinc, and tungsten are presented in this work, which is one in a series of similar works on the electrical resistivity of selected elements, some already published.[1-3] The comprehensive study of the electrical resistivity of the elements at the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) has been a continuation of a similar extensive work on the thermal conductivity of the elements.[4]

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

Discussions on the electrical resistivity of hafnium and tantalum are given in Secs. 3.1 and 3.2, respectively, and references to the electrical resistivity of these two elements are given in Sec. 3.3. Similarly, molybdenum and zinc are covered in Secs. 4.1–4.3, and tungsten is covered in Secs. 5.1 and 5.2.

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. The values cover the temperature range from 1 K to above the melting point into the molten state.

2. General Background

2.1. Theoretical Background

It was found experimentally by Matthiessen that the increase in the electrical resistivity of a metal due to the presence of a small amount of another metal in the solid solution is independent of the temperature.[5] According to Matthiessen's rule, the total electrical resistivity of an impure metal may, therefore, be separated into additive contributions: ρ_0, residual resistivity caused by the scattering of electrons by impurity atoms and lattice defects and is temperature independent but dependent on the impurity concentration (c); and ρ_i, the temperature-dependent intrinsic resistivity arising from the scattering of electrons by lattice waves or phonons. However, in reality it is observed that

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

where Δ is the deviation from Matthiessen's rule.

It is to be noted that for some metals, especially transition metals, an electron–electron scattering term (ρ_e) makes a significant contribution to ρ_i at low temperatures, and is generally included along with the Bloch–Gruneisen term[6,7] in representing ρ_i. Further comments on Matthiessen's rule and on ρ_0, ρ_i, ρ_e, and Δ are given in Ref. 8.

2.2. Presentation of Data and Information

In each of the subsections discussing the electrical resistivity of each of the elements covered, the 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 recommended values and selected experimental data as a function of temperature in a log-log scale, and

(4) A figure presenting recommended values and selected experimental data as a function of temperature in a linear scale.

In the discussion text on the electrical resistivity of each element, individual pieces of the data and information on which the recommendations are based are indicated, the considerations involved in arriving at the final assessment and recommendation are discussed, and the uncertainties of the recommended values are stated.

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

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

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

where $\Delta L = L - L_0$ and L and L_0 are the lengths of the specimen at any temperature T and at a reference temperature T_0, respectively.

The 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 tables has no bearing on the degree of accuracy of 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 supplementary 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 supplementary 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 supplementary tables are deposited in AIP's Physics Auxiliary Publication Service. In the supplementary tables providing measurement information, the experimental methods used for the measurement of the electrical resistivity are indicated in the column headed "Method Used" by the following code letters:

A	Direct-current potentiometer method
B	Direct-current bridge method
C	Alternating-current potentiometer method
D	ac bridge method
G	Galvanometer–amplifier method
K	Direct heating method
M	Mutual-inductance method
P	Van der Paw method
R	Rotating magnetic field 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.

In the supplementary tables tabulating the experimental data, all the original data reported in different units have been converted to have the same, SI units: 10^{-8} Ω m. The recommended values generated are also given in the SI units.

2.3. References

[1]T. C. Chi, J. Phys. Chem. Ref. Data 8, 339 (1979).
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[3]R. A. Matula, J. Phys. Chem. Ref. Data 8, 1147 (1979).
[4]C. Y. Ho, R. W. Powell, and P. E. Liley, J. Phys. Chem. Ref. Data 3, Suppl. 1 (1974).
[5]A. Matthiessen and C. Vogt, Ann. Phys. (Leipzig) 122, 19 (1864).
[6]F. Bloch, Z. Phys. 52, 555 (1928).
[7]F. Bloch, Z. Phys. 59, 208 (1930).
[8]C. Y. Ho, M. W. Ackerman, K. Y. Wu, T. N. Havill, R. H. Bogaard, R. A. Matula, S. G. Oh, and H. M. James, J. Phys. Chem. Ref. Data 12, 183 (1983).

3. Electrical Resistivity of Hafnium and Tantalum

3.1. Hafnium

There are only 19 sets of experimental data available for the electrical resistivity of hafnium. These are listed in Table S-1 and tabulated in Table S-2. The data reported so far in the literature are far from ideal for the generation of recommended values of ρ, mainly because of the unavailability of pure hafnium samples. The residual resistivity of the purest sample reported in this investigation for which reliable data are available is 1×10^{-8} Ω m; the claimed purity is about 99.9%. It appears that material containing as much as 2% zirconium has in the past been identified as pure hafnium. The temperature range covered by these data sets is from 1.7 to 2500 K. The data are shown partially in Figs. 1 and 2.

The recommended values of the electrical resistivity are for a sample with residual resistivity of 1.0×10^{-8} Ω m, approximately the lowest value that has been reported. The recommended values below 40 K are based primarily on the data of Volkenshtein *et al.*[9] (data set 7). The resistance ratios reported by Volkenshtein *et al.* were converted to numerical values of $\rho(T)$ using the CINDAS recommended value of 30.39×10^{-8} Ω m for $\rho(T)$ at 273 K.

The recommended values from 40 to 300 K are based on the data of Volkenshtein *et al.*[9] (data set 7), Volkenshtein and Galoshina[13] (data set 13), and of White and Woods[14] (data set 14), which agree fairly well. It will be noted that the behavior of the electrical resistivity of hafnium in the temperature range 100–300 K, as indicated by the data of these studies, is not as simple as might be expected. A log–log plot of the electrical resistivity versus temperature in this temperature range deviates from the more commonly observed linear behavior by the presence of a significant downward curvature. This behavior is believed to be real, and is included in the current data analysis.

The recommended values above 1000 K are based on the data of Rumyantsev *et al.*[1] (data set 1), Cezairliyan[2] (data set 2), Savin *et al.*[3] (data set 3), Martynyuk and Tsapkov[4] (data set 4), Filippov *et al.*[5,6] (data set 5), and of Zhorov[11] (data set 11). Little weight has been given to data that diverge strongly from those in these data sets.

The recommended values describing the α–β transition at 2015 K treat this transition as of the first order without premonitory changes in the temperature coefficient of the electrical resistivity. Deviations from these values are to be expected if thermal equilibrium is not fully attained.

There is no consensus of reliable data between 300 and 1000 K. Therefore, the recommended values in this temperature range represent a reasonable interpolation between the higher and lower temperature ranges.

There is only one data point available for the electrical resistivity of hafnium at the melting point. Martynyuk and Tsapkov[4] (data set 4) reported a value of 156.0×10^{-8} Ω m for the electrical resistivity at the beginning and at the end of melting.

The data available in the literature for the temperature dependence of bulk samples have been reviewed in this re-

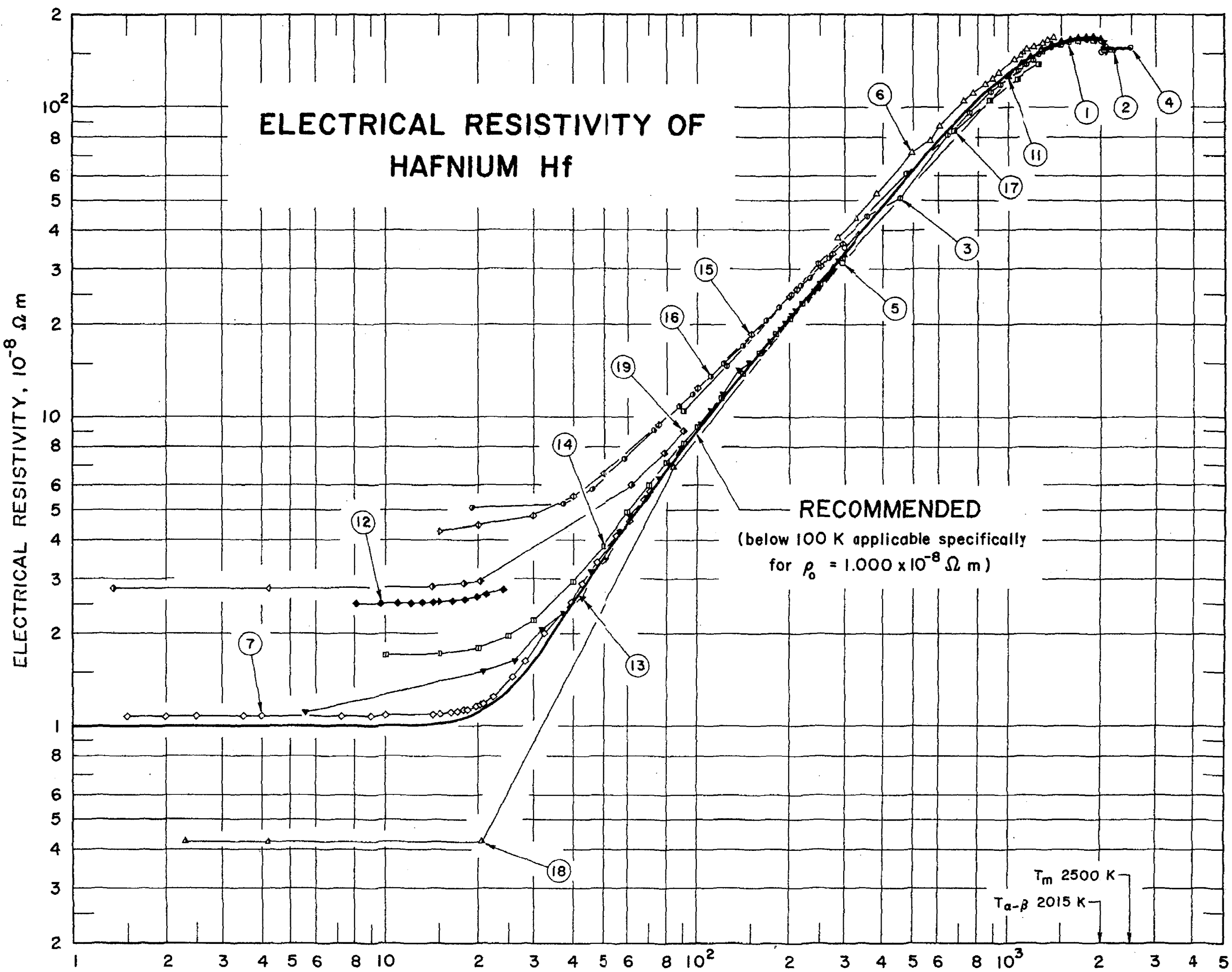
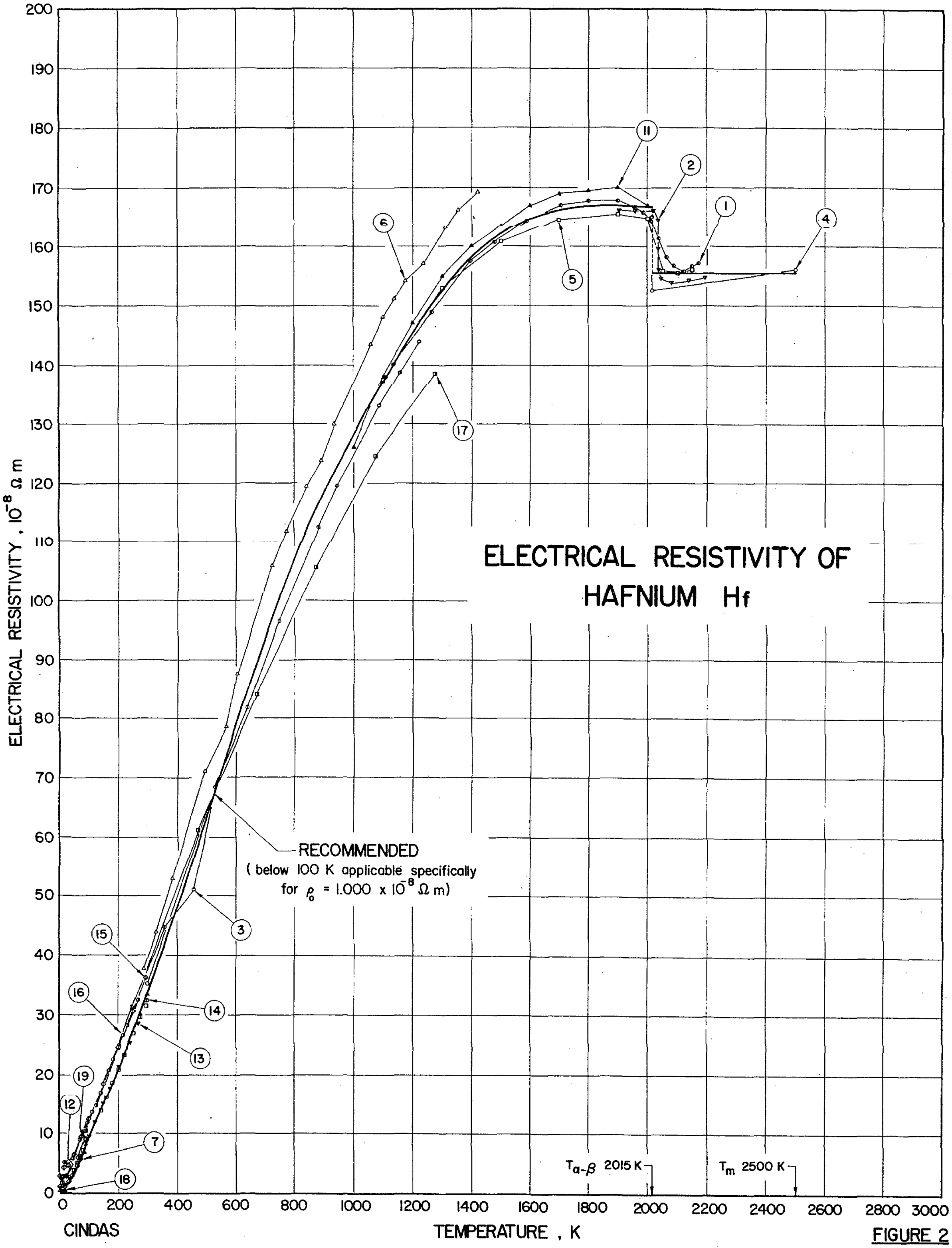

ELECTRICAL RESISTIVITY OF
HAFNIUM Hf
RECOMMENDED
(below 100 K applicable specifically
for ρ_0 = 1.000 x 10^{-8} Ω m)
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS
T_m 2500 K
$T_{\alpha-\beta}$ 2015 K
1
2
3
4
5
6
7
11
12
13
14
15
16
17
18
19

FIGURE 1


ELECTRICAL RESISTIVITY OF
HAFNIUM Hf
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 100 K applicable specifically for ρ_0 = 1.000 x 10^{-8} Ω m)
$T_{\alpha-\beta}$ 2015 K
T_m 2500 K
CINDAS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
1
2
3
4
5
6
7
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17
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19

FIGURE 2

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

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
1	1.000	1.000	700	93.29	93.53
4	1.000	1.000	750	100.3	100.6
7	1.000	1.000	800	106.9	107.3
10	1.002	1.002	850	113.0	113.4
15	1.017	1.017	900	118.5	119.0
20	1.110	1.110	950	123.5	124.0
25	1.306	1.306	1000	128.3	128.9
30	1.638	1.638	1100	137.2	138.0
35	2.064	2.064	1200	145.5	146.4
40	2.523	2.523	1300	152.5	153.6
45	2.992	2.992	1400	158.1	159.3
50	3.482	3.482	1500	162.1	163.5
60	4.526	4.526	1600	164.7	166.3
70	5.620	5.620	1700	166.2	167.9
80	6.751	6.751	1800	166.9	168.8
90	7.923	7.923	1900	167.0	169.0
100	9.118	9.118	2000	166.8	169.0
150	15.01	15.01	2015(α)	166.8	169.0
200	21.02	21.02	2015(β)	155.4	157.5
250	27.36	27.36	2100	155.4	157.8
273	30.39	30.39	2200	155.4	157.6
293	33.08	33.08	2300	155.4	157.9
300	34.03	34.03	2400	155.4	158.1
350	40.96	40.97	2500	155.4	158.3
400	48.08	48.11			
450	55.42	55.47			
500	63.10	63.18			
550	70.88	70.99			
600	78.52	78.67			
650	86.00	86.19			

[a]The values are for hafnium of purity 99.9% or higher, but those below 40 K are applicable specifically to hafnium having a residual resistivity of 1.000 x 10^{-8} Ω m. The estimated uncertainty in the values is within ±5% below 500 K and from 1000 to 2000 K, and ±10% from 500 to 1000 K and above 2000 K. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal linear expansion, respectively. Dotted line separating tabular values indicates solid phase transformation.

port. However, additional information on the electrical resistivity is available in Refs. 21–43 and 47–55. Attention is directed to Refs. 44–46 for data on films and Ref. 48 for data on the pressure dependence of resistivity.

It can be seen from the data presented in Figs. 1 and 2 that electrical resistivity values above 100 K from various data sets converge to a set of values within experimental uncertainty, irrespective of specimen purity. The recommended values of the electrical resistivity given in Table 1 and shown in Figs. 1 and 2 are for hafnium of purity 99.9% or better; below 40 K the values are specifically for samples with $\rho_0 = 1.000\times10^{-8}\ \Omega$ m. The table gives values both uncorrected and corrected for thermal expansion, while Figs. 1 and 2 show only the uncorrected values. Thermal expansion values needed to carry out thermal expansion corrections were taken from Ref. 20.

The uncertainty in the recommended values is estimated to be within $\pm 5\%$ below 500 K and from 1000 to 2000 K, and $\pm 10\%$ from 500 to 1000 K and above 2000 K.

3.2. Tantalum

There are 74 sets of experimental data available for the electrical resistivity of undoped bulk tantalum as a function of temperature. These are listed in Table S-3 and tabulated in Table S-4. The residual resistivities of samples for which low-temperature (below 293 K) data are available range from $0.01\times10^{-8}\ \Omega$ m of Zablocki[56] (data set 1) to the data of White and Woods[14] (data set 65) with $\rho_0 \simeq 0.17\times10^{-8}\ \Omega$ m, and that of Berner *et al.*[60] (data set 6) and Ermolaev *et al.*[61] (data set 7) with $\rho_0 = 0.197\times10^{-8}\ \Omega$ m. The high-temperature data are for samples with purity 99.9% or better. The data sets are partially shown in Figs. 3 and 4.

The recommended values of electrical resistivity below 20 K are based on the very careful studies of Startsev *et al.*[59] (data set 5) and Ermolaev *et al.*[61] (data set 7), who find that in this temperature range Matthiessen's rule is well obeyed and that the ideal resistivity can be well represented by a T^4 law. The recommended values of electrical resistivity are for a sample with $\rho_0 = 0.1000 \times 10^{-8}$ Ω m. The constant multiplier term was determined from the following data sources: Zablocki[56] (data set 1) with $\rho_0 = 0.01 \times 10^{-8}$ Ω m, and Startsev *et al.*[59] (data set 5) with $\rho_0 = 0.0182 \times 10^{-8}$ Ω m.

The analysis of the data reported for relatively pure samples in the temperature range $20 \leqslant T \leqslant 30$ K indicates that one cannot rely on Matthiessen's rule in or above this temperature range. Fortunately, the data of Volkenshtein *et al.*[9] (data set 50) for a sample with $\rho_0 = 0.072 \times 10^{-8}$ Ω m and of White and Woods[14] (data set 65) provide a satisfactory basis for extending the recommended values to higher temperatures. The data of these authors together with those of Startsev *et al.*[59] (data set 5), and of Williams *et al.*[90] (data set 69) are used as the basis for the recommended values up to 300 K.

Above 300 K, the data of Williams *et al.*[90] (data set 69) from 300 to 400 K and of Taylor *et al.*[75,76] (data set 54) above 400 K follow with surprising consistency the mean of the values of other investigators. The data of Tye[86] (data set 64) are slightly higher and those of Williams[91] (data set 71) are slightly lower than the recommended values above 400 K. Unlike most of the raw data presented in Figs. 3 and 4, the data of Vetrogradskii[70] (data set 44) have been corrected for thermal expansion of the sample, and for better comparison with the recommended values should be corrected downward. Above 2600 K, the data tend to split into two groups: the lower lying data of Cezairliyan *et al.*[69] (data sets 21–43), Filippov *et al.*[6,71,72] (data sets 45–49), and of Shaner *et al.*[58] (data set 4) and the higher lying results of Lebedev and Mozharov[63] (data set 10). The recommended values for the electrical resistivity above 2600 K are based on a natural extension of the data at lower temperatures, and lie between the values reported by the investigators mentioned above.

The values given for the melting temperature of tantalum have varied quite significantly over the years. The very recent work gives relatively low values: Gathers[94] (data set 74) reports 3270 K and Lebedev and Mozharov[63] (data set 10) report 3258 K. Since Lebedev and Mozharov[63] (data set 10) made their observation on what should have been effectively a black body cavity, we have given preference to their melting temperature over that of Gathers,[94] which was determined on the basis of an assumption concerning the emissivity of the material.

Above the melting point, the two available sets of data on the electrical resistivity by Gathers[94] and by Lebedev and Mozharov[63] are in serious conflict. The data of Lebedev and Mozharov show the electrical resistivity falling slowly as temperature increases during the application of strong pulse heating. On the other hand, the data of Gathers[94] show ρ rising rather more rapidly as T increases. This difference cannot be attributed to errors in the temperature measurements. In both cases, the sample under observation is hydrodynamically unstable after it is melted, but significant deformation of the samples was neither expected nor observed during the 10–100 μs period of the measurements. The sample of Gathers,[94] of compact cylindrical form, seems particularly unlikely to be deformed. The arrangement of foils that made up the black body of Lebedev and Mozharov[63] might be more likely to be deformed by electromagnetic forces, but one might expect such a deformation to increase rather than to decrease ρ. In the absence of an understanding of the differing trends of the two available data sets, a constant value of $130 \pm 5 \times 10^{-8}$ Ω m was chosen for the electrical resistivity from 3258 to 4000 K. Recommendations above 4000 K cannot be made at this time.

The recommended values of the electrical resistivity given in Table 2 and shown in Figs. 3 and 4 are for tantalum of 99.9% purity or higher. However, the recommended values below 273 K should be used with caution for specimens less than 99.99% pure. The values below 60 K are applicable specifically to samples with $\rho_0 = 0.1000 \times 10^{-8}$ Ω m. The shape of resistivity curves below 60 K for specimens with higher and lower residual resistivities are indicated by the data shown in Fig. 3. The table gives both values uncorrected and corrected for thermal expansion, while Figs. 3 and 4 show only the uncorrected values along with selected experimental data. Thermal expansion values needed to carry out expansion corrections were taken from Ref. 20. The uncertainty in the recommended values is estimated to be within $\pm 2\%$ below the melting point and $\pm 3\%$ in the liquid region.

There appears to be a considerable interest in sputtered tantalum films. The usefulness of these films in the fabrication of resistors and capacitors is due partly to the formation of tetragonal β-tantalum with an electrical resistivity an order of magnitude higher than that of bulk tantalum, and a small temperature coefficient of resistance (TCR). This tetragonal phase, which exists only in sputtered film, has an electrical resistivity of about 200×10^{-8} Ω m at 293 K, compared to the electrical resistivity of 13.15×10^{-8} Ω m for the normal bcc phase of bulk tantalum.

Higher electrical resistivity and lower TCR values were achieved by various researchers using a variety of processes. Tantalum films deposited on various substrates in various gaseous atmosphere yielded low TCR values from -100 to 100 ppm C^{-1} and electrical resistivities of about 300×10^{-8} Ω m. Westwood *et al.*[95] deposited tantalum films in a triode sputtering system operated in an argon–water vapor mixture; Willmott[96] used a nitrogen atmosphere; Hardy *et al.*[97] used an oxygen and nitrogen atmosphere simultaneously in a dc sputtering system. TCR values of their films ranged from -50 to 900 ppm C^{-1} with corresponding resistivities 400 to 30000×10^{-8} Ω m. On the other hand, Westwood and Livermore[98] have reported the electrical properties of films deposited on glass and polycrystalline alumina substrates by sputtering tantalum in a dc diode sputtering system under a variety of conditions. Additional information on the electrical resistivity of tantalum films is reported in Refs. 95–162.

The data available in the literature for the temperature dependence of the electrical resistivity of bulk samples have been exhaustively reviewed in this report, and a brief mention is also made of the data on the films. Attention may also be directed to Refs. 163–167 for data on irradiated samples, Ref. 168 for annealing effects on the electrical resistivity, Refs. 169–176 for data on pressure dependence, Refs. 177–182 for data on hydrogen-doped tantalum samples, Refs. 183 and 184 for magnetic field effects, and Ref. 185 for the effect of elastic strain on the electrical resistivity. Further-

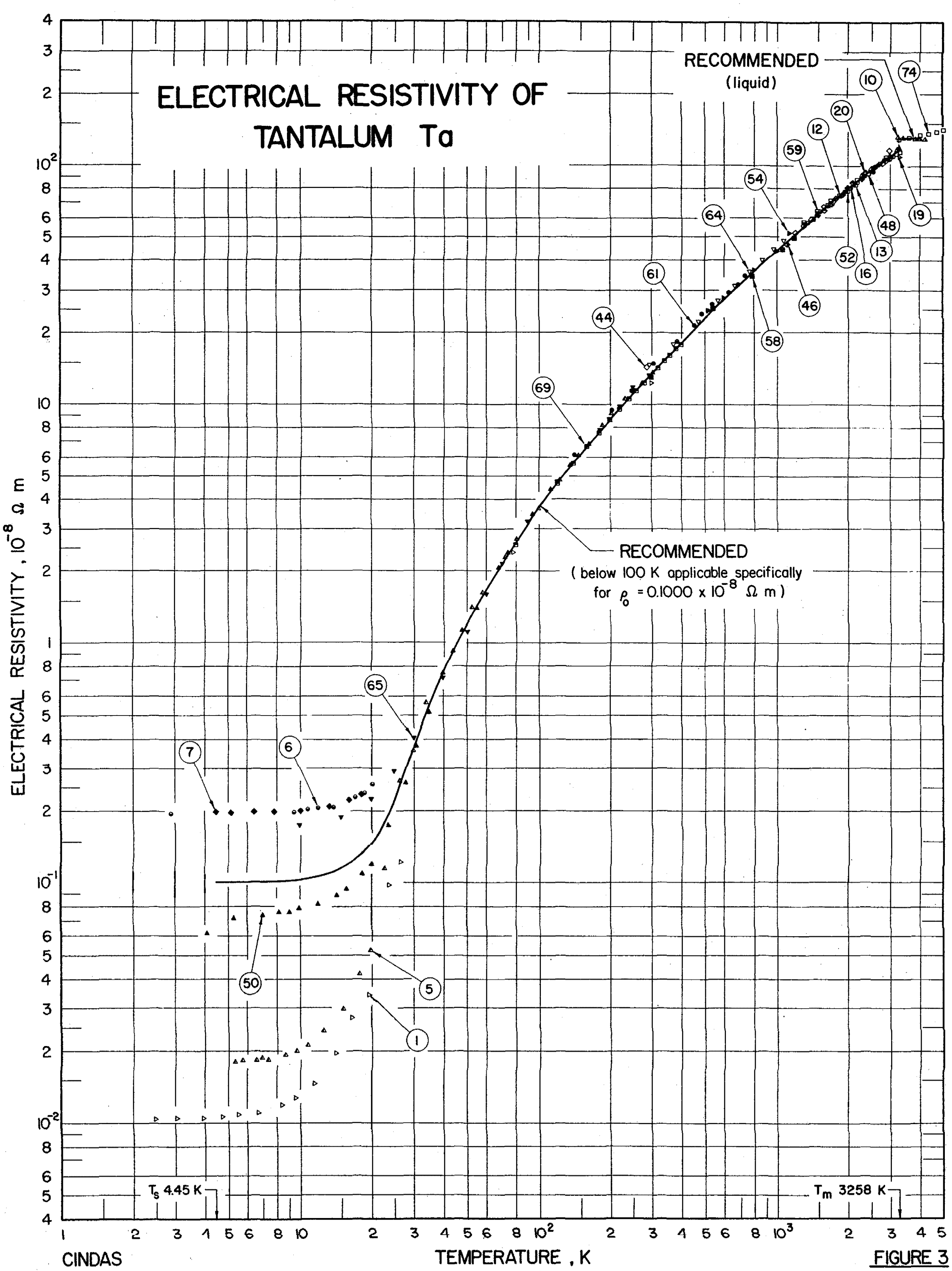
ELECTRICAL RESISTIVITY OF TANTALUM Ta
RECOMMENDED (liquid)
RECOMMENDED (below 100 K applicable specifically for ρ_0 = 0.1000 x 10^{-8} Ω m)
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
T_s 4.45 K
T_m 3258 K
CINDAS

FIGURE 3

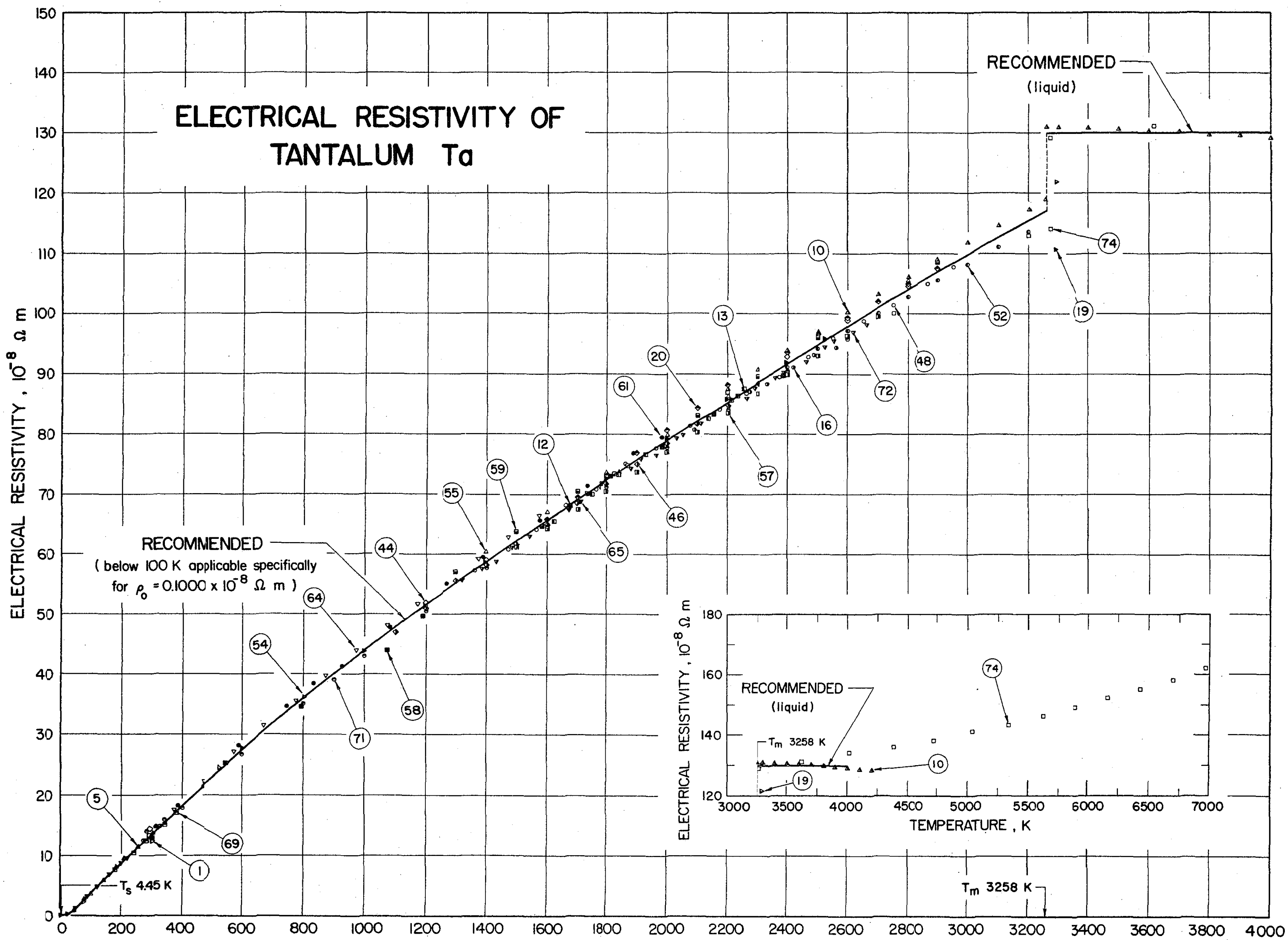
ELECTRICAL RESISTIVITY OF
TANTALUM Ta
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 100 K applicable specifically for ρ_0 = 0.1000 x 10^{-8} Ω m)
RECOMMENDED
(liquid)
T_s 4.45 K
T_m 3258 K
CINDAS
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
1
5
10
12
13
16
19
20
44
46
48
52
54
55
57
58
59
61
64
65
69
71
72
74
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(liquid)
T_m 3258 K
180
160
140
120
3000
3500
4000
4500
5000
5500
6000
6500
7000
10
19
74

FIGURE 4

TABLE 2. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF TANTALUM[a]

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
4	0.1001	0.1000	1000	44.03	44.24
7	0.1005	0.1004	1100	47.88	48.15
10	0.1023	0.1022	1200	51.60	51.93
15	0.1114	0.1113	1300	55.22	55.61
20	0.1465	0.1463	1400	58.77	59.23
25	0.224	0.224	1500	62.21	62.75
30	0.362	0.362	1600	65.63	66.25
35	0.549	0.548	1700	69.07	69.78
40	0.751	0.750	1800	72.42	73.22
45	0.963	0.961	1900	75.69	76.60
50	1.185	1.184	2000	78.92	79.94
60	1.647	1.645	2100	82.18	83.32
70	2.129	2.127	2200	85.41	86.68
80	2.623	2.620	2300	88.57	89.99
90	3.128	3.123	2400	91.65	93.22
100	3.642	3.638	2500	94.76	96.52
150	6.191	6.188	2600	97.83	99.77
200	8.660	8.655	2700	100.9	103.1
250	11.09	11.09	2800	103.9	106.3
273	12.20	12.20	2900	106.9	109.7
293	13.15	13.15	3000	109.8	112.7
300	13.48	13.48	3100	112.6	115.9
350	15.82	15.82	3200	115.5	119.1
400	18.21	18.22	3258(s)	119	122.2
450	20.58	20.61	3258(ℓ)		130
500	22.92	22.95	3300		130
550	25.18	25.22	3400		130
600	27.40	27.45	3600		130
650	29.61	29.68	3800		130
700	31.79	31.88	4000		130
750	33.89	33.99			
800	35.92	36.04			
850	38.00	38.14			
900	40.09	40.26			
950	42.09	42.28			

[a]The values are for well-annealed tantalum of purity 99.9% or higher; those below 273 K should be used with caution for tantalum less than 99.99% pure; those below 60 K are applicable specifically to tantalum with ρ_0 = 0.1000 x 10^{-8} Ω m. The estimated uncertainty in the values is within ±2% below the melting point and ±3% in the liquid region. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively.

more, Refs. 186–237 contain information on the electrical resistivity without numerical data.

3.3. References

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4. Electrical Resistivity of Molybdenum and Zinc

4.1. Molybdenum

There are 175 data sets available for the electrical resistivity of molybdenum. These are listed in Table S-5 and tabulated in Table S-6. Not surprisingly, because of its high-temperature application, most of the electrical resistivity measurements were carried out at high temperatures. The experimental data are shown in Figs. 5 and 6.

Because of its high melting temperature, zone-refined molybdenum of high purity is readily available, and specimens with residual resistivity ratios of a few thousand have been investigated. See, for example, Glebovskii *et al.*,[11] Pirogova *et al.*,[33] Whitmire and Brotzen,[50] and Capp *et al.*[53] However, the above-mentioned references give only residual resistivity values. Overall, there are only a few low-temperature data sets giving resistivity values at close temperature intervals. These are, notably, from Cox *et al.*[7] (data sets 7–10), Volkenshtein *et al.*[62] (data set 154), Volkenshtein *et al.*[63] (data sets 155,156), and from Makarov and Sverbilova[67] (data sets 171–174). Other low-temperature data sets include those of McLennan *et al.*[6] (data set 6), Meissner and Voigt[28] (data sets 50–52), Potter[41] (data set 72), Brog *et al.*[48] (data set 82), Rosenberg[58] (data set 147), Clinard and Kempter[60] (data sets 149,150), White and Woods[61] (data sets 151–153), and of Powell *et al.*[64] (data set 157), all for specimens of higher residual resistivity and apparently of lower purity. The specimens from data sets 7, 154, 156, and 170 are apparently of similar purity and are single crystals, although specimen orientations are not aligned with any particular crystal direction. Except in the residual resistance region, the agreement of these data sets is reasonable ($\pm 10\%$ of each other). Both Volkenshtein *et al.*[62] and Makarov and Sverbilova[67] reported that the temperature-dependent part of the resistivity contained both T^2 and T^5 components. Volkenshtein *et al.*[63] (data set 156) also reported values for the coefficients of these two components which, however, are not consistent with their graphical data. The present recommendations for the electrical resitivity of molybdenum at the lowest temperatures are, therefore, based on the data of Makarov and Sverbilova[67] (data set 171), whose sample has the highest reported residual resistance ratio. The coefficients used for the recommended values are slightly different from those reported by the authors in order to take into account both the experimental uncertainties and the results of Volkenshtein *et al.* and of Cox *et al.*

The T^2 and T^5 dependence of the electrical resistivity of molybdenum up to ~ 55 K has been reported by Volkenshtein *et al.*[63] and Makarov and Sverbilova.[67] The latter authors reported data up to 77 K, including data for three specimens of lower purity (data sets 171,173,174). Volkenshtein *et al.*[63] (data sets 155,156) reported data up to ~ 300 K for two specimens of different purity. The recommended values of the electrical resistivity from 30 to 300 K are based on these data sets. In addition, the data of Savitskii and Kuritnyk[19] (data sets 36,37), Holmwood and Glang[37] (data set 68), and of van Torne[46] (data set 80), all for zone-refined specimens, are also taken into account. For the upper part of this temperature range, the recommended values are adjusted so as to be consistent with the extrapolation of the values from higher temperatures.

For the temperature range 300–1000 K, the available data show large relative scatter. For example, the data of Khusainova and Fillipov[44] (data set 78) at ~ 1000 K are

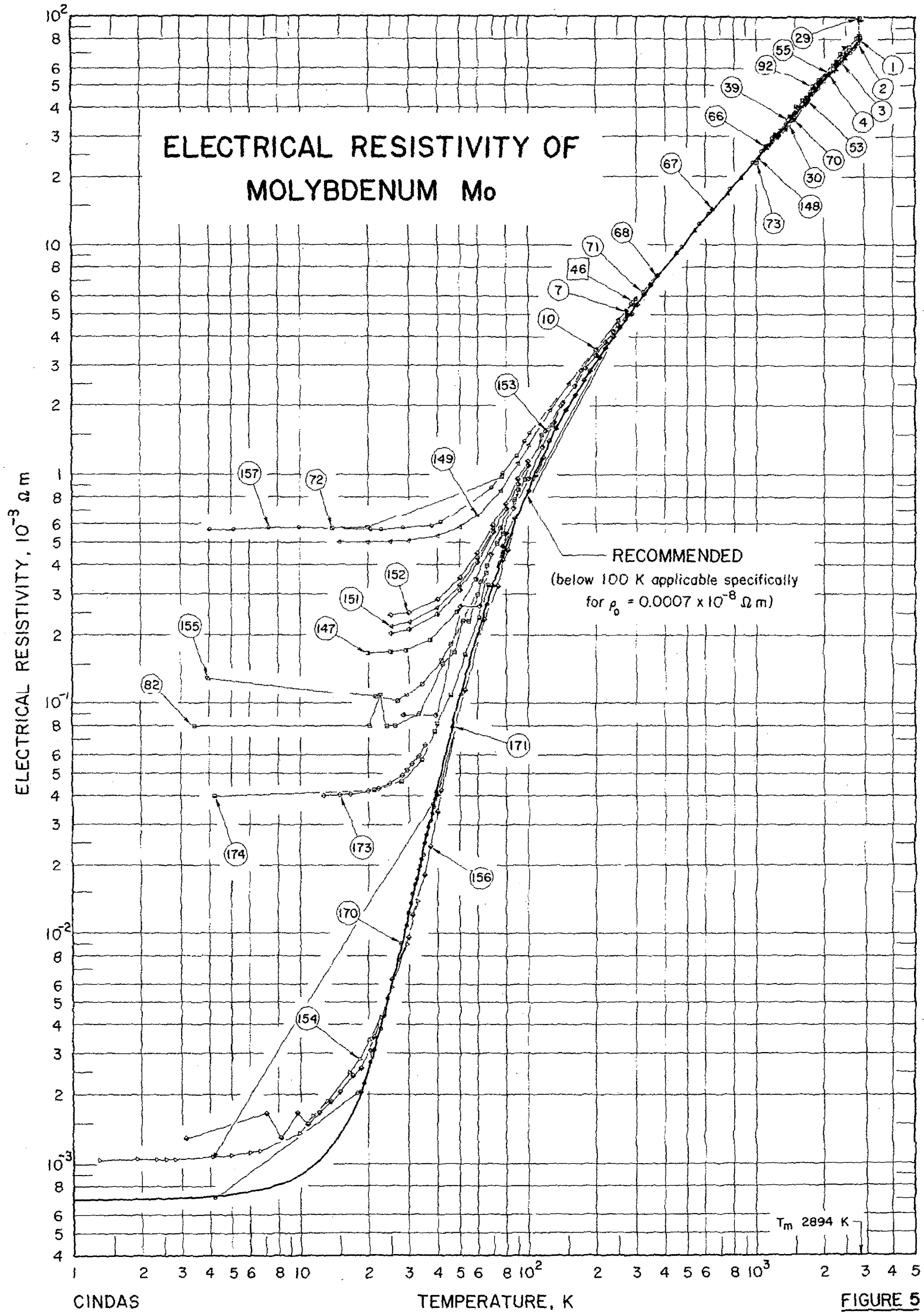
ELECTRICAL RESISTIVITY OF
MOLYBDENUM Mo
RECOMMENDED
(below 100 K applicable specifically for ρ_0 = 0.0007 x 10^{-8} Ω m)
T_m 2894 K
ELECTRICAL RESISTIVITY, 10^{-3} Ω m
TEMPERATURE, K
CINDAS

FIGURE 5

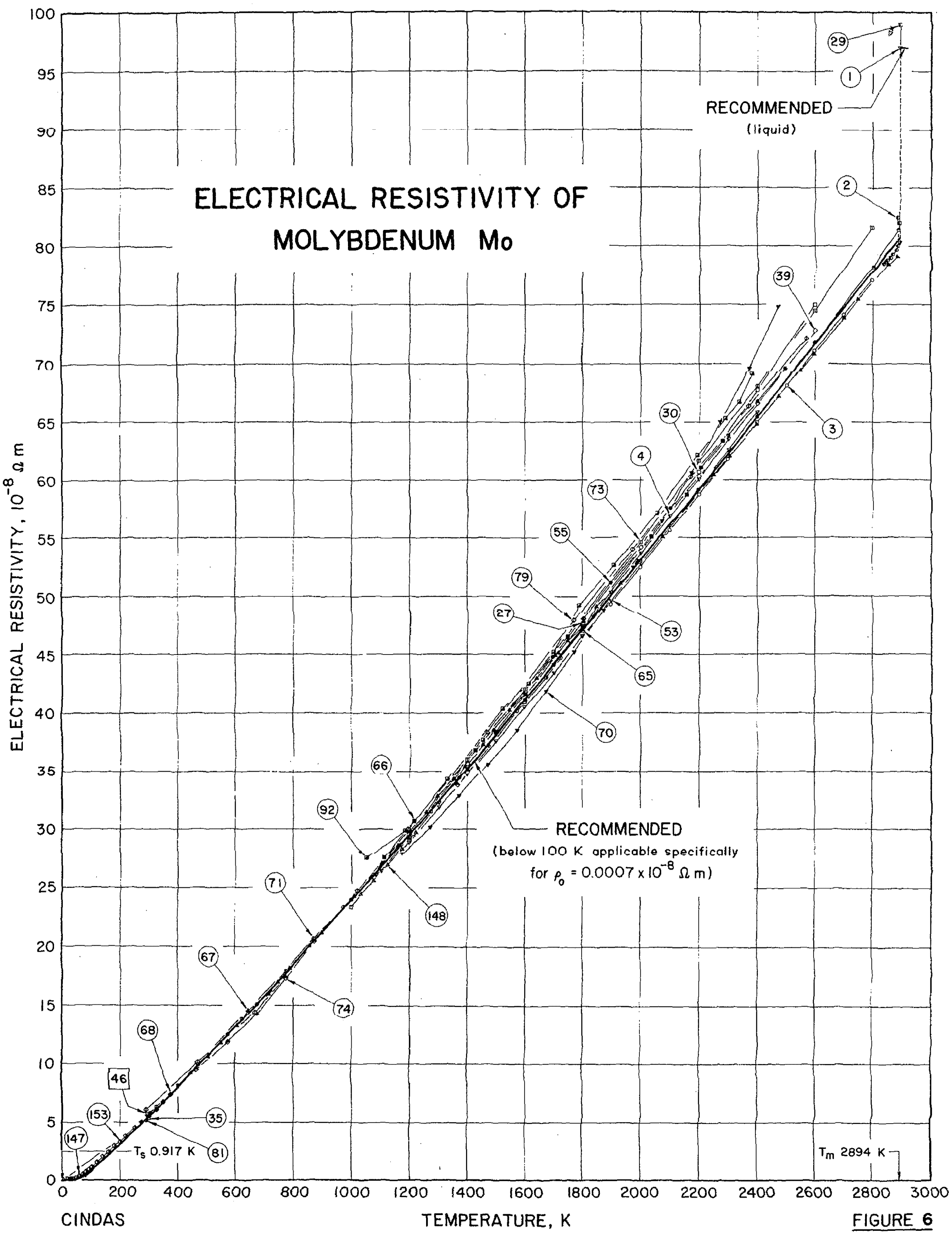
ELECTRICAL RESISTIVITY OF
MOLYBDENUM Mo
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(liquid)
RECOMMENDED
(below 100 K applicable specifically
for ρ_0 = 0.0007 x 10^{-8} Ω m)
T_s 0.917 K
T_m 2894 K
CINDAS
FIGURE 6

TABLE 3. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF MOLYBDENUM[a]

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
1	0.00070	0.00070	600	13.15	13.17
4	0.00072	0.00072	700	15.78	15.81
7	0.00078	0.00078	800	18.45	18.50
10	0.00089	0.00088	900	21.16	21.23
15	0.00135	0.00133	1000	23.91	24.00
20	0.00261	0.00258	1100	26.69	26.81
25	0.00565	0.00560	1200	29.51	29.66
30	0.0120	0.0120	1300	32.35	32.54
35	0.0249	0.0248	1400	35.23	35.46
40	0.0457	0.0456	1500	38.14	38.42
50	0.111	0.1107	1600	41.08	41.41
60	0.206	0.206	1700	44.04	44.43
70	0.330	0.330	1800	47.02	47.48
80	0.482	0.481	1900	50.03	50.56
90	0.659	0.658	2000	53.06	53.67
100	0.858	0.858	2200	59.18	59.98
150	1.990	1.989	2400	65.37	66.40
200	3.132	3.131	2600	71.61	72.93
250	4.283	4.282	2800	77.90	79.57
273	4.85	4.85	2894(s)	80.86	82.73
293	5.34	5.34	2894(ℓ)	97.0	
300	5.52	5.52			
350	6.76	6.76			
400	8.02	8.02			
500	10.56	10.57			

[a]The values are for molybdenum of purity 99.99% or higher, but those below 100 K are applicable specifically to zone-refined molybdenum having a residual resistivity of 0.0007 x 10^{-8} Ω m. The estimated uncertainty in the values is ±5% below 100 K, ±3% from 100 to 250 K, ±3% between 250 and 1100 K, and ±10% above 2894 K. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. The solid line separating tabular values indicates the solid-to-liquid state transformation.

about 3×10^{-8} Ω m below those of Tye[40] (data set 71). The data of Potter[41] (data set 72) show about the same discrepancy. The data of Schneider[32] (data set 56), on the other hand, are about 2×10^{-8} Ω m higher than those reported in data set 71. However, there are a few data sets which show good agreement: those of Taylor and Finch[36] (data set 67), Holmwood and Glang[37] (data set 68), and Tye[40] (data set 71). These data sets agree to within $\pm0.5\times10^{-8}$ Ω m in the temperature ranges where they overlap. In addition, the data of Zwilskii *et al.*[43] (data set 74) and of Feith[45] (data set 79) show approximately the same level of agreement, even though they seem to be slightly low at around 600 K. The recommended values in this temperature range are based on data sets 67, 68, 71, 74, and 79. More emphasis was given to data sets 71 and 67 since these extend to much higher temperatures.

In the temperature range 1000–2000 K, the following data sets show agreement to about $\pm1\times10^{-8}$ Ω m: Vertogradskii and Chekhovskoi[16] (data set 30), Timrot *et al.*[21] (data sets 39,40), Worthing[35] (data sets 65,66), Taylor and Finch[36] (data set 67), Tye[40] (data set 71), Baldwin *et al.*[42] (data set 73), Feith[45] (data set 79), and Taylor *et al.*[65] (data sets 158,159). All these data sets indicate a positive deviation from a linear temperature dependence in this temperature range. The agreement among the available data is not as good above 2000 K. The data of Taylor and Finch[36] (data set 67) seem to indicate a change of slope at 1800 K, indicating negative deviation from a linear temperature dependence. This negative deviation appears to be substantiated by data sets 39 and 79 and is also consistent with the data of Cezairliyan[3] (data set 3). On the other hand, the data of Vertogradskii and Chekhovskoi[16] (data set 30), Worthing[35] (data sets 65,66), and of Baldwin *et al.*[42] (data set 73) show a positive deviation. These deviations, however, are rather small so that, with the exception of data sets 73 and 30, the resistivity values are within a band of width 3×10^{-8} Ω m at ~2600 K. The present recommendation of the electrical resistivity values follows a slightly positive deviation from the linear temperature dependence. The recommended value at the melting point is about 1% lower than that given by Worthing[35] (data set 65) and about 1.2% higher than that given by Cezairliyan *et al.*[2] (data set 2). It is also within ± 1.5% of the values given by Martynyuk and Tsapkov[1] (data set 1) and by Shaner *et al.*[15] (data set 29), and within ± 2% of that given by Lebedev *et al.*[14] (data set 28). The data of Cezairliyan *et al.* show also a slight upturn (data set 2) from the linear temperature dependence in the premelting region.

There are only two data sets for the electrical resistivity of molten molybdenum: by Martynyuk and Tsapov[1] (data set 1) and by Shaner *et al.*[15] (data set 29). These values agree to within 2×10^{-8} Ω m. The recommended values are taken from the average of these two data sets.

Molybdenum is a transition element with a bcc structure. It becomes superconducting at temperatures below ~0.9 K (see, for example, Refs. 68 and 69). It is also reported that there is no anisotropy in its electrical resistivity.[19] Thus, even though the recommended values for low temperatures are derived from data for single-crystalline specimens, these values should also be applicable to polycrystals. For the sake of numerical manipulation, the following polynomial equations are given for the calculation of the electrical resistivity of molybdenum. It should be noted that this does not imply a recommendation for the temperature derivative of the electrical resistivity.

$1\ \mathrm{K} \leqslant T \leqslant 30\ \mathrm{K}$,

$$\rho = 0.0007 + 1.48\times10^{-6}T^2 + 4.12\times10^{-10}T^5.$$

$30\ \mathrm{K} \leqslant T \leqslant 100\ \mathrm{K}$,

$$\rho = 0.1077 - 8.1932\times10^{-3}T + 1.6778\times10^{-4}T^2 - 1.0794\times10^{-9}T^4.$$

$100\ \mathrm{K} \leqslant T \leqslant 250\ \mathrm{K}$,

$$\rho = 0.1187 - 1.6159\times10^{-2}T + 3.5461\times10^{-4}T^2 - 1.3884\times10^{-6}T^3 + 1.9803\times10^{-9}T^4.$$

$250\ \mathrm{K} \leqslant T \leqslant 2894\ \mathrm{K}$,

$$\rho = -1.7021 + 2.3319\times10^{-2}T + 2.5507\times10^{-6}T^2 - 2.5930\times10^{-10}T^3.$$

The recommended values should be applicable to molybdenum of purity 99.99% or higher except for temperatures below 100 K, where they apply specifically to zone-refined materials of residual resistivity $0.0007\times10^{-8}\ \Omega$ m. The uncertainty is estimated to be $\pm 5\%$ below 100 K and $\pm 3\%$ from 100 to 2894 K. Table 3 gives values both uncorrected and corrected for thermal expansion, while Figs. 5 and 6 show only uncorrected values along with selected experimental data. Thermal expansion values needed to carry out thermal expansion correction were taken from Ref. 70. Because of the existence of resistance minima (Kondo effect) in nominally pure molybdenum [see, for example, Ref. 63 (data set 155)] and in dilute molybdenum alloys (see, for example, Ref. 71), the resistivity of molybdenum of lower purity is difficult to estimate, especially in view of the fact that the residual resistivity of the specimens for which a resistance minimum has been observed varies from 0.02×10^{-8} Ω m (Ref. 71) to $0.65\times10^{-8}\ \Omega$ m (Ref. 24, data set 50).

4.2. Zinc

There are 70 data sets available for the electrical resistivity of zinc. These are listed in Table S-7 and tabulated in Table S-8. Most of them are for temperatures above ~100 K, and 10 data sets are for the molten state. The temperature ranges of the data reported vary from near 0 to ~1650 K. Among these, about 20 data sets are for single crystals. The experimental data are shown in Figs. 7 and 8.

Zinc has a hexagonal crystal structure and is superconducting below ~0.85 K. The electrical resistivity of zinc at low temperatures (< 100 K) has been studied quite sparingly. Aleksandrov and D'yakov[74,75] (data sets 5,6) reported electrical resistivity values up to ~110 K for current in both the parallel (to the c axis) and the perpendicular directions. Their specimens also had the highest purity (impurities 0.000 05% total) and the highest residual resistivity ratio (RRR), $\rho(273\ \mathrm{K})/\rho(4.2\ \mathrm{K}) \sim 60\,000$. Alderson and Hurd[109] (data sets 57,59) reported values for temperatures below 280 K for two single-crystal specimens which had nearly parallel and perpendicular orientations. Their specimens were not quite as pure as those of Aleksandrov and D'yakov, as indicated by RRR values which were lower by more than one order of magnitude. Gibbons and Falicov[112] (data sets 65,66) reported data for temperatures below 25 K on two single-crystal specimens in the parallel as well as in the perpendicular directions. The RRR values for their specimens were about one-third those of Aleksandrov and D'yakov. Collings *et al.*[80] (data set 11), Salvadori *et al.*[102] (data set 42), and Tuyn[107] (data sets 53,54) reported data below 90 K for polycrystalline specimens. In addition, Pawlek and Rogalla[84] (data sets 15–18), Goens and Gruneisen[95] (data sets 31–34), and Schimank[108] (data set 55) have reported data at wide temperature intervals. Specimens for these data sets appear to be of lower purity, judging from their higher residual resistivity values of $\sim0.001\times10^{-8}\ \Omega$ m. There are large discrepancies in the temperature dependences of the reported electrical resistivity values below 20 K. The ideal resistivity, or the temperature-dependent part of the electrical resistivity, was reported by Aleksandrov and D'yakov to have a $T^{5.1}$ dependence for "parallel" resistivity. The corresponding exponent was reported to be 4.6 by Alderson and Hurd, and was ~5.4 from the data of Gibbons and Falicov. On the other hand, for the "perpendicular" specimen, the reported exponents were 4.8, 4.1, and 4.4, respectively. In addition, the resistivity anisotropy, i.e., the ratio of the ideal resistivities in directions parallel and perpendicular to the c axis ($\rho_{i,\parallel}/\rho_{i,\perp}$), decreased monotonically to one at 0 K as indicated by the data of Aleksandrov and D'yakov above 14 K, whereas Alderson and Hurd observed a limiting value of ~0.4 at 0 K. The anisotropy observed by these latter authors can be explained by the result of Salvadori *et al.*[102] on the change in ρ_i with the residual resistivity. Salvadori *et al.* found that the ideal resistivity of zinc and of very dilute zinc alloys increased with the residual resistivity for a certain critical value of residual resistivity. Since the parallel specimen of Alderson and Hurd had a lower residual resistivity value than their perpendicular specimen, a resistivity anisotropy value of less than one appears to be reasonable. On the other hand, both the parallel and the perpendicular specimens of Gibbons and Falicov[112] (data sets 65,66) had low residual resistivity values, below the critical value suggested by Salvadori *et al.* Therefore their resistivity anisotropy, according to this argument, should be equal to one. However, calculation of the resistivity anisotropy from the data of Gibbons and Falicov seems to support the result of Alderson and Hurd.[109] It is concluded that the available data on the electrical resistivity of zinc single crystals are not sufficient for a complete analysis, and the recommended values are generated for polycrystalline material only.

Among the data for polycrystalline specimens, those of Salvadori *et al.*[102] (data set 42) gave values at close temperature intervals below ~40 K. These authors also reported the temperature-dependent part of the resistivity in a graph. Their results showed that the temperature-dependent part of the resistivity has T^5 dependence below ~15 K. Unfortunately, the data set of Collings *et al.*[80] (data set 11) was presented in a graph that did not yield enough resolution to determine the temperature dependence accurately. The T^5 temperature dependence was consistent with the result of Aleksandrov and D'yakov who found, to within their experimental uncertainty, the same dependence for their single-crystalline specimens. The data of Gibbons and Falicov[112] with $T^{5.5}$ and $T^{4.4}$ dependences, respectively, for the parallel (to the *c* axis) and perpendicular directions, also appeared to support this conclusion. For the present recommendation, the residual resistivity of $0.000\,060\times10^{-8}\,\Omega$ m is based on the data of Aleksandrov and D'yakov, who apparently had the purest specimen so far reported in the literature. The temperature-dependent part is taken to have a T^5 dependence, as discussed above. The coefficient of 1.2×10^{-8} Ω m K^{-5} is based on a mean of the results of Salvadori *et al.*, Aleksandrov and D'yakov, and of Gibbons and Falicov.

Above ~15 K, the resistivity of zinc shows a gradual decrease from the T^5 dependence. The recommended values from 15 to 80 K follow the trend of the data of Salvadori *et al.*[102] (data set 42) and of Aleksandrov and D'yakov[75] (data sets 5,6). Since the latter data sets are for single crystals, the resistivity of the polycrystal ρ_{poly} is estimated from

$$\rho_{\text{poly}} = \frac{1}{3}(\rho_{\parallel} + 2\rho_{\perp}),$$

where $\rho_{\parallel}$ and $\rho_{\perp}$ are the resistivities in the directions parallel and perpendicular to the *c* axis, respectively. The data of Tuyn[107] (data sets 53,54) are also taken into account.

Even though there are a number of data sets available in the temperature range 80–300 K, only those of Lees[92] (data set 27) and of Alderson and Hurd[109] (data sets 57–59) give values at reasonably close temperature intervals of 30 K. The values from data set 27 are judged to be too high by $\sim0.4\times10^{-8}\,\Omega$ m in that temperature range, and are ignored. The other two data sets reported values which are slightly high at the lower end of this temperature range, but are in reasonable agreement with the data of Aleksandrov[74] (data sets 3,4) for the high-purity specimens. Among the other data sets, those of Holborn[27] (data set 50), Pawlek and Rogalla[84] (data sets 17,18), Wilkes[97] (data set 36), and of Schimank[108] (data set 55) also show reasonable agreement (± ~5%). The recommended values in this temperature range are based on these data sets. The room-temperature values of Hedgcock and Muir[77] (data set 8) and of Bridgman[105] (data sets 46–49) are also taken into consideration.

The availability and the general agreement of reliable data for the electrical resistivity of zinc from room temperature up to the melting point is fairly good. The data of Holborn[27] (data set 50), Busch and Tieche[72] (data set 1), Roll and Motz[88] (data set 22), Roll *et al.*[90] (data set 25), Grube and Burkhardt[91] (data set 26), Jaeger and Diesselhorst[94] (data set 30), and of Staebler[96] (data set 35), fall within a band of width $\pm\sim0.5\times10^{-8}\,\Omega$ m in the temperature range where they overlap. Surprisingly, the data of Mikryukov and Rabotnov[93] (data set 28) for a single-crystal specimen (orientation not given) agree with the above data sets, whereas their data for a polycrystalline specimen (data set 29) are higher (by more than $1\times10^{-8}\,\Omega$ m at ~500 K). The recommended values from room temperature to the melting point are based on the above data sets with the exception of data set 29.

There are large discrepancies among the various data sets for zinc in the molten state. At temperatures slightly above the melting point, the scatter of the available data is about $\pm0.8\times10^{-8}\,\Omega$ m and, at 900 K, the scatter increases to about $\pm2\times10^{-8}\,\Omega$ m. Nonetheless, the general shape of the resistivity-versus-temperature curve for zinc in the molten state from the different data sources is similar. For example, the data of Busch and Guntherodt[73] (data set 2), Roll and Motz[88] (data set 22), and of Scala and Robertson[89] (data sets 23,24) indicate that the resistivity has a minimum value at ~950 K. The recommended values below 1100 K are based on the data of Roll and Motz[88] (data set 22), Busch and Guntherodt[73] (data set 2), and of Scala and Robertson[89] (data set 24). The data of Busch and Guntherodt[73] and of Roll and Motz[88] below the melting point are considered more reliable. The only data set for temperatures above ~1100 K, that of Regel[83] (data set 14), is considered to be too high for both the solid and the liquid states. However, the temperature variation of this data set is consistent with that of data sets 2, 22, and 24, and it is also taken into account in the recommendation process. The recommended values for temperatures above 1100 K are obtained by numerical extrapolation, following loosely the temperature variation displayed in data set 14. The recommended value at 1600 K is about 12% lower than that reported in data set 14.

For the sake of numerical manipulation, the following polynomial equations are given for the electrical resistivity of zinc. It is to be noted that these equations do not necessarily imply a recommendation for the temperature derivative of the electrical resistivity.

$T\leqslant15$ K,

$$\rho = 0.000\,06 + 1.2\times10^{-8}T^5.$$

$15\text{ K}\leqslant T\leqslant90$ K,

$$\rho = 0.077\,17 - 1.330\,38\times10^{-2}T + 6.691\,87\times10^{-4}T^2 - 5.932\,55\times10^{-6}T^3 + 2.001\,68\times10^{-8}T^4.$$

$90\leqslant T\leqslant240$ K,

$$\rho = 0.540\,84 + 1.925\,06\times10^{-2}T + 1.233\,99\times10^{-5}T^2 - 2.319\,77\times10^{-9}T^3 - 1.988\,74\times10^{-11}T^4.$$

$240\leqslant T\leqslant692.75$ K,

$$\rho = -0.729\,92 + 2.159\,13\times10^{-2}T + 3.827\,86\times10^{-6}T^2 + 1.415\,47\times10^{-9}T^3.$$

$692.73\leqslant T\leqslant1600$ K (molten state),

$$\rho = 40.818\,24 + 8.514\,02\times10^{-3}T - 3.360\,74\times10^{-5}T^2 + 2.067\,37\times10^{-8}T^3.$$

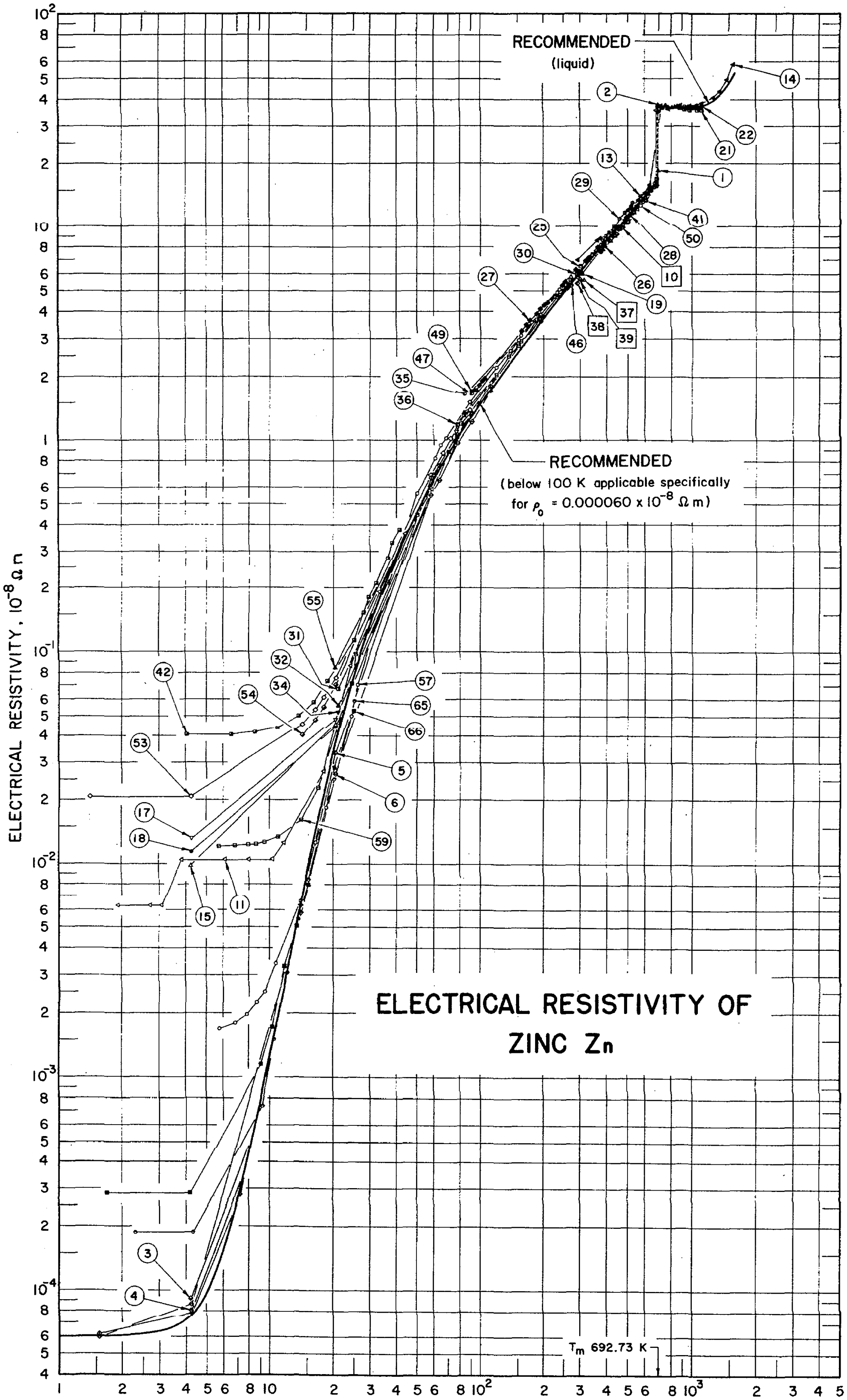
RECOMMENDED
(liquid)
RECOMMENDED
(below 100 K applicable specifically
for ρ_0 = 0.000060 x 10^{-8} Ω m)
ELECTRICAL RESISTIVITY OF
ZINC Zn
T_m 692.73 K
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
CINDAS

FIGURE 7

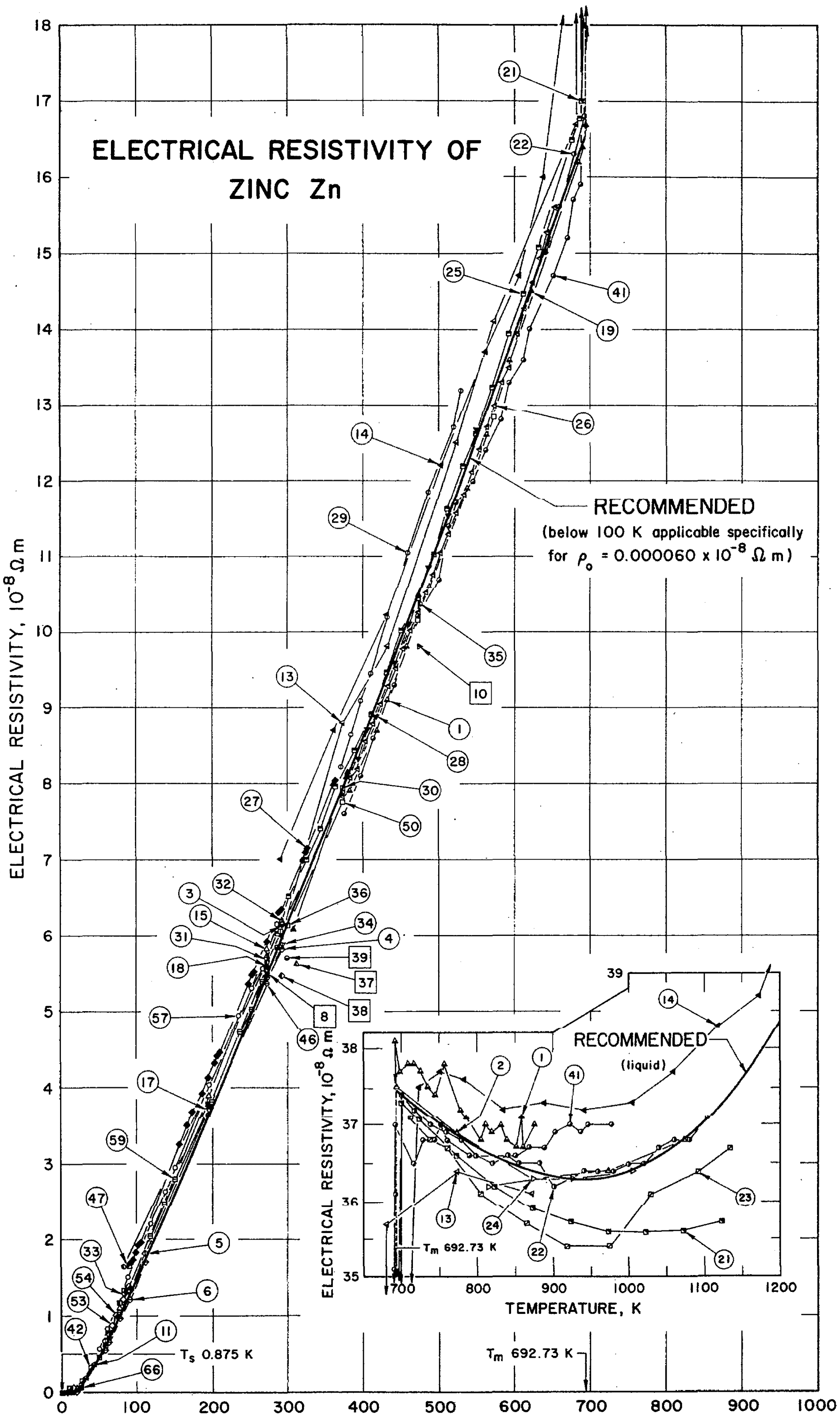
ELECTRICAL RESISTIVITY OF
ZINC Zn
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 100 K applicable specifically
for ρ_0 = 0.000060 x 10^{-8} Ω m)
RECOMMENDED
(liquid)
T_m 692.73 K
T_s 0.875 K
CINDAS

FIGURE 8

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

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
1	0.000060	0.000060	550	12.54	12.64
4	0.0000723	0.0000723	600	13.91	14.05
7	0.000262	0.000260	650	15.31	15.49
10	0.00126	0.00125	692.73(s)	16.53	16.75
15	0.00917	0.00911	692.73(ℓ)		37.46
20	0.0345	0.0343	700		37.40
25	0.0779	0.0774	750		37.02
30	0.136	0.135	800		36.71
40	0.287	0.285	850		36.47
50	0.468	0.465	900		36.33
60	0.666	0.662	950		36.30
70	0.871	0.865	1000		36.40
80	1.078	1.072	1050		36.64
90	1.289	1.281	1100		37.04
100	1.503	1.495	1200		38.36
150	2.607	2.596	1300		40.51
200	3.753	3.742	1400		43.60
250	4.929	4.923	1500		47.75
273	5.479	5.479	1600		53.09
293	5.964	5.964			
300	6.13	6.13			
350	7.36	7.37			
400	8.61	8.64			
450	9.89	9.94			
500	11.20	11.27			

[a]The values are for zinc of purity 99.99% or higher, but those below 100 K are applicable specifically to zinc having a residual resistivity of 0.000060 x 10^{-8} Ω m. The estimated uncertainty in the values is ±10% below 100 K, ±5% from 100 to 250 K, ±3% between 250 and 1100 K, and ±10% above 1100 K. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. The solid line separating tabular values indicates the solid-to-liquid state transformation.

The recommended values of the electrical resistivity given in Table 4 and shown in Figs. 7 and 8 are for zinc of 99.99% purity or higher. The table gives both uncorrected and corrected values 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. 70. As is common in the behavior of the elements at low temperatures, there are large differences in the electrical resistivity of specimens with different purity. Therefore, the values tabulated for temperatures below 100 K should be considered applicable specifically to a specimen of residual resistivity $0.000\,060\times 10^{-8}\ \Omega$ m only.

The uncertainty of the recommended values is estimated to be within ± 10% below 100 K, ± 5% from 100–250 K, ± 3% from 250–1100 K, and ± 10% at temperatures above 1100 K. The high uncertainties at the lowest and the highest temperatures are obviously due to the lack of mutually supportive data. A more definitive recommendation will have to await further experimental investigation.

From the available data, it is apparent that zinc of very high purity has been available for some time. The electrical resistivity of such pure material at low temperature is sample-size dependent. This problem has been investigated, for example, by Alderson and Hurd,[109] by Desalvo *et al.*,[113] and by Skove and Stillwell.[114]

4.3. References

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5. Electrical Resistivity of Tungsten

5.1. Tungsten

There are 201 data sets available for the electrical resistivity of tungsten. These are listed in Table S-9 and tabulated in Table S-10. Because of its high-temperature applications, a large number of the available data are for high temperatures. The experimental data are shown in Figs. 9 and 10.

The electrical resistivity of tungsten has been studied extensively, probably due to the availability of high-purity specimens obtained by zone-refining techniques. The specimen with the highest residual resistance ratio (RRR), of the order of 3×10^5, is reported by Berthel[78] (data set 199). Most authors in recent publications on low-temperature measurements reported both T^2 and T^5 components in the resistivity of tungsten. Some of them are Volkenshtein *et al.*[16] (data sets 18–21) from 2.5–33 K; Wagner *et al.*[51] (data sets 105–112), and Garland and van Harlingen[52] (data sets 113,114) from 1.4–6 K; Volkenshtein *et al.*[74] (data set 168) from 0.4–33 K; and Batdalov *et al.*[77] (data sets 182–187) from ~1.8–38 K. In addition, Berthel[78] reported a T^2 dependence for temperatures below 4 K and a T^5 dependence from 19 to 27 K. Berthel[78] also reported that the coefficient of the T^2 term is dependent on the residual resistivity of the specimen, and gives a systematic and graphical account of this dependence. Using values of the coefficient calculated from the data of Baer and Wagner[43] (data sets 78,81), van den Berg[47] (data sets 91,92), and Wagner *et al.*[51] (data sets 105,109–112), the results of Batdalov *et al.* are substantially verified. The data of Shukovsky *et al.*[72] (data set 152) and of Volkenshtein *et al.*[74] (data set 168) yield coefficients which were higher by a factor of ~2. Batdalov *et al.* arrived at an asymptotic value ($\rho_0\rightarrow0$) of $7\times10^{-13}\ \Omega$ m K^{-2} for the coefficient of the T^2 term. This is close to the value of $8\times10^{-13}\ \Omega$ m K^{-2} given by Berthel.[78] At higher temperature, there is some disagreement between the data of Berthel and of Batdalov *et al.* Berthel reported that a sum of T^2 and T^5 terms did not fit his data as well as a constant and a T^5 term. Batdalov *et al.* presented their results (data sets 182–187) in a ρ_i/T^2 versus T^3 plot, where ρ_i is the temperature-dependent part of the resistivity. Their data for temperatures from 10–38 K followed a linear behavior with a positive intercept. A similar plot for the tabular data of Berthel (data sets 194,201) gave a linear behavior in the temperature range 24–27 K, but with a slightly negative intercept. Inclusion of Berthel's data for temperatures 14–20 K (data sets 195–200) showed a good agreement with those of Batdalov *et al.* when adjusted upward by $\sim5\%$ at 17 K, 10% at 20 K, and 2% at 24 K. Such adjustments are probably not inconsistent with the experimental uncertainties ($\pm10\%$ according to Batdalov *et al.* and not given by Berthel). The coefficient of the T^5 term thus obtained from Berthel's data is about 4% higher than that given by Batdalov *et al.* for their purest specimen (data set 182). The present recommendations for the electrical resistivity of tungsten at temperatures below 40 K are based on the data of Batdalov *et al.* The values are for a specimen with residual resistivity of $0.000\,015\,0\times10^{-8}\ \Omega$ m reported by Berthel (data set 199) which represents the lowest value and, hence, the purest sample reported in the literature for tungsten.

For temperatures above 40 K, there are a few data sets for quite pure tungsten specimens. Batdalov *et al.*[77] (data set 182) reported values up to ~80 K; Batdalov *et al.*[77] (data set 178) to 288 K; and DeHaas and DeNobel[31] (data set 53) to 90 K. The data of DeHaas and DeNobel agree to within $\pm5\%$ with the other two at ~70 K, even though their residual resistivity is an order of magnitude higher. In addition, the data of White and Woods[11] (data set 12) are also in good agreement ($\pm7\%$) with those of Batdalov *et al.*[77] (data set 178) and those of DeHaas and DeNobel[31] (data set 53) in the temperature range ~80 to 280 K. Also, the data of Moore *et al.*[58] (data set 123) for an electron-beam melted specimen agree to within $\pm1\%$ above 100 K with those of White and Woods. The recommended values from 40 K to room temperature are based on the data discussed above. Although specimens investigated within this temperature range have slightly different purity, equal weight was given to all five data sets.

There are a large number of data sets available for the electrical resistivity of tungsten above 300 K. With some exceptions, the agreement among the available data is fairly good both in magnitude and in the general trend of the variation with temperature. For example, with the exception of those of Forsythe and Worthing[29] (data set 50), the data of Martynyuk and Tsapkov[45] (data set 87), Cezairliyan and McClure[50] (data set 96), Shaner *et al.*[57] (data set 120), and Jones[63] (data set 127) at around the melting point show a scatter of only about $\pm5\times10^{-8}\ \Omega$ m. The majority of the data near 1600 K fall within a band of $\pm2\times10^{-8}\ \Omega$ m. The recommended values are based on the data of Blewitt[4] (data set 4), Roberts[14] (data set 16), Neimark and Voronin[23] (data set 39), Kraev and Evgenev[33] (data set 65), Osborn[34] (data set 66), Zwikker[41] (data set 72), Fitzer[44] (data set 86), Cezairliyan and McClure[50] (data sets 96–104), Vertogradskii and Chekhovskoi[55] (data set 118), Moore *et al.*[58] (data set 121), Williams[59] (data set 124), Jones[63] (data set 127), Minges[64] (data set 129), Taylor *et al.*[65] (data set 130), and of Taylor[66]

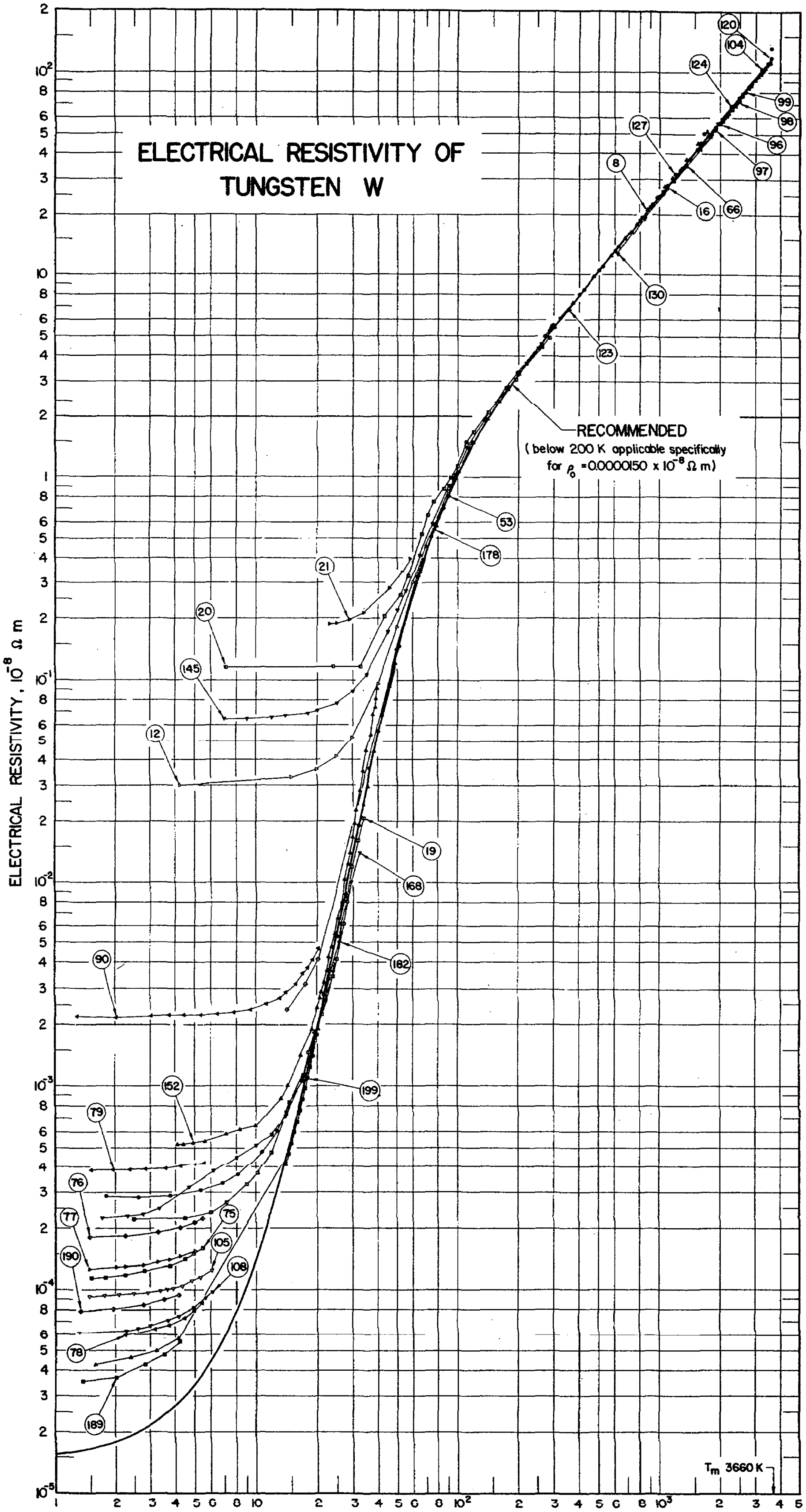
ELECTRICAL RESISTIVITY OF
TUNGSTEN W
RECOMMENDED
(below 200 K applicable specifically for ρ_0 =0.0000150 x 10^{-8} Ω m)
T_m 3660 K
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE , K
CINDAS

FIGURE 9

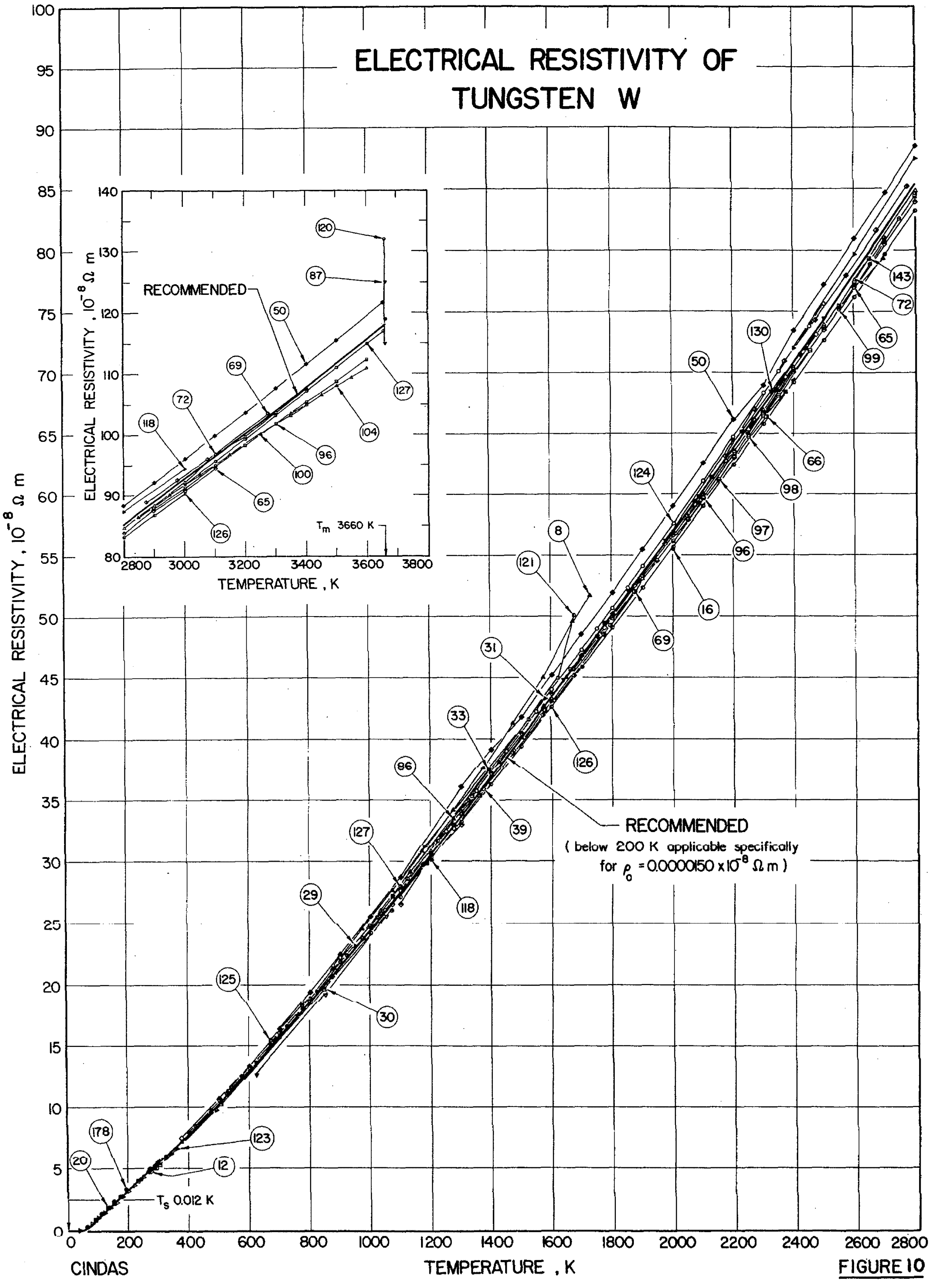
ELECTRICAL RESISTIVITY OF TUNGSTEN W
ELECTRICAL RESISTIVITY, 10^{-8} Ω m
TEMPERATURE, K
RECOMMENDED
(below 200 K applicable specifically for ρ_0 = 0.0000150 x 10^{-8} Ω m)
T_s 0.012 K
T_m 3660 K
CINDAS

FIGURE 10

TABLE 5. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF TUNGSTEN[a]

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

T	ρ uncorrected	ρ corrected	T	ρ uncorrected	ρ corrected
0	0.0000150	0.0000150	1100	27.46	27.57
1	0.0000157	0.0000157	1200	30.54	30.68
4	0.0000267	0.0000267	1300	33.68	33.84
7	0.0000580	0.0000580	1400	36.86	37.06
10	0.000137	0.000137	1500	40.09	40.33
15	0.000567	0.000567	1600	43.36	43.65
20	0.00196	0.00196	1700	46.67	47.01
25	0.00553	0.00553	1800	50.02	50.41
30	0.0133	0.0133	1900	53.41	53.85
40	0.0544	0.0543	2000	56.83	57.33
50	0.142	0.141	2200	63.76	64.41
60	0.266	0.266	2400	70.81	71.63
70	0.423	0.422	2600	77.98	79.00
80	0.606	0.606	2800	85.26	86.51
90	0.809	0.809	3000	92.66	94.18
100	1.021	1.020	3200	100.2	102.0
150	2.090	2.088	3400	107.8	110.0
200	3.18	3.18	3600	115.6	118.3
250	4.30	4.30	3660	118(s)	120.8(s)
273	4.82	4.82	3660		131(ℓ)
293	5.28	5.28	4000		135
298	5.40	5.40	4500		151
300	5.44	5.44	5000		160
400	7.83	7.83			
500	10.34	10.35			
600	12.98	13.00			
700	15.73	15.76			
800	18.56	18.61			
900	21.47	21.53			
1000	24.43	24.51			

[a] The values are for tungsten of purity 99.99% or higher, but those below 200 K are applicable specifically to tungsten having a residual resistivity of 0.0000150 x 10^{-8} Ω m. The estimated uncertainty in the values is within ±5% at low temperatures, ±3% from 100 K to 300 K, ±2% from 300 K to 2500 K, ±3% from 2500 K to the melting point, and about ±5% in the liquid region. The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. The solid line separating tabular values indicates solid to liquid state transformation.

(data set 143). For temperatures below 500 K, the data of Tye[6] (data set 8), Moore *et al.*[58] (data set 123), and Forsythe and Watson[62] (data set 126) are also taken into account.

The recommended value at the melting point is $6\times10^{-8}\ \Omega$ m higher than that of Martynyuk and Tsapkov[45] (data set 87), and $1\times10^{-8}\ \Omega$ m lower than that of Shaner *et al.*[57] (data set 120). The ratio of electrical resistivity for liquid and solid tungsten at the melting point is in excellent agreement with a value of 1.08 ± 0.01 reported by Lebedev.[81] Grosse,[82] based on his studies on low melting metals, suggested a hyperbolic behavior to electrical conductivity $(1/\rho)$ of liquid tungsten with a value equal to zero at its critical temperature. Although Grosse reported values up to the critical temperature, due to lack of supporting evidence, values only up to 5000 K are included in the present data analysis.

There are only two data sets available for the electrical resistivity of tungsten in the molten state (data sets 87, 120). Both of these measurements were carried out with the pulse-heating technique. The difference between these two data sets is $7\times10^{-8}\ \Omega$ m ($4\times10^{-8}\ \Omega$ m for the solid state) at the melting point. The recommended value for molten tungsten is obtained by multiplying the recommended value for the solid state by the resistivity ratios at melting from these two data sets.

For the purpose of easy numerical manipulation, the following polynomial expressions are given for calculating the electrical resistivity of tungsten:

$1\ \text{K}\leqslant T\leqslant 40\ \text{K}$,

$$\rho=0.000\,015+7\times10^{-7}T^2+5.2\times10^{-10}T^5.$$

$40\ \text{K}\leqslant T\leqslant 90\ \text{K}$,

$$\rho=0.144\,07-1.166\,51\times10^{-2}T+2.414\,37\times10^{-4}T^2-3.663\,35\times10^{-9}T^4.$$

$90\ \text{K}\leqslant T\leqslant 750\ \text{K}$,

$$\rho=-1.068\,71+2.068\,84\times10^{-2}T+1.279\,71\times10^{-6}T^2+8.531\,01\times10^{-9}T^3-5.141\,95\times10^{-12}T^4.$$

$750\ \mathrm{K} \leqslant T \leqslant 3600\ \mathrm{K}$,

$$\rho = -1.725\,73 + 2.143\,50 \times 10^{-2} T + 5.748\,11 \times 10^{-6} T^2 - 1.136\,98 \times 10^{-9} T^3 + 1.1167 \times 10^{-13} T^4.$$

It should be noted that the fact that these polynomials are given does not necessarily imply a recommendation for the temperature derivative of the electrical resistivity of tungsten.

The recommended values of the electrical resistivity given in Table 5 and shown in Figs. 9 and 10 are for tungsten of 99.99% purity or higher, but those below 200 K are applicable specifically to tungsten with residual resistivity $0.000\,015\,0 \times 10^{-8}\ \Omega$ 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. 80. The uncertainty is estimated to be $\pm 5\%$ below 100 K, $\pm 3\%$ from 100 to 300 K, $\pm 2\%$ from 300 to 2500 K, $\pm 3\%$ from 2500 K to the melting point, and about $\pm 5\%$ in the liquid region.

Because of its high melting temperature, tungsten of high purity is apparently quite readily available. There have been studies on the effect of external-boundary scattering on the electrical resisitivity of tungsten at liquid-helium temperatures when the electron mean free path becomes comparable to the smallest dimensions of the specimens. See, for example, Baer and Wagner,[43] Batdalov *et al.*,[77] Berthel,[78] and Stone *et al.*[79] Batdalov *et al.* concluded that at liquid-helium temperatures, boundary scattering accounts for more than 80% of the total resistivity for their purest specimen (RRR 86000). This contribution diminishes rapidly to less than 3% at 20 K. This conclusion, at least for liquid-helium temperatures, appears to be confirmed by the result of Stone *et al.* In addition, the electron–electron scattering term (i.e., the T^2 term) makes a large relative contribution at temperatures below 20 K. Thus, the electrical resistivity of tungsten with slightly higher residual resistivity (say, with RRR of $\sim$10 000) is difficult to estimate. However, for specimens in which impurity scattering becomes quite important, where the residual resistivity is $\sim 0.01 \times 10^{-8}\ \Omega$ m, it appears that the application of Matthiessen's rule for temperatures below 200 K would not introduce uncertainties in excess of those given in the preceding paragraph [see data of White and Woods[10] (data set 12) and of Moore *et al.*[58] (data set 123)].

It should be mentioned that even though a large portion of the data are for single-crystalline specimens, the difference between these and polycrystalline specimens seems to be insignificant. Since tungsten has a bcc structure, the effect of crystal orientation on its electrical resistivity should indeed be very small. This is also exemplified by the lack of interest of the authors (of the data compiled in this study) in reporting the orientation of their single-crystalline specimens.

5.2. References

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