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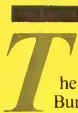
NBS SPECIAL PUBLICATION 260-90

U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Standard Reference Materials:

Update of Thermal Conductivity and Electrical Resistivity of Electrolytic Iron, Tungsten, and Stainless Steel

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Update of Thermal Conductivity and Electrical Resistivity of Electrolytic Iron, Tungsten, and Stainless Steel

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PREFACE

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This 260 Series is dedicated to the dissemination of elemental concentration data for NBS biological, geological, and environmental SRM's. More information will be found in this 260 than is generally found in NBS Certificate of Analysis. This 260 enables the user of these SRM's to assess the validity of data not available in the Certificate of Analysis. We hope that this 260 will provide sufficient additional information so that new applications of these SRM's may be sought and found.

Inquiries concerning the technical content of this compilation should be directed to the authors. Other questions concerned with the availability, delivery, price of specific SRM's should be addressed to:

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National Bureau of Standards
Gaithersburg, MD 20899

Stanley D. Rasberry, Chief
Office of Standard Reference Materials

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An update is given of the thermal conductivity and electrical resistivity of the metals: electrolytic iron, tungsten, and stainless steel. This document describes the measurement effort that has occurred since the establishment of these SRM's. New data are presented and, based on these, changes in the recommended values are described. The new recommended values are presented in the form of equations, graphs, and tables. The temperature ranges included are: 2 to 1000 K for electrolytic iron, 2 to 3000 K for tungsten, and 2 to 1200 K for stainless steel.

Key words: electrical resistivity; electrolytic iron; Lorenz ratio; stainless steel; Standard Reference Material; thermal conductivity; tungsten.

1. Introduction

The first Standard Reference Materials (SRM's) for transport properties issued by the Office of Standard Reference Materials (OSRM) of the National Bureau of Standards (NBS) were described by Hust and Sparks [1-3]. Later, the certification data for these SRM's were extended to higher temperatures as described by Hust and Giarratano [4-6]. Additional data and information on this original work can be found in refs. 7 through 11. These SRM's, in addition to serving as the basis for apparatus calibration in the technical community, drew the attention of the Task Group on Thermophysical Properties of Solids, Committee on Data for Science and Technology (CODATA). This Task Group, originally chaired by Y. S. Touloukian of the Thermophysical Properties Research Center, Purdue (TPRC) and now chaired by M. L. Minges of the Air Force Materials Laboratory, Dayton (AFML), undertook a program to intercompare the thermophysical property measurement capabilities of numerous laboratories on a world-wide basis. A secondary purpose was to improve existing SRM's and establish new SRM's where needed. As a consequence, the three NBS SRM's (electrolytic iron, tungsten, and stainless steel)* were chosen for measurement by the participating laboratories. In addition, AXM-5Q1 graphite was included in the program.

As a consequence of this program, along with related activities, a considerable number of new measurements were made available. The purpose of this document is to describe the new measurements and use them to improve the recommended values and uncertainty in the values for these materials. The graphite data generated by this program are described in another NBS Special Publication of this series (in press). A description of the CODATA program has been given by Minges [12].

*These materials are currently available from the Office of Standard Reference Materials as SRM 1460-1462 (stainless steel), RM 8420 and 8421 (electrolytic iron) and RM 8422 and 8423 (sintered tungsten).

2. New Measurements

For convenience, the new measurements are divided into two categories, a) Low temperatures and b) High temperatures. The dividing line between these two categories is taken to be approximately 300 K. For the most part, these new data have been published in the open literature; however, in a few instances the data are referenced by private communication only.

The low temperature measurements were coordinated by Dr. R. Berman, Oxford University, the high temperature measurements by Dr. M. L. Minges, Air Force Materials Laboratory under the auspices of the CODATA Task Group on Thermophysical Properties of Solids. J. G. Hust was responsible for specimen characterization and distribution as well as specimen collection, post characterization, and final data analysis.

2.1 Low Temperature Measurements

The most significant low temperature measurements conducted on these materials are described by Berman, et al. [13]. The measurements include only values of thermal conductivity and electrical resistivity. Measurements were conducted by other laboratories but they were unpublished and judged to be unreliable by the coordinator. The data described by Berman, et al. [13] will be identified in this document according to the measurement facility, e.g., Leeds (Physics Department, University of Leeds, U.K.), NML (CSIRO, Division of Applied Physics, National Measurement Laboratory, Sydney, Australia), and NBS. The uncertainty from these sources is estimated to be about one percent for electrical resistivity, and two to four percent for thermal conductivity. In general, these data agree quite well with each other and the original NBS data. The largest deviations occur at the lowest temperatures, i.e., in the vicinity of the peak in the λ curve and below.

2.2 High Temperature Measurements

The new high temperature measurements summarized in Table 1 on these materials include: thermal conductivity, electrical resistivity, thermal diffusivity, thermal expansion, specific heat, and Seebeck coefficient. Although it would be desirable to analyze each of these measured properties at this time, funding limitations restrict this document to the analysis of thermal conductivity and electrical resistivity only. It is anticipated that the measurements of the other properties will be analyzed in the future. The results of these future analyses will be the basis for recommended values for the additional properties. The data that have been obtained since 1979 are summarized below. The experimental data have been corrected for thermal expansion by the participants. No further corrections were performed.

The high temperature electrical resistivity data are believed accurate to about one to two percent. The thermal conductivity data accuracy varies from about one to five percent. Exceptions are noted in the section on data analysis (Section 3).

Table 1.

Materials	Properties	Temperature Range (K)	Reference
Arc-Cast Tungsten	D	500-2400	14
"	λ, ρ	349-1266	19
"	λ	293-773	20
Sintered Tungsten	λ, ρ, C_p, D	1300-2600	22
Tungsten	C_p, ρ	2000-3600	18
Electrolytic Iron	D	296-1373	15
Stainless Steel	D	286-1450	15
"	λ, ρ, S	4-1100	16
"	D	500-1200	17
"	λ, ρ	322-1173	21
"	C_p	323-773	23
"	C_p	320-800	24
"	D	450-1000	25
λ = Thermal Conductivity ρ = Electrical Resistivity D = Thermal Diffusivity S = Seebeck Coefficient C_p = Specific Heat			

3. Data Analysis

The data analysis for each of the materials was performed using both the old and new data. An equation was developed to describe the temperature dependence of each property for each material. In the case of the purer metal SRM's, iron and tungsten, these equations include the dependence on impurity variations. These equations were used to examine the detailed differences between the data sets. Finally, the equations were used to establish smoothed recommended values for each property and SRM.

The general form of the thermal conductivity equation for the pure metals, iron, and tungsten is given by

$$\lambda = (W_0 + W_i + W_{i0})^{-1} \quad (3.1)$$

where

$$W_0 = \beta/T, \text{ where } \beta = \frac{\rho_0}{L_0} \quad (3.2)$$

where L_0 = the Sommerfeld value of the Lorenz ratio = 2.443×10^{-8}

$$W_i = P_1 T^{P_2} / (1 + P_1 P_3 T^{(P_2+P_4)} \exp(-(P_5/T)^{P_6})) + W_c \quad (3.3)$$

and

$$W_{i0} = P_7 W_i W_0 / (W_i + W_0) \quad (3.4)$$

The general form of the electrical resistivity equation is given by

$$\rho = \rho_0 + \rho_i + \rho_{i0} \quad (3.5)$$

where ρ_0 = residual electrical resistivity

$$\rho_i = P_1 T^{P_2} / (1 + P_1 P_3 T^{(P_2+P_4)} \exp(-(P_5/T)^{P_6})) + \rho_c \quad (3.6)$$

and

$$\rho_{i0} = P_7 \rho_i \rho_0 / (\rho_i + \rho_0) \quad (3.7)$$

W_c and ρ_c are empirical functions chosen to represent the undulatory systematic residuals in the fit of the data. These equations are chosen so they can be programmed easily on small calculators requiring a minimum of precision in the parameters. They also maintain a theoretical basis at low temperatures.

3.1 Electrolytic Iron

The experimental thermal conductivity data reported for this RM are illustrated in figure 3.1.1. The high temperature data of Fulkerson, et al. [26] are included because their data is the basis of the previous SRM certification in this temperature range. Unfortunately, no new data in this range were established.

The identification of each data source is difficult in figure 3.1.1, however, it is more clear in the later deviation plots. Equation 3.1 was fitted to these data by nonlinear least squares techniques, and the resulting parameters are

$$\begin{aligned} P_1 &= 274.6 \times 10^{-8} & P_5 &= 245.4 \\ P_2 &= 1.757 & P_6 &= 1.375 \\ P_3 &= 1.5167 \times 10^5 & P_7 &= 0.0 \\ P_4 &= -1.22 \end{aligned}$$

where λ is in $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and T in K.

The residuals were represented by

$$\begin{aligned} W_c &= -0.004 \ln(T/440) \exp(-(\ln(T/650)/0.8)^2) \\ &\quad -0.002 \ln(T/90) \exp(-(\ln(T/90)/0.45)^2) \end{aligned} \quad (3.8)$$

where W_c and T are in $\text{m}\cdot\text{K}\cdot\text{W}^{-1}$ and K, respectively.

To obtain a good fit at low temperatures, it was found that the experimental value of β had to be multiplied by 0.98. This is equivalent to a Lorenz ratio 2% higher than the Sommerfeld value. The resulting deviations of the experimental data from this equation are illustrated in figure 3.1.2.

The deviations of the previously recommended thermal conductivity values for this RM are illustrated in figure 3.1.3. It is noted that the most significant change is below 30 K. Otherwise the differences are within the combined uncertainties of the recommended values.

The previous certification indicated that if a prescribed heat treatment was followed, the resulting specimen would have a specified residual electrical resistivity, ρ_0 . The recent work has shown that this is not the case and the form of equation (3.1) contains the proper correction for variations in ρ_0 .

The experimental electrical resistivities for this RM are illustrated in figure 3.1.4. Again, no new high temperature data are available. Equation (3.5) was fitted by nonlinear least squares to these data. The resulting parameters are

$$\begin{aligned} P_1 &= 42.17 \times 10^{-16} & P_5 &= 178.5 \\ P_2 &= 3.243 & P_6 &= 1.98 \\ P_3 &= 7.638 \times 10^{11} & P_7 &= 0.05944 \\ P_4 &= 1.95 \end{aligned}$$

where ρ is in $\Omega \cdot m$ and T is in K.

The residuals were represented by

$$\begin{aligned} \rho_c &= -3 \times 10^{-8} \ln(T/370) \exp(-(\ln(T/600)/0.6)^2) \\ &\quad - 3 \times 10^{-9} \ln(T/105) \exp(-(\ln(T/120)/0.45)^2) \end{aligned} \quad (3.9)$$

where ρ_c and T are in $\Omega \cdot m$ and K, respectively.

The resulting deviations of the experimental data from this equation are illustrated in figure 3.1.5. The deviations of the previously recommended values are shown in figure 3.1.6.

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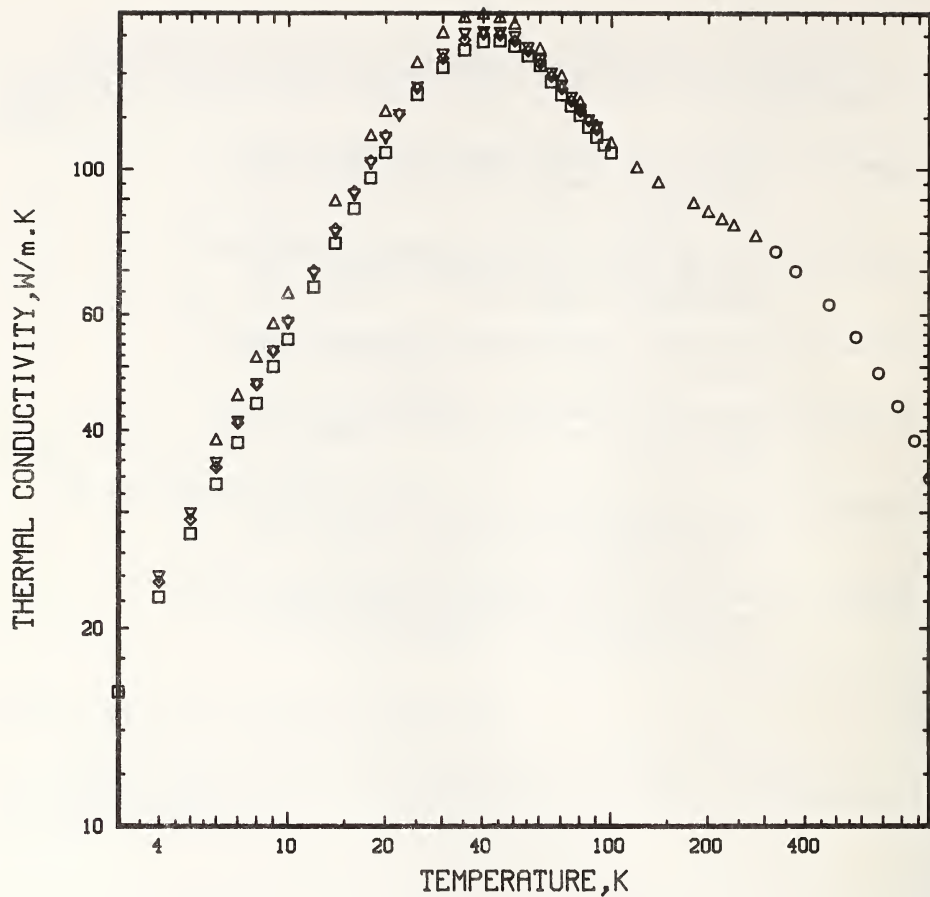


Figure 3.1.1 Experimental thermal conductivity data for the electrolytic iron RM from the following sources: (8,13,26)

○ - (26), △ - (8), □ - (13), ▽ - (13),
 ◇ - (13), + - (13)

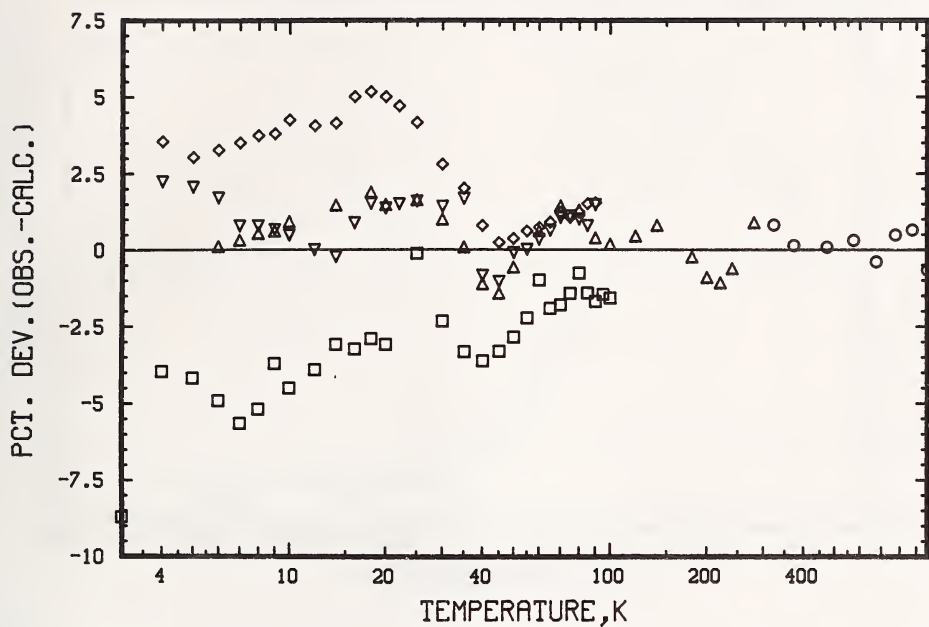


Figure 3.1.2 Thermal conductivity deviations of the electrolytic iron
RM data of the following references from eq.(3.1):
(8,13,26)

○ - (26), △ - (8), □ - (13), ▽ - (13),
◇ - (13)

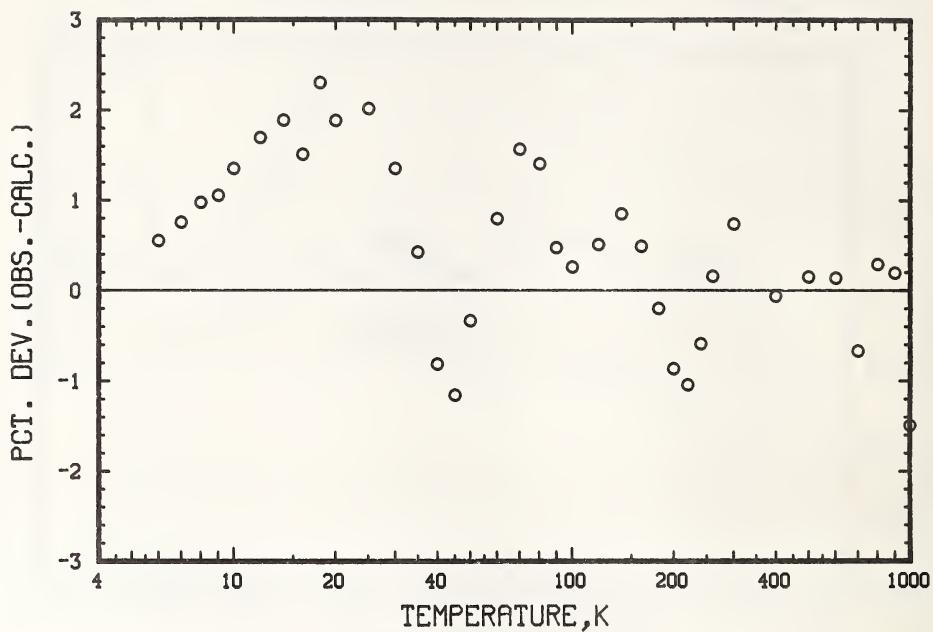


Figure 3.1.3 Deviations of the previously recommended thermal conductivity values (6) from eq.(3.1).

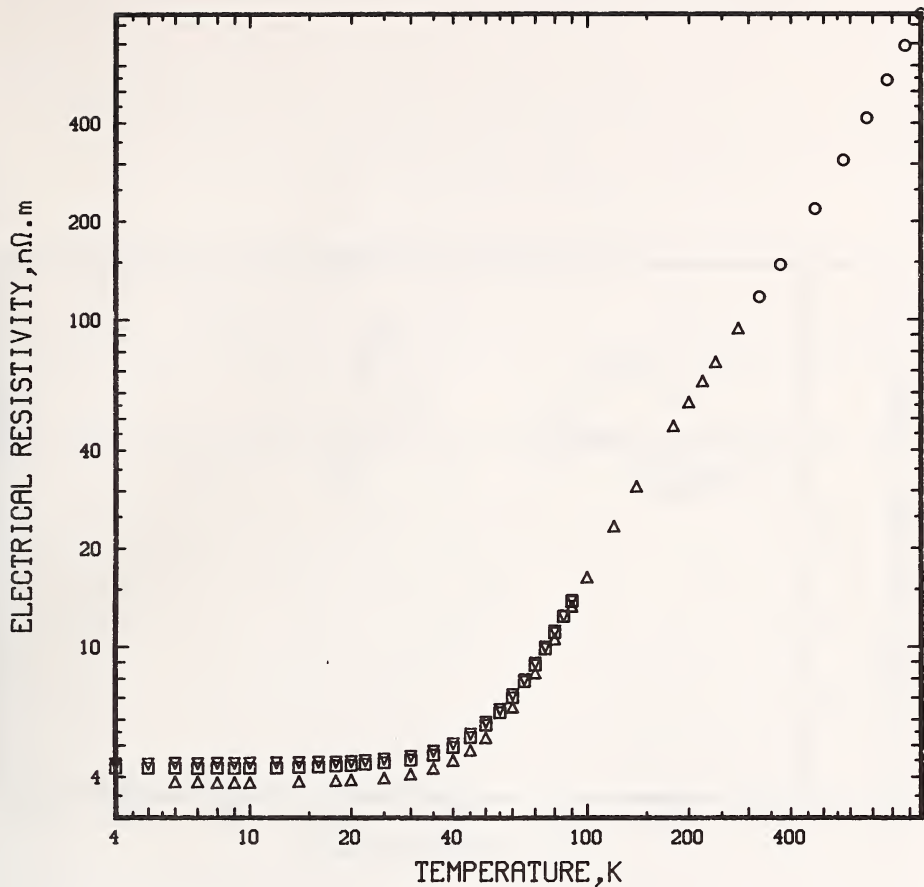


Figure 3.1.4 Experimental electrical resistivity data for the electrolytic iron RM from the following sources: (8,13,26)

O - (26), Δ - (8), \square - (13), ∇ - (13)

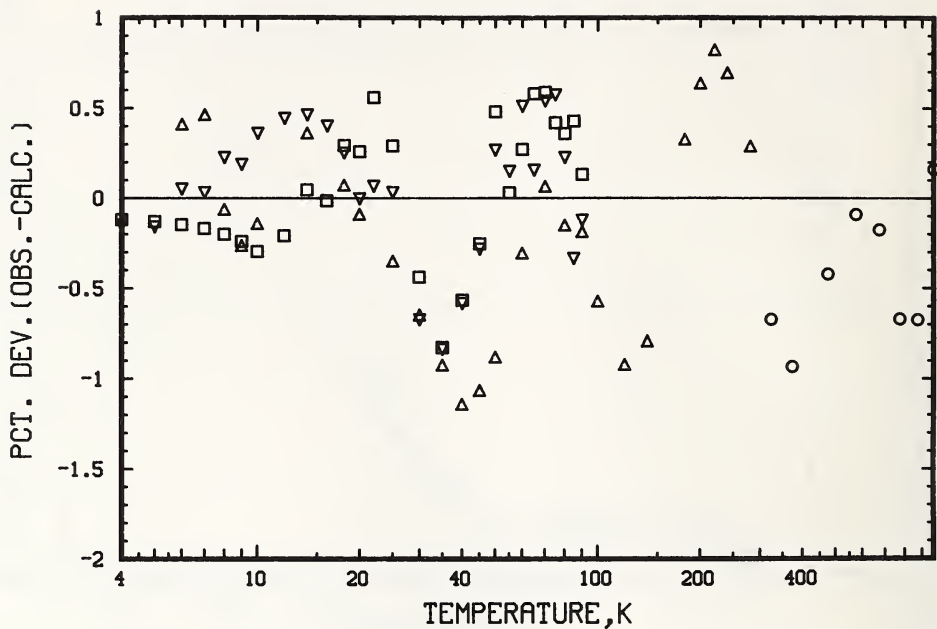


Figure 3.1.5 Electrical resistivity deviations of the electrolytic iron RM data of the following references from eq.(3.5): (8,13,26)

O - (26), Δ - (8), □ - (13), ▽ - (13)

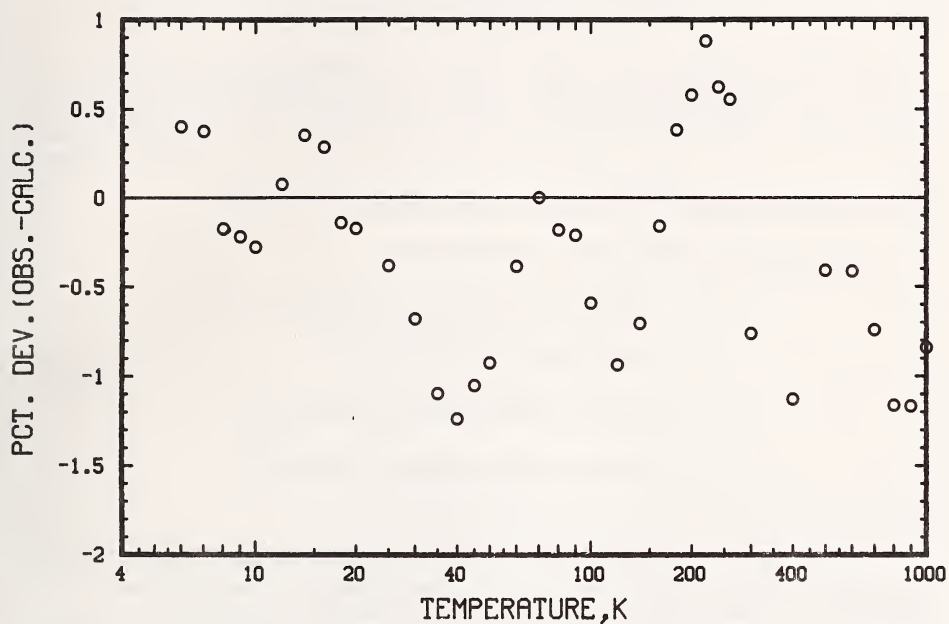


Figure 3.1.6 Deviations of the previously recommended electrical resistivity values (6) from eq.(3.5).

3.2 Tungsten

The experimental thermal conductivity data reported for tungsten are illustrated in figures 3.2.1 through 3.2.3. Figure 3.2.3 is a composite of 3.2.1 and 3.2.2 but without a legend. Equation (3.1) was fitted to the experimental data by nonlinear least squares. The resulting parameters are

$$\begin{aligned} P_1 &= 16.4 \times 10^{-8} & P_5 &= 69.21 \\ P_2 &= 2.449 & P_6 &= 3.986 \\ P_3 &= 541.3 & P_7 &= 0.1 \\ P_4 &= -0.22 \end{aligned}$$

where λ and T are in $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and K , respectively.

The systematic residuals were represented by

$$\begin{aligned} W_c = & -0.00085 \ln(T/130) \exp(-(\ln(T/230)/0.7)^2) \\ & + 0.00015 \exp(-(\ln(T/3500)/0.8)^2) \\ & + 0.0006 \ln(T/90) \exp(-(\ln(T/80)/0.4)^2) \\ & + 0.0003 \ln(T/24) \exp(-(\ln(T/33)/0.5)^2) \end{aligned} \quad (3.10)$$

where W_c and T are in $\text{m}\cdot\text{K}\cdot\text{W}$ and K , respectively.

The resulting deviations of the experimental data from this equation are illustrated in figures 3.2.4 through 3.2.6. The deviations of the previously recommended thermal conductivity values for this RM are illustrated in figure 3.2.7. Here we observe significant differences at both ends of the temperature range. As with iron, the variations at low temperatures due to impurity variations are accounted for by the presence of the β/T term.

The experimental electrical resistivity data reported for tungsten are illustrated in figures 3.2.8 through 3.2.10. Equation (3.1) was fitted to the experimental data by nonlinear least squares. The resulting parameters are:

$$\begin{aligned} P_1 &= 4.801 \times 10^{-16} & P_5 &= 55.63 \\ P_2 &= 3.839 & P_6 &= 2.391 \\ P_3 &= 1.88 \times 10^{10} & P_7 &= 0.0 \\ P_4 &= 1.22 \end{aligned}$$

where ρ and T are in $\Omega \cdot m$ and T , respectively.

The systematic residuals were represented by

$$\rho_C = 7 \times 10^{-9} \ln(T/560) \exp(-(\ln(T/1000)/0.6)^2)$$

where ρ_C and T are in $\Omega \cdot m$ and K , respectively.

The resulting deviations of the experimental data from this equation are illustrated in figures 3.2.11 through 3.2.13. The deviations of the previously recommended electrical resistivity values for this RM are shown in figure 3.2.14. The differences are not significant compared to the uncertainties in the recommended values.

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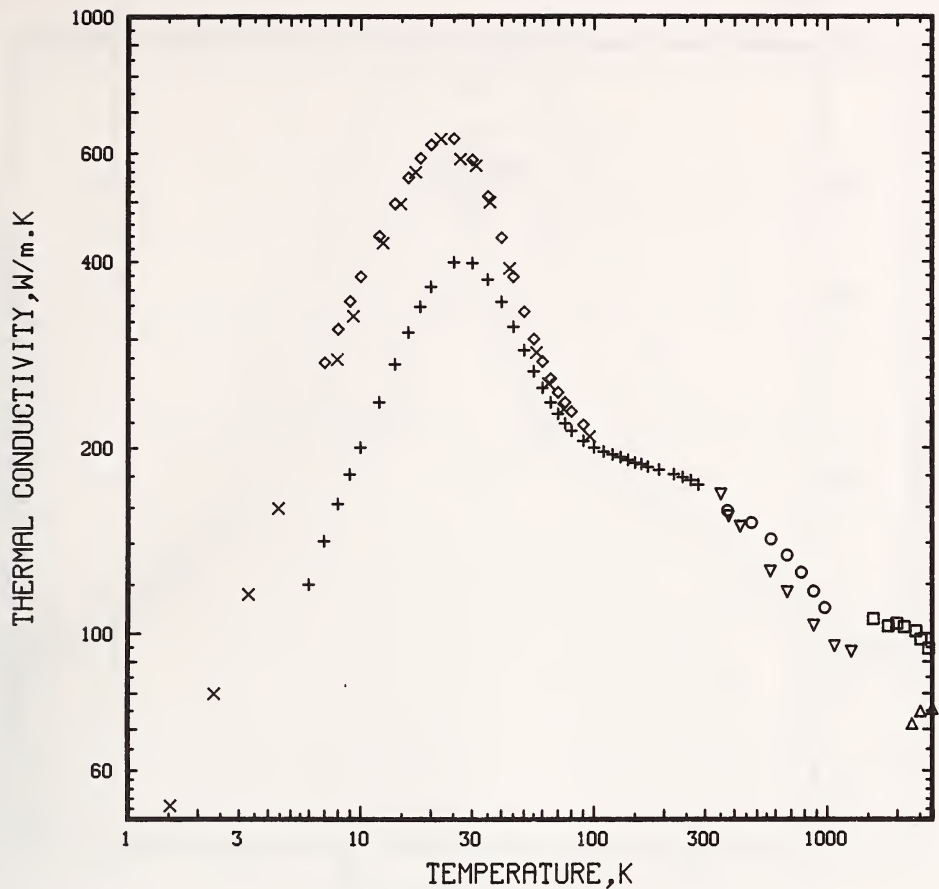


Figure 3.2.1 Experimental thermal conductivity data for the tungsten RM from the following sources:
(11,13,19,27)

O - (27), Δ - (27), □ - (27), ▽ - (19),
◇ - (11), + - (11), X - (13)

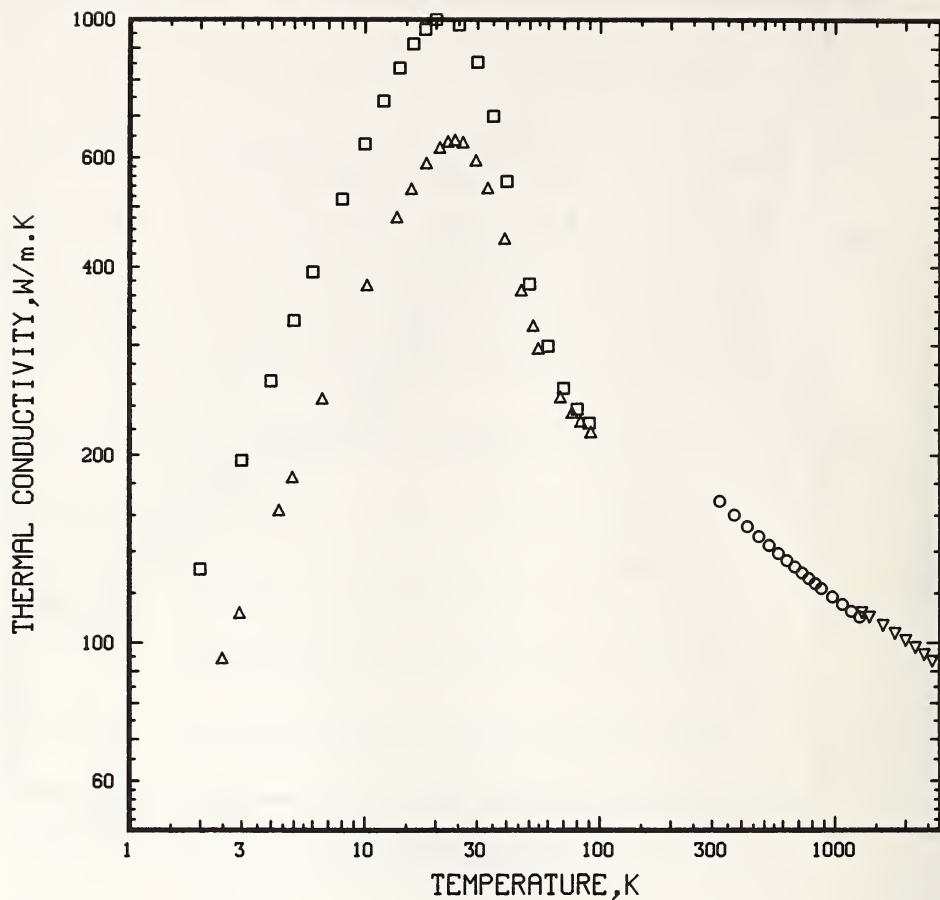


Figure 3.2.2 Experimental thermal conductivity data for the tungsten RM from the following sources: (13,22,28)

\circ - (28), Δ - (13), \square - (13), ∇ - (22),

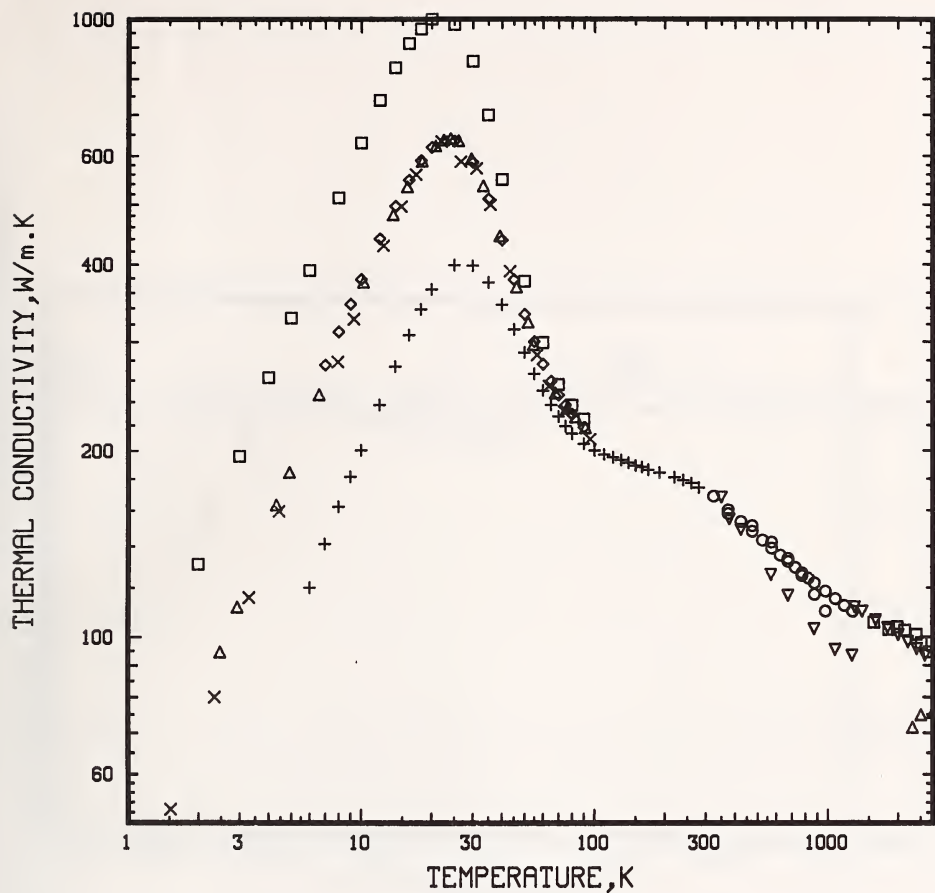


Figure 3.2.3 Composite of the data in figs. 3.2.1 and 3.2.2

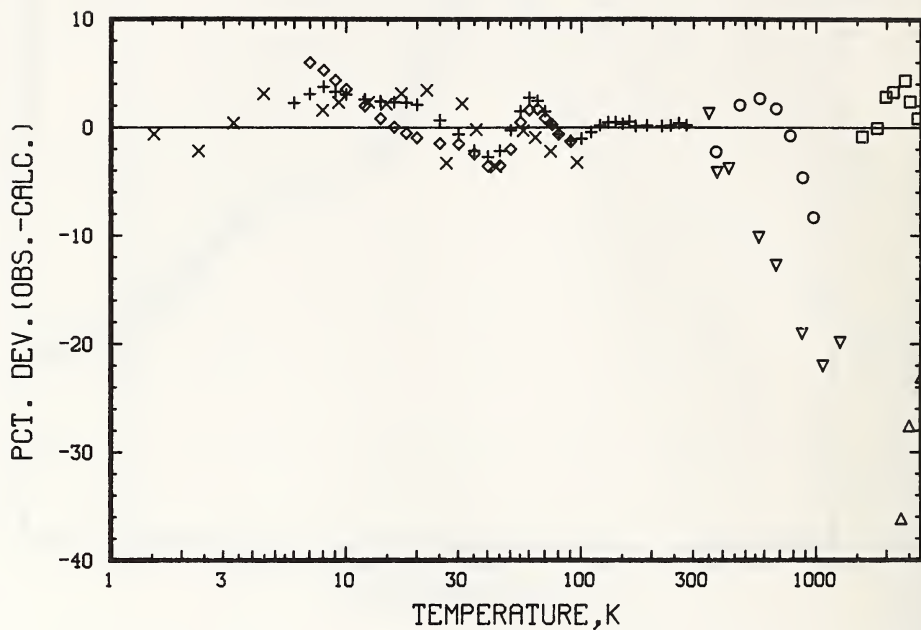


Figure 3.2.4 Thermal conductivity deviations of the tungsten
RM data of the following references from eq.(3.1):
(11,13,19,27)

○ - (27), △ - (27), □ - (27), ▽ - (19),
◇ - (11) + - (11), × - (13)

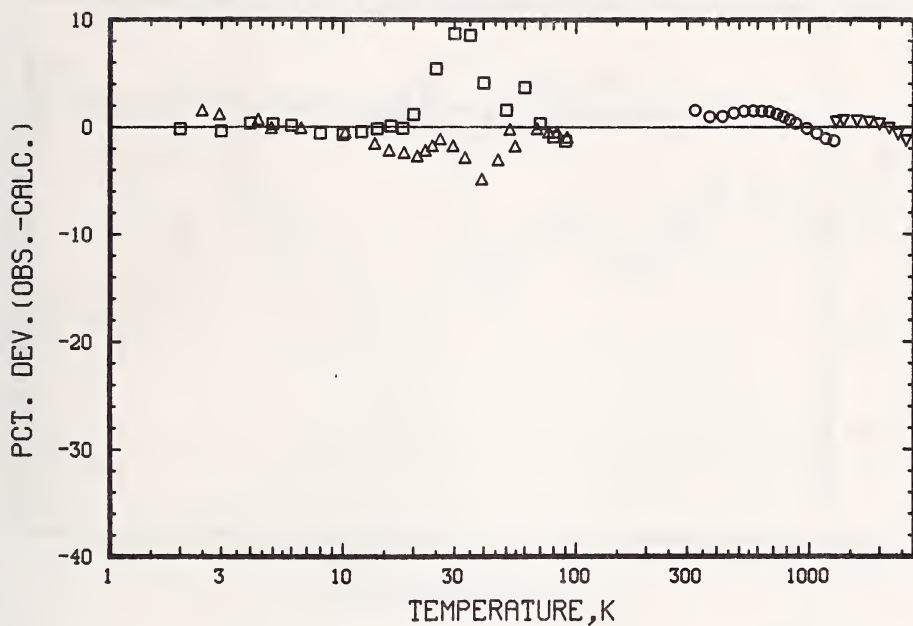


Figure 3.2.5 Thermal conductivity deviations of the tungsten
RM data of the following references from eq.(3.1):
(13,22,28)

○ - (28), △ - (13), □ - (13), ▽ - (22)

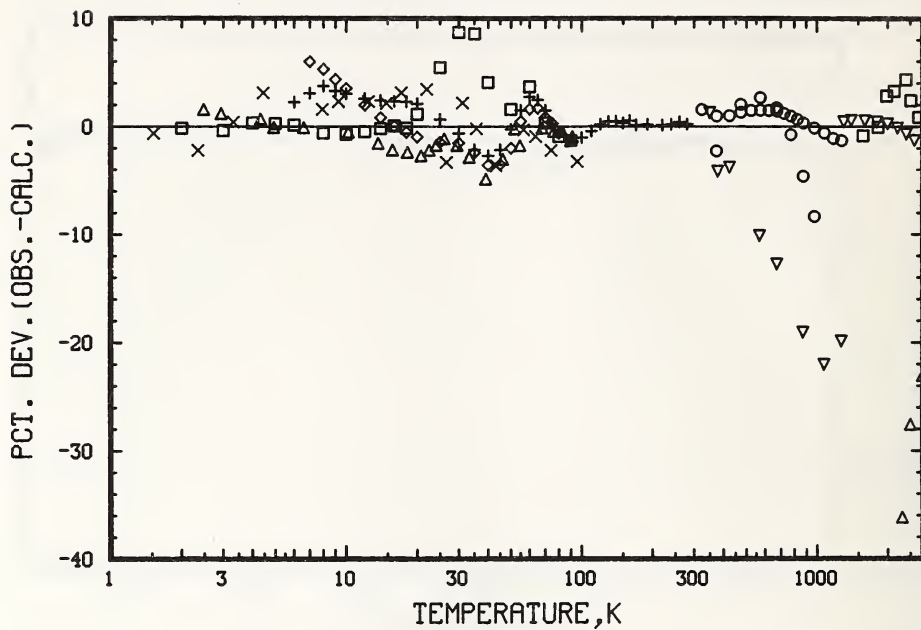


Figure 3.2.6 Composite of the data in figs. 3.2.4 and 3.2.5

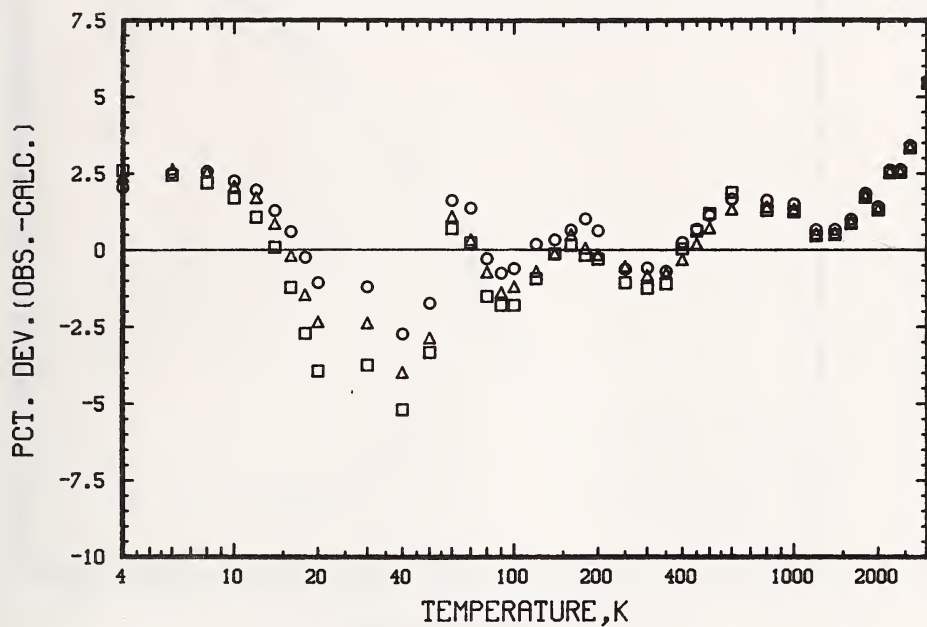


Figure 3.2.7 Deviations of the previously recommended thermal conductivity values (5) from eq.(3.1).

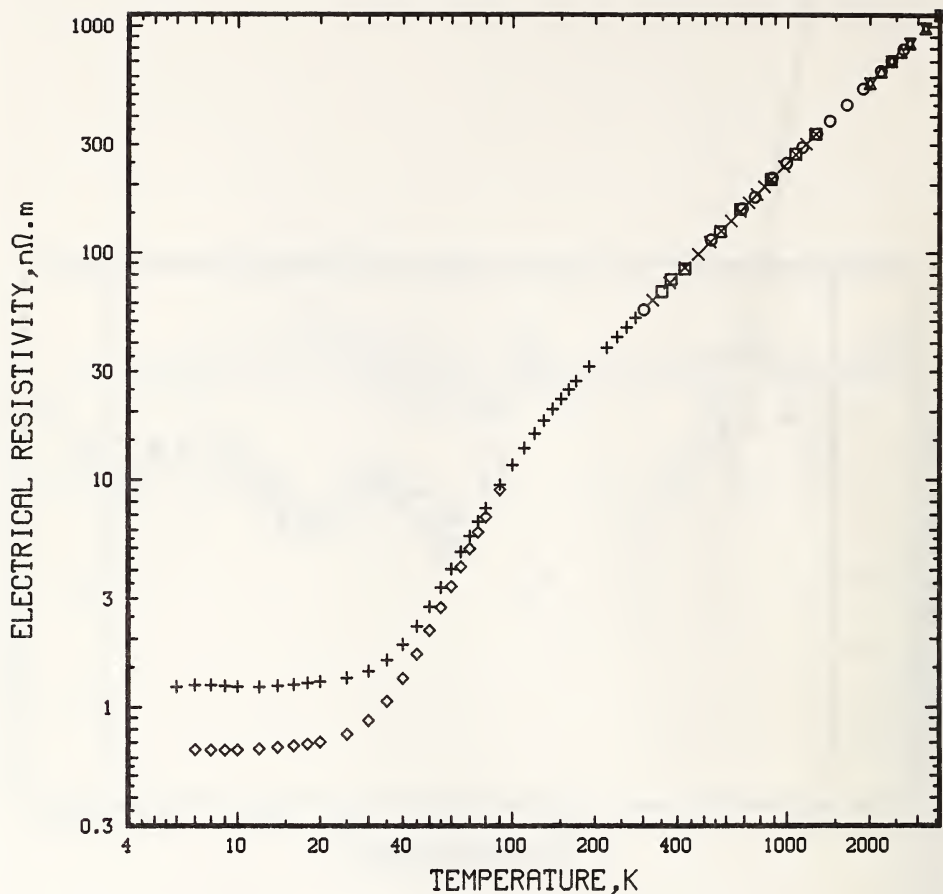


Figure 3.2.8 Experimental electrical resistivity data for the tungsten RM from the following sources: (11,18,19,27,28)

○ - (27), △ - (27), □ - (19), ▽ - (18)
 ◇ - (11), + - (11), × - (28)

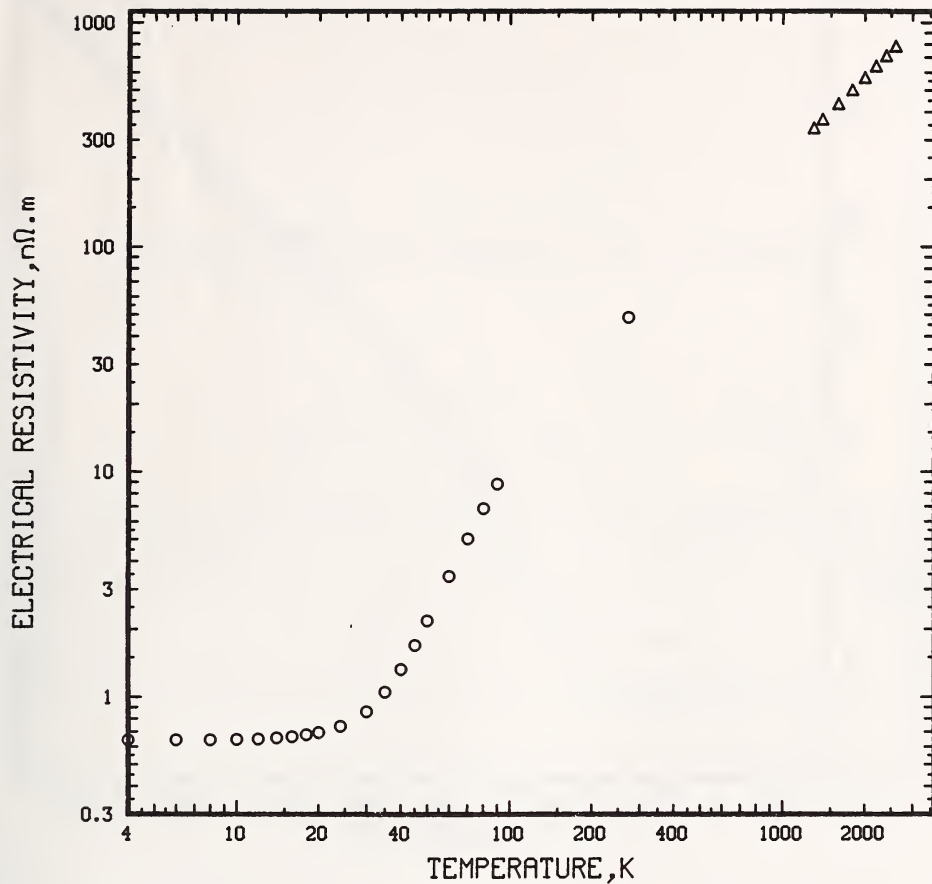


Figure 3.2.9 Experimental electrical resistivity data for the tungsten RM from the following sources: (13,22)

O - (13), Δ - (22)

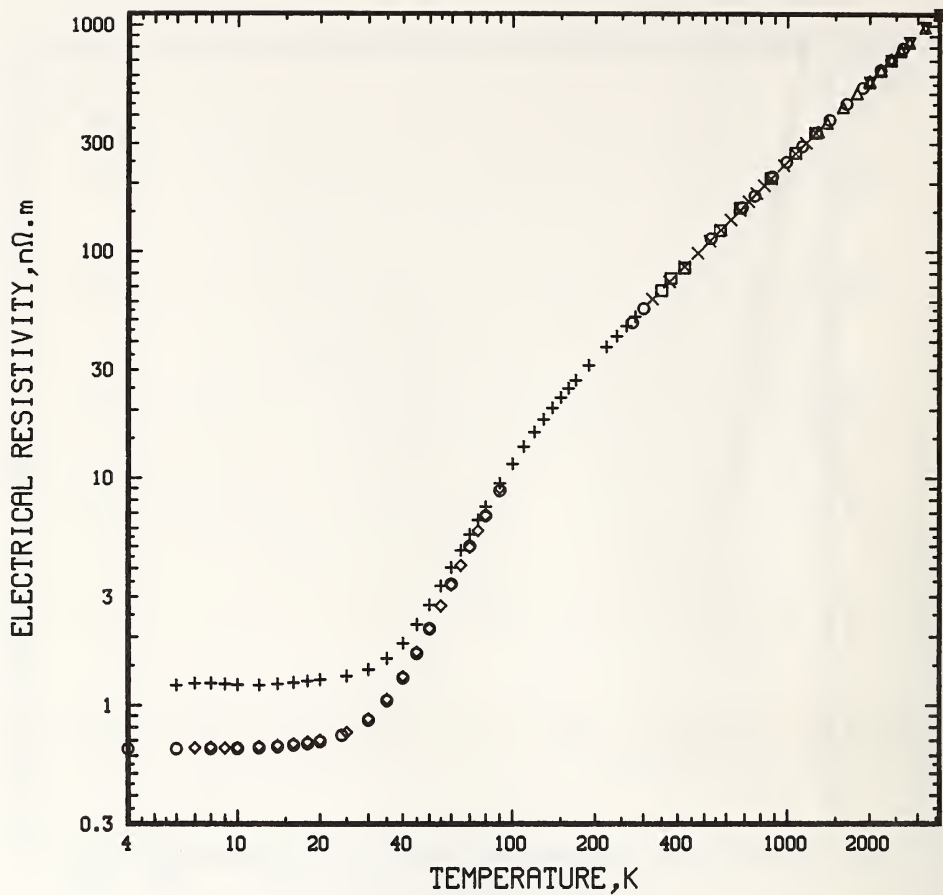


Figure 3.2.10 Composite of data in figs. 3.2.8 and 3.2.9

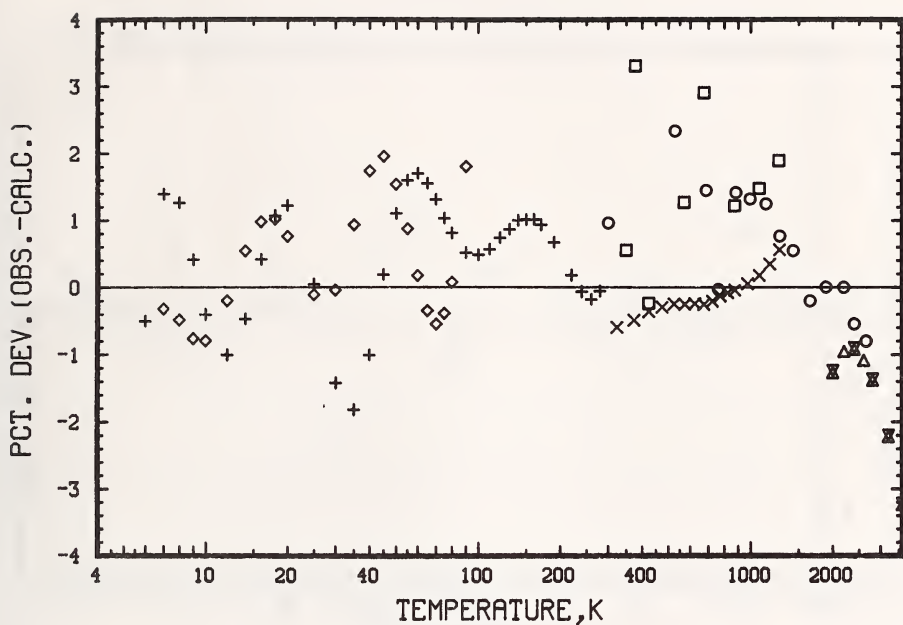


Figure 3.2.11 Electrical resistivity deviations of the tungsten RM data of the following references from eq.(3.5): (11,18,19,27,28)

○ - (27), △ - (27), □ - (19), ▽ - (18)
 ◇ - (11), + - (11), × - (28)

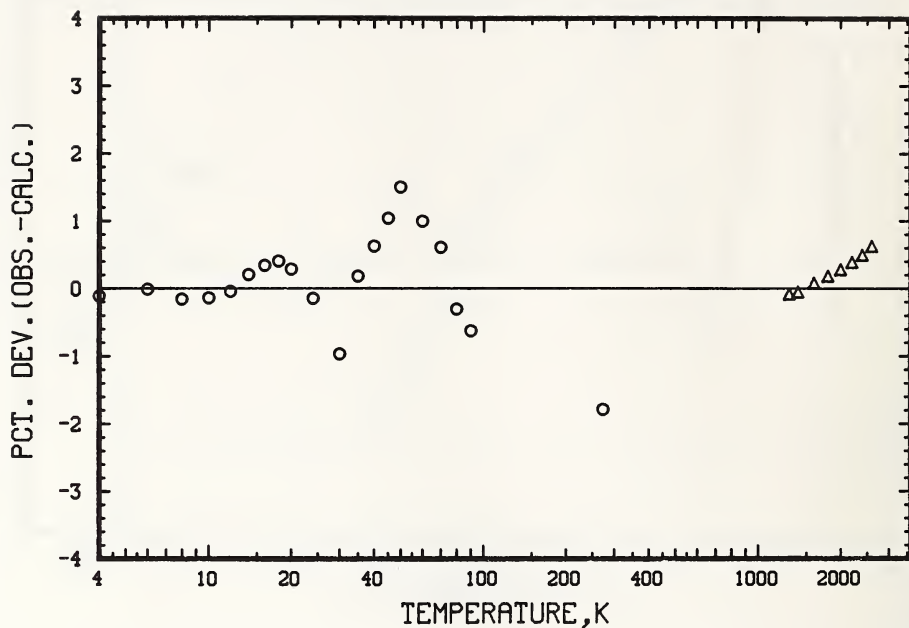


Figure 3.2.12 Electrical resistivity deviations of the tungsten
RM data of the following references from eq.(3.5):
(13,22)

O - (13), Δ - (22)

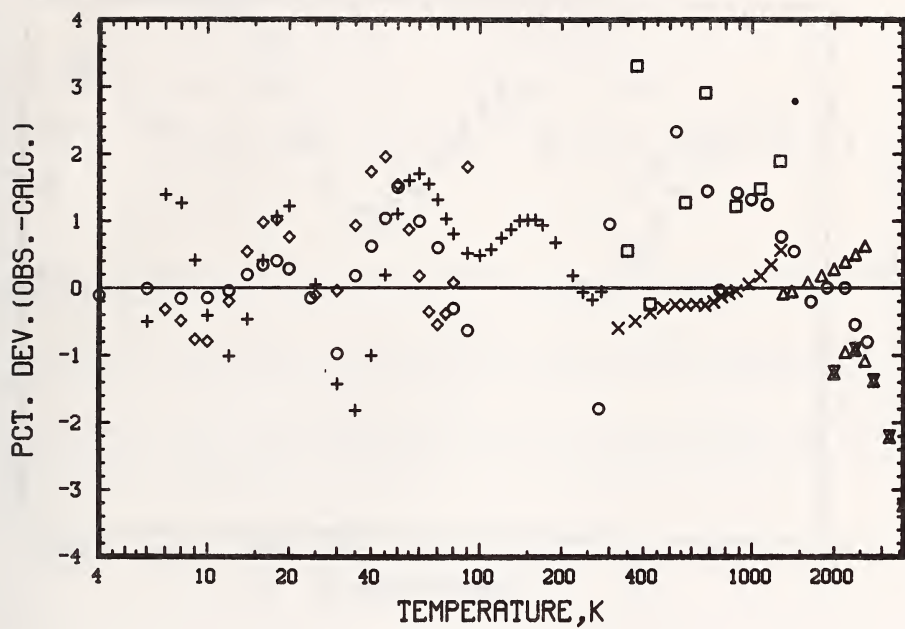


Figure 3.2.13 Composite of the data in figs. 3.2.11 and 3.2.12

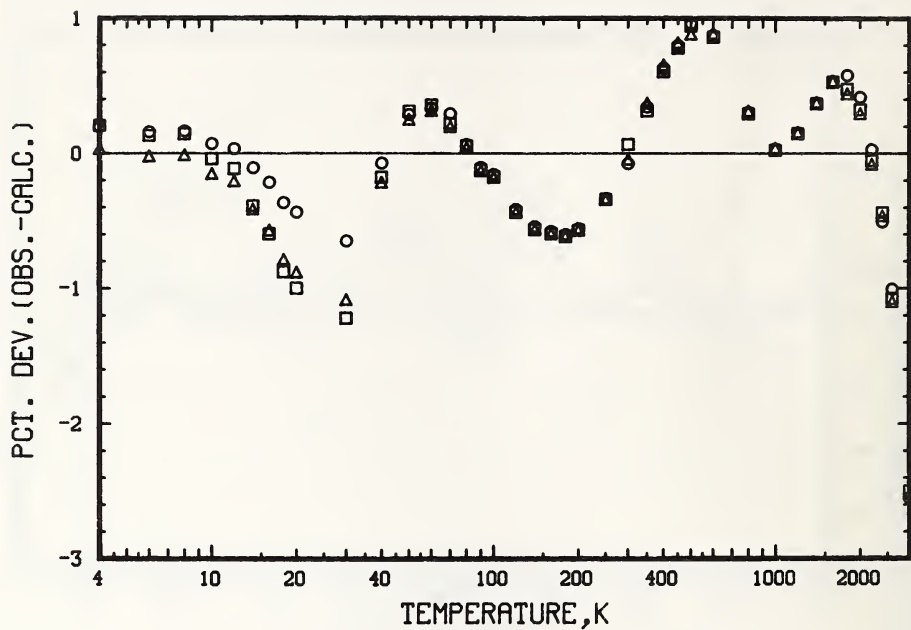


Figure 3.2.14 Deviations of the previously recommended electrical resistivity values(5) from eq.(3.5).

3.3 Stainless Steel

The experimental thermal conductivity data reported for this SRM are illustrated in figure 3.3.1. Because this is a highly alloyed metal, the relative importance of the conduction/scattering mechanisms are considerably different than for a pure metal. Nevertheless, the base equation chosen for representation of these data is of the same form as equation (3.1). The only change is that the ρ/T term was replaced by B/T^n , where $B = 15.2$ and $n = 1.211$.

The resulting parameters of a nonlinear least squares fit of this equation are

$$\begin{aligned} P_1 &= 2.477 \times 10^{-4} & P_5 &= 60 \\ P_2 &= 1.303 & P_6 &= -0.1436 \\ P_3 &= 1.918 & P_7 &= 0.0 \\ P_4 &= 0.592 \end{aligned}$$

where λ and T are in $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ and K , respectively. No systematic residuals were observed from this fit.

The resulting deviations of the experimental data from this equation are illustrated in figure 3.3.2. The deviations of the previously recommended values from this equation are illustrated in figure 3.3.3.

The experimental electrical resistivity data for this stainless steel are illustrated in figure 3.3.4. These data were represented by equation (3.5) with the following parameters

$$\begin{aligned} P_1 &= 1.217 \times 10^{-10} & P_5 &= 450 \\ P_2 &= 1.315 & P_6 &= 3.031 \\ P_3 &= 6.836 \times 10^6 & P_7 &= 0.0 \\ P_4 &= 0.3 \end{aligned}$$

where ρ and T are $\Omega\cdot\text{m}$ and K , respectively.

The systematic residuals were represented by

$$\begin{aligned} \rho_c &= 2.5 \times 10^{-8} \ln(T/135) \ln(T/270) \ln(T/530) \exp(-(\ln(T/350)/1.4)^2) \\ &\quad - 5.5 \times 10^{-8} \exp(-(\ln(T/1300)/0.4)^2) \end{aligned}$$

The resulting deviations of the experimental data from this equation are shown in figures 3.3.8 and 3.3.9. The deviations of the previously recommended values are shown in figure 3.2.10.

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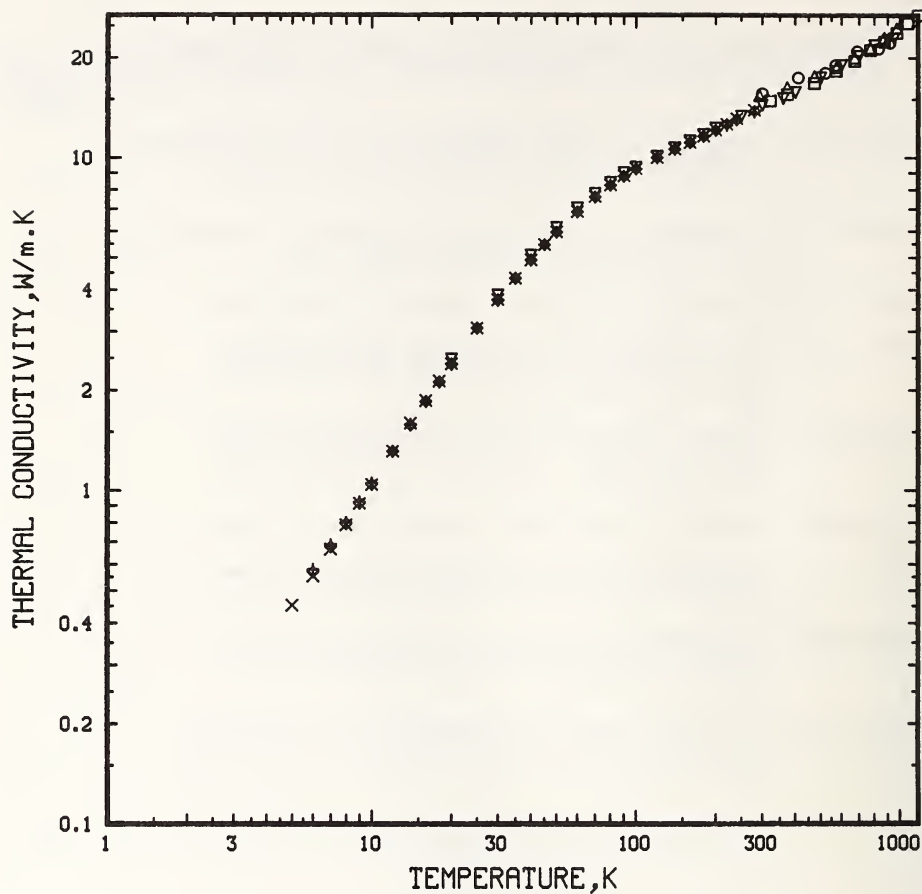


Figure 3.3.1 Experimental thermal conductivity data for the stainless steel SRM from the following sources: (9,10,16,21,27)

○ - (27), △ - (27), □ - (21), ▽ - (16),
 ◇ - (9), + - (9), × - (10)

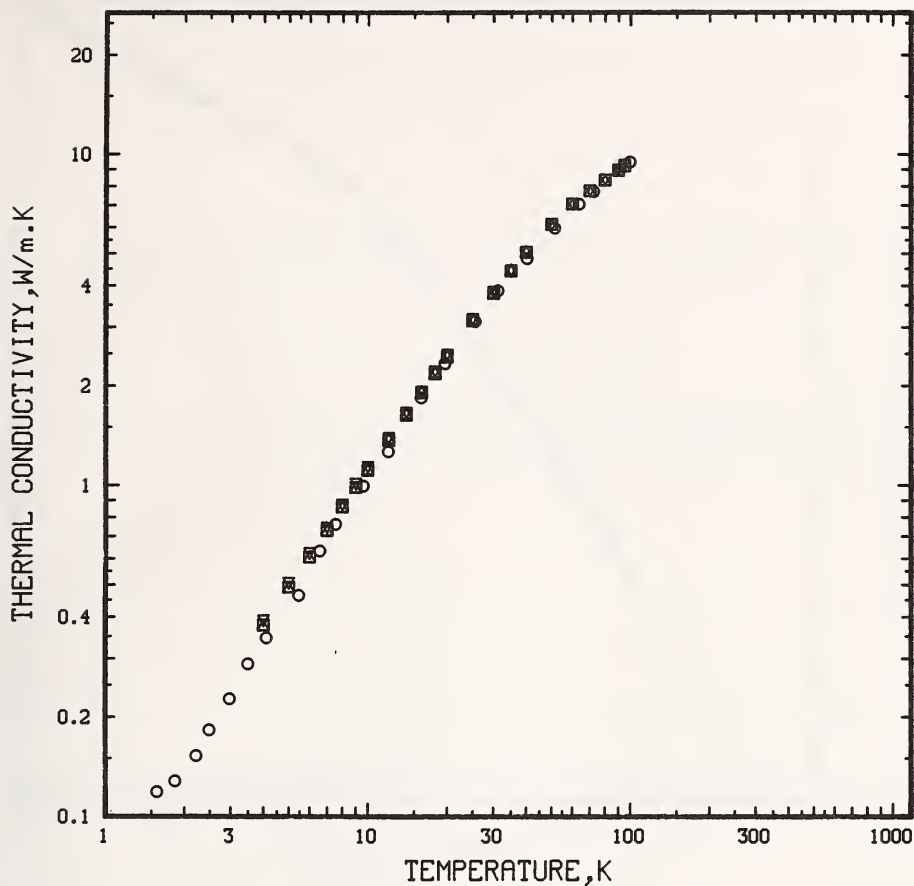


Figure 3.3.2 Experimental thermal conductivity data for the stainless steel SRM from the following sources:
(13)

○ - (13), △ - (13), □ - (13), ▽ - (13)

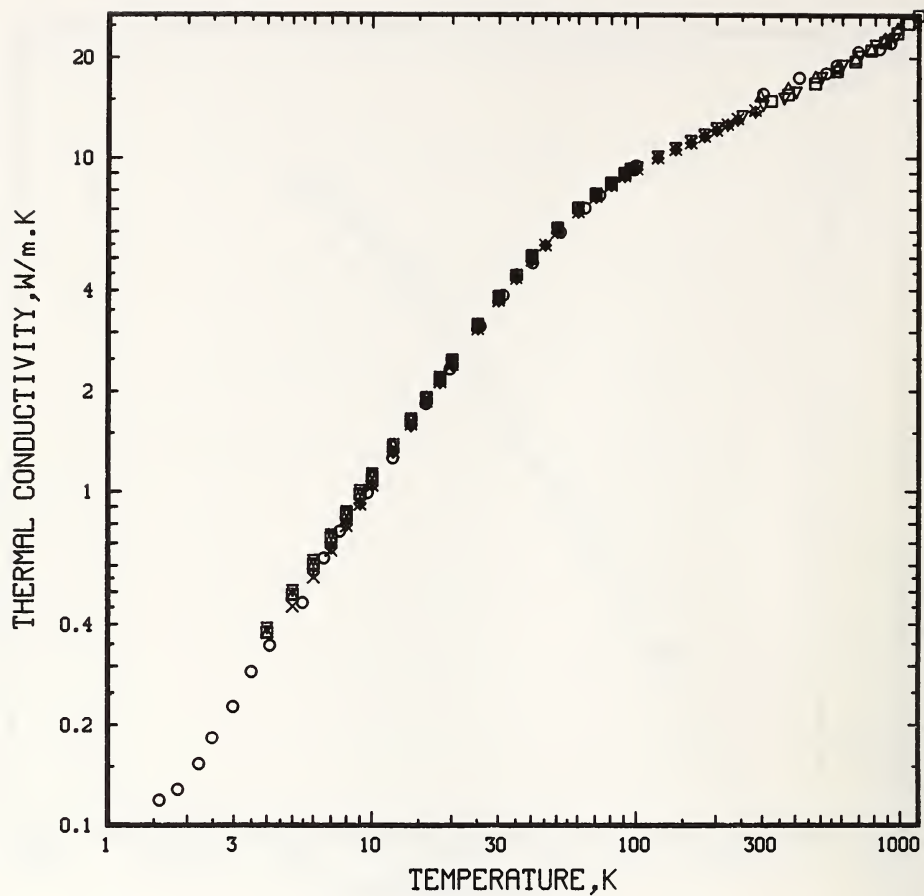


Figure 3.3.3 Composite of the data in figs. 3.3.1 and 3.3.2

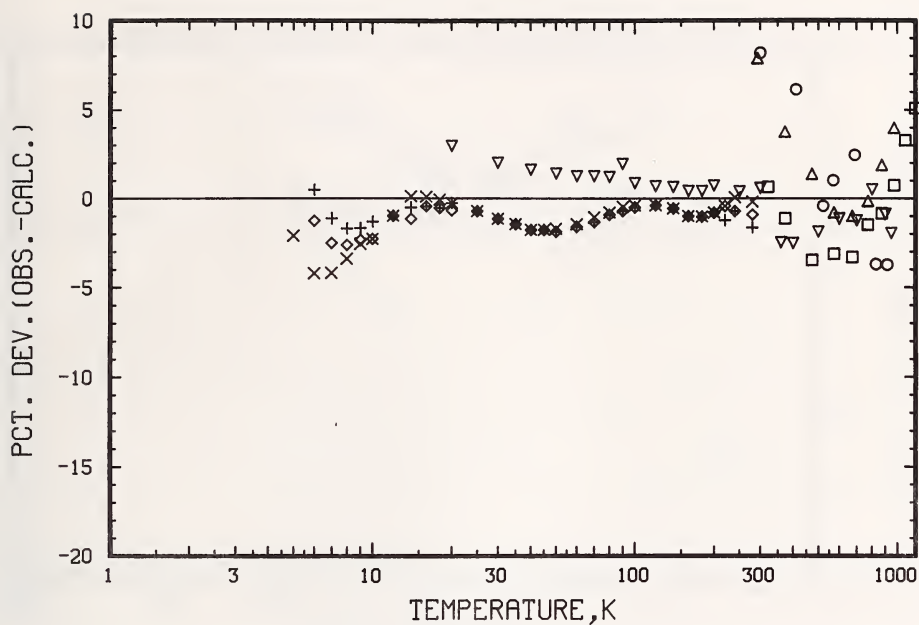


Figure 3.3.4 Thermal conductivity deviations of the stainless steel SRM data of the following references from eq.(3.1):
(9,10,16,21,27)

○ - (27), △ - (27), □ - (21), ▽ - (16), ◇ - (9),
+ - (9), × - (10)

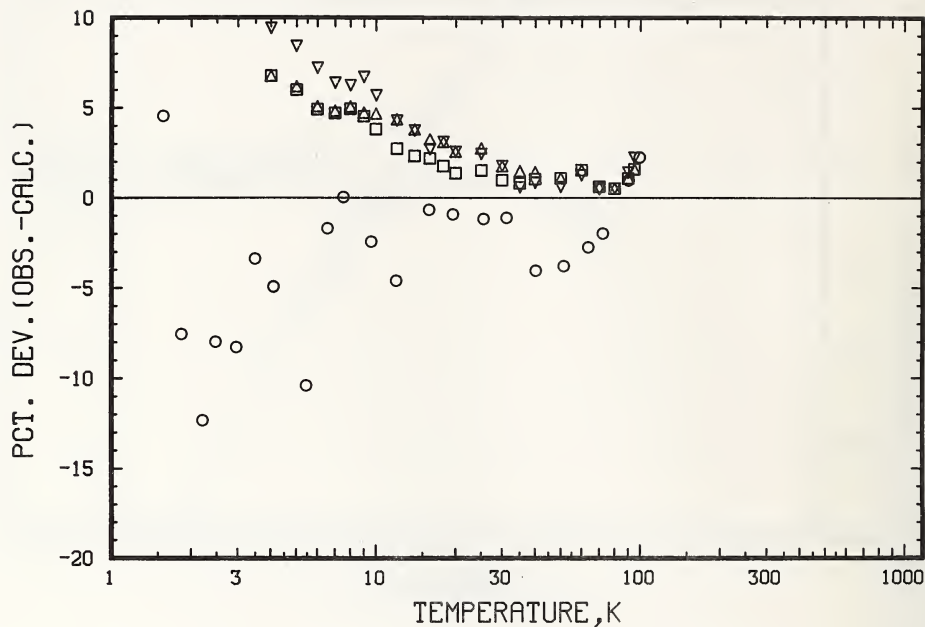


Figure 3.3.5 Thermal conductivity deviations of the stainless steel SRM data of the following references from eq.(3.1):
(13)

○ - (13), △ - (13), □ - (13), ▽ - (13)

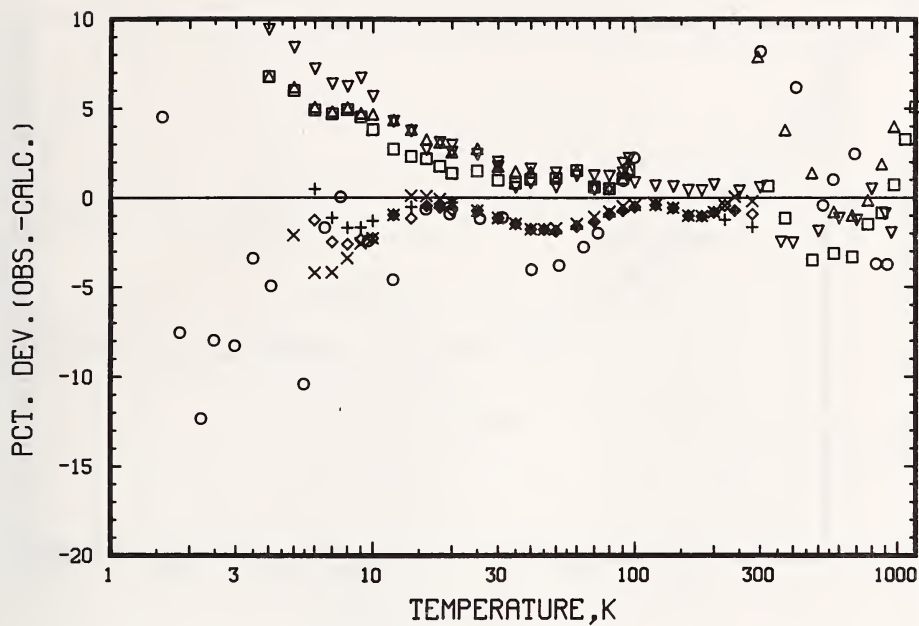


Figure 3.3.6 Composite of the data in figs. 3.3.4 and 3.3.5

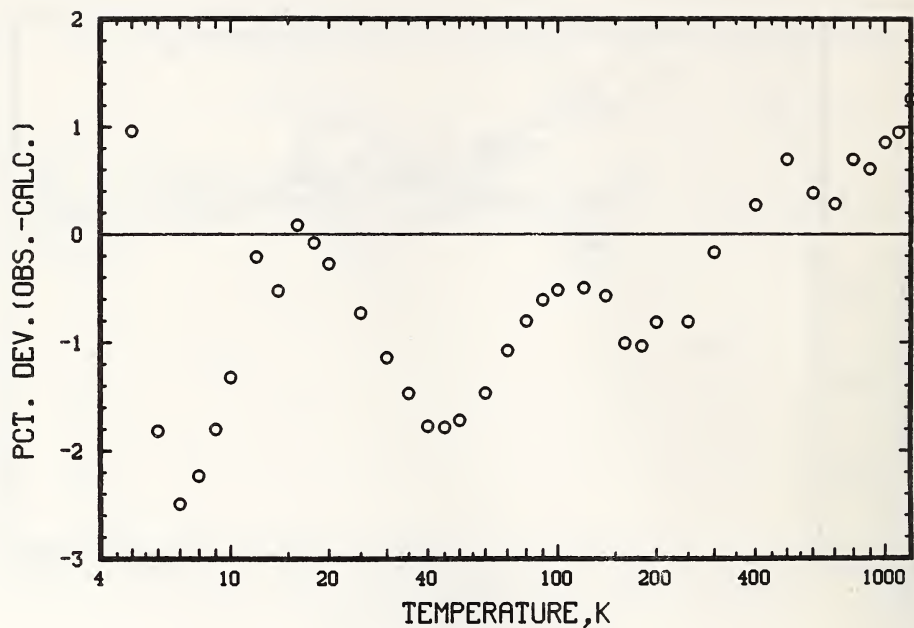


Figure 3.3.7 Deviations of the previously recommended thermal conductivity values (6) from eq.(3.1).

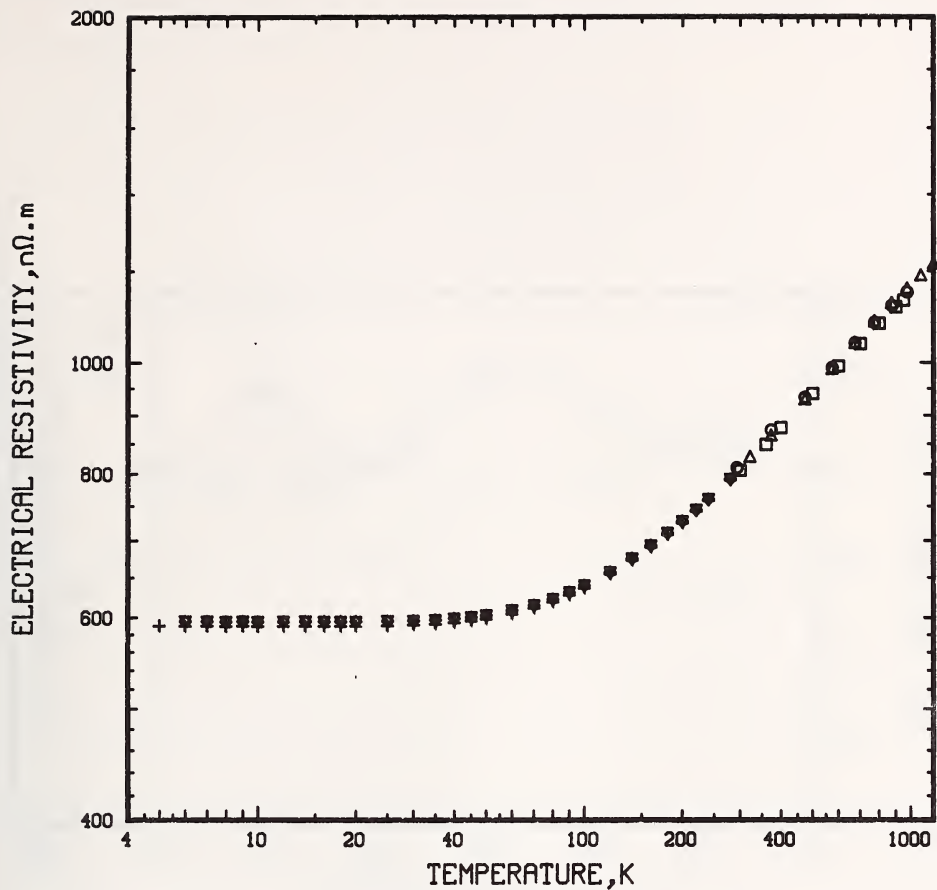


Figure 3.3.8 Experimental electrical resistivity data for the stainless steel SRM from the following sources: (9,10,16,21,27)

○ - (27), △ - (21), □ - (16), ▽ - (9) ◇ - (9),
 + - (10)

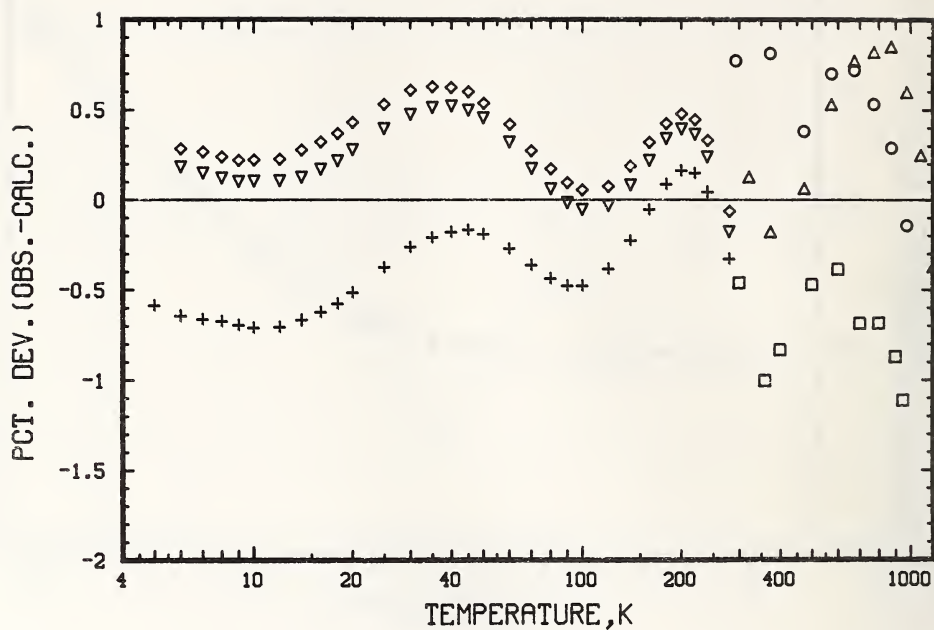


Figure 3.3.9 Electrical resistivity deviations of the stainless steel SRM data of the following references from eq.(3.5):
(9,10,16,21,27)

○ - (27), △ - (21), □ - (16), ▽ - (9) ◇ - (9),
+ - (10)

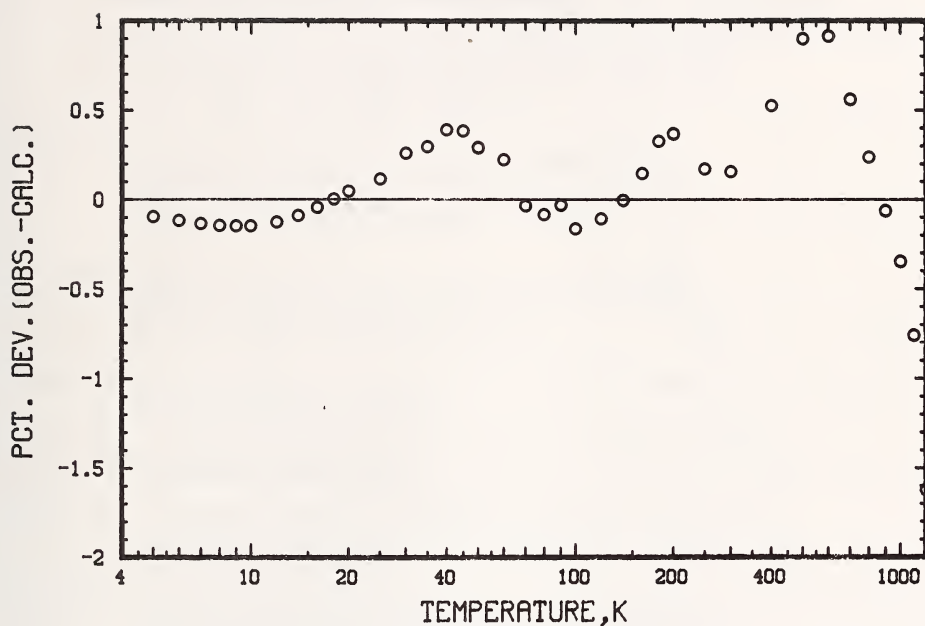


Figure 3.3.10 Deviations of the previously recommended electrical resistivity values (6) from eq.(3.5).

4. Recommended Values

The equations given in this report were used to calculate smoothed values of λ and ρ at selected temperatures and, when appropriate, selected values of RRR, corresponding to appropriate values of ρ_0 . These smoothed values are presented in tables 4.1, 4.2, and 4.3. The values are illustrated in figures 4.1 through 4.6. For completeness, values of the Lorenz ratio were also obtained from $\rho\lambda/T$ and plotted in figures 4.7 through 4.9.

The conversion from residual resistivity to RRR was made using the following equation and adopted intrinsic resistivity at the ice point.

$$RRR = 1 + \frac{\rho_{i273}}{\rho_0}$$

$$\text{Iron: } \rho_{i273} = 87.0 \text{ n}\Omega\cdot\text{m}$$

$$\text{Tungsten: } \rho_{i273} = 48.4 \text{ n}\Omega\cdot\text{m}$$

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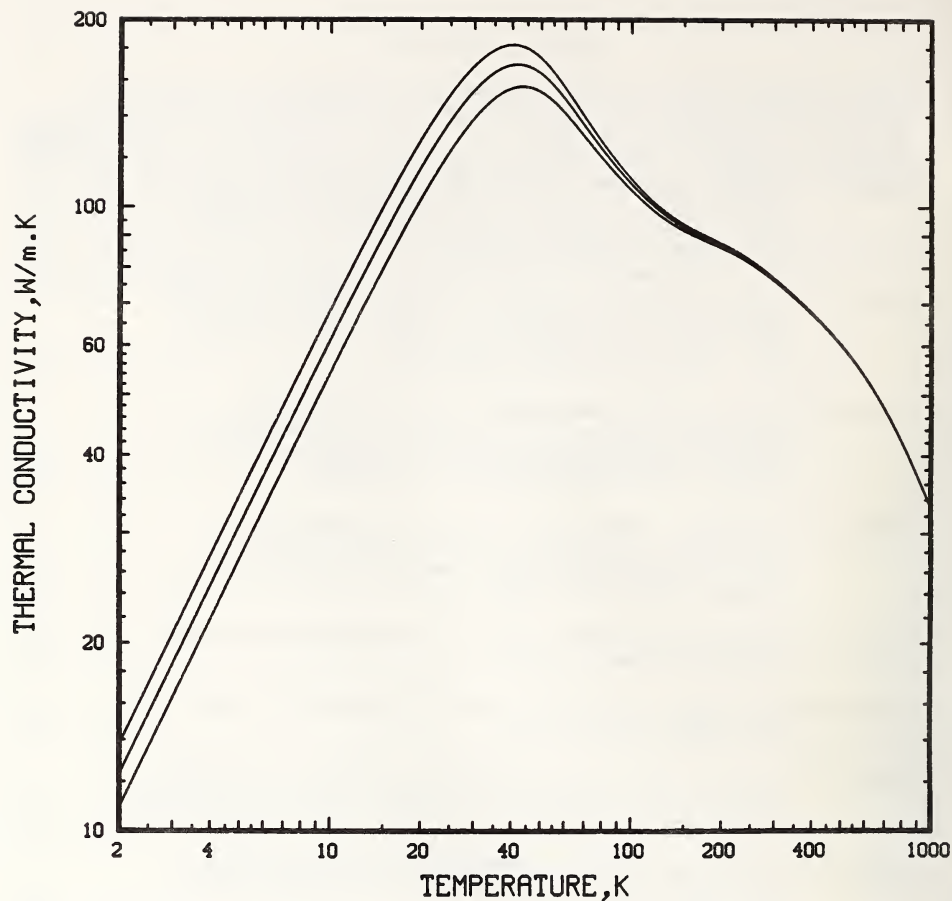


Figure 4.1 Thermal conductivity values for the electrolytic iron RM calculated from eq.(3.1) at RRR=20.0, 22.5, and 25.0 (the corresponding values of residual resistivity are: 4.579, 4.046, and 3.625 $\text{n}\Omega\cdot\text{m}$)

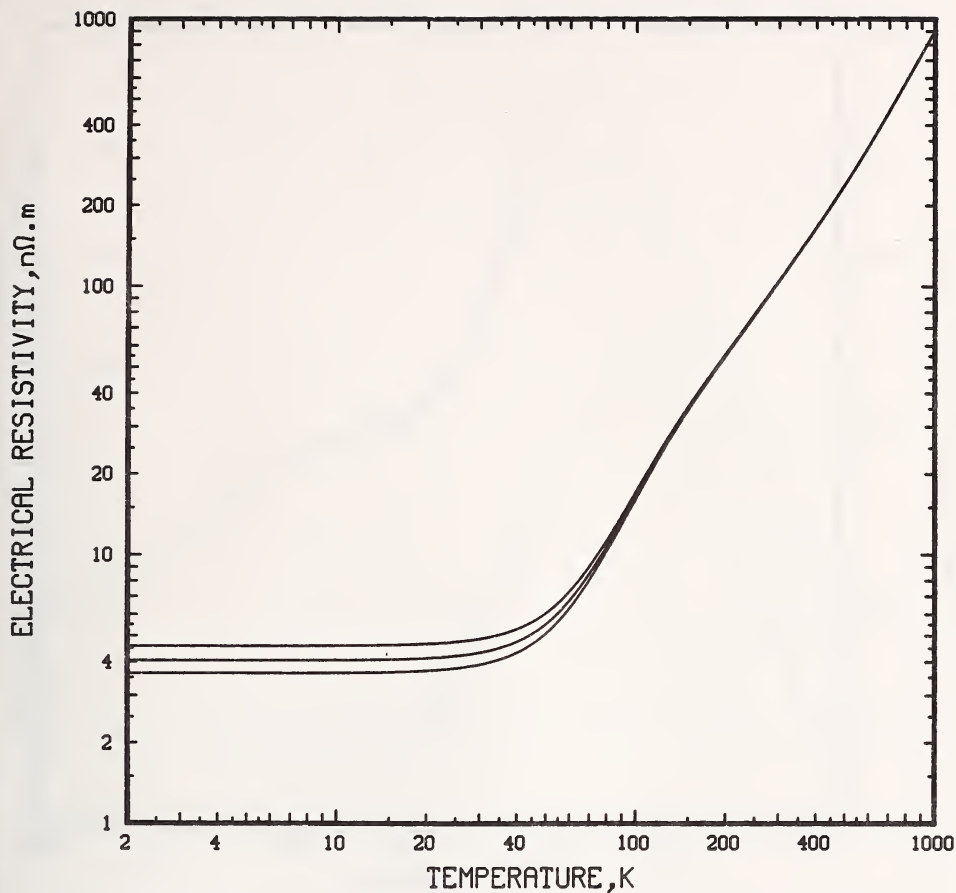


Figure 4.2 Electrical resistivity values for the electrolytic iron RM calculated from eq.(3.5) at RRR=20.0, 22.5, and 25.0 (the corresponding values of residual resistivity are: 4.579, 4.046, and 3.625 nΩ.m)

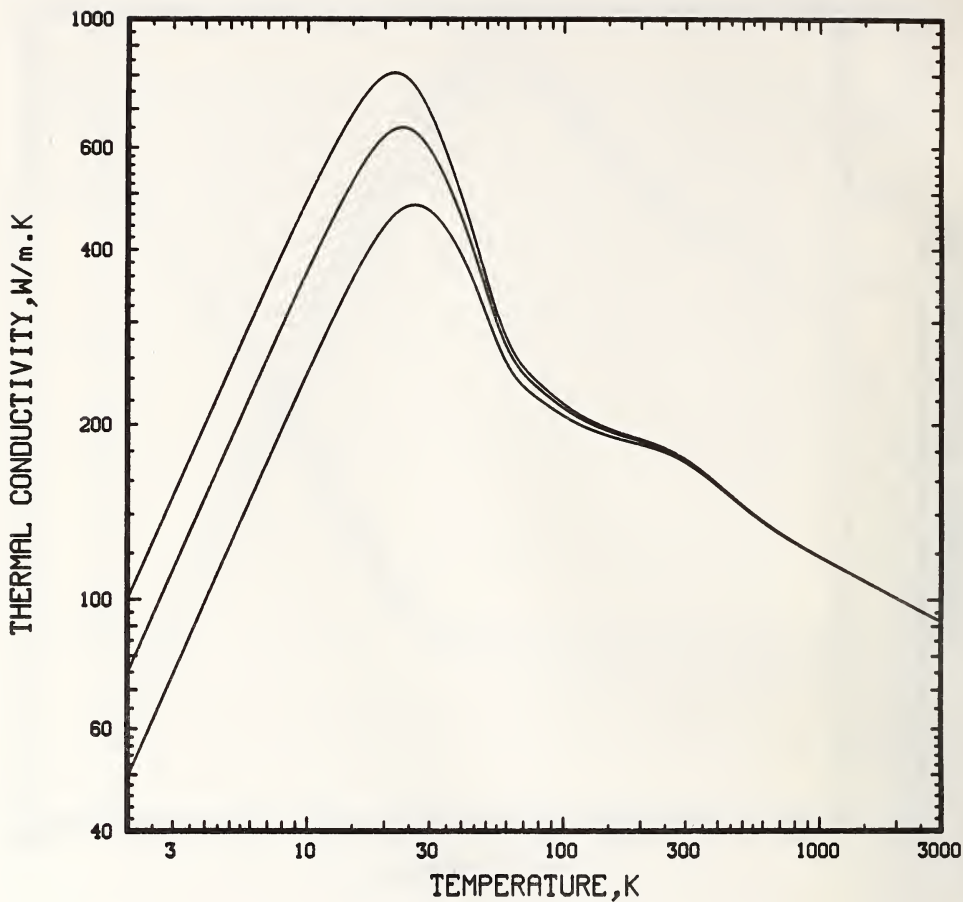


Figure 4.3 Thermal conductivity values for the tungsten RM calculated from eq.(3.1) at RRR=50, 75, and 100 (the corresponding values of residual resistivity are: 0.9878, 0.6540, and 0.4889 n Ω .m)

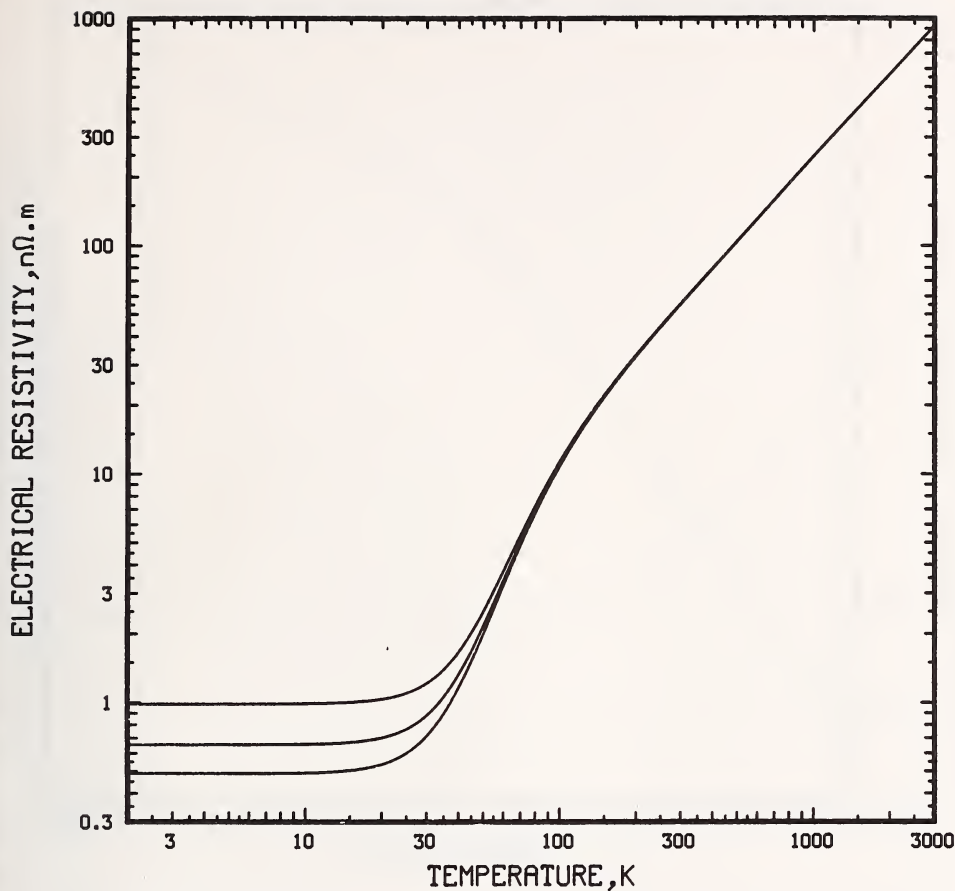


Figure 4.4 Electrical resistivity values for the tungsten RM calculated from eq.(3.5) at RRR=50, 75, and 100 (the corresponding values of residual resistivity are: 0.9878, 0.6540, and 0.4889 nΩ.m)

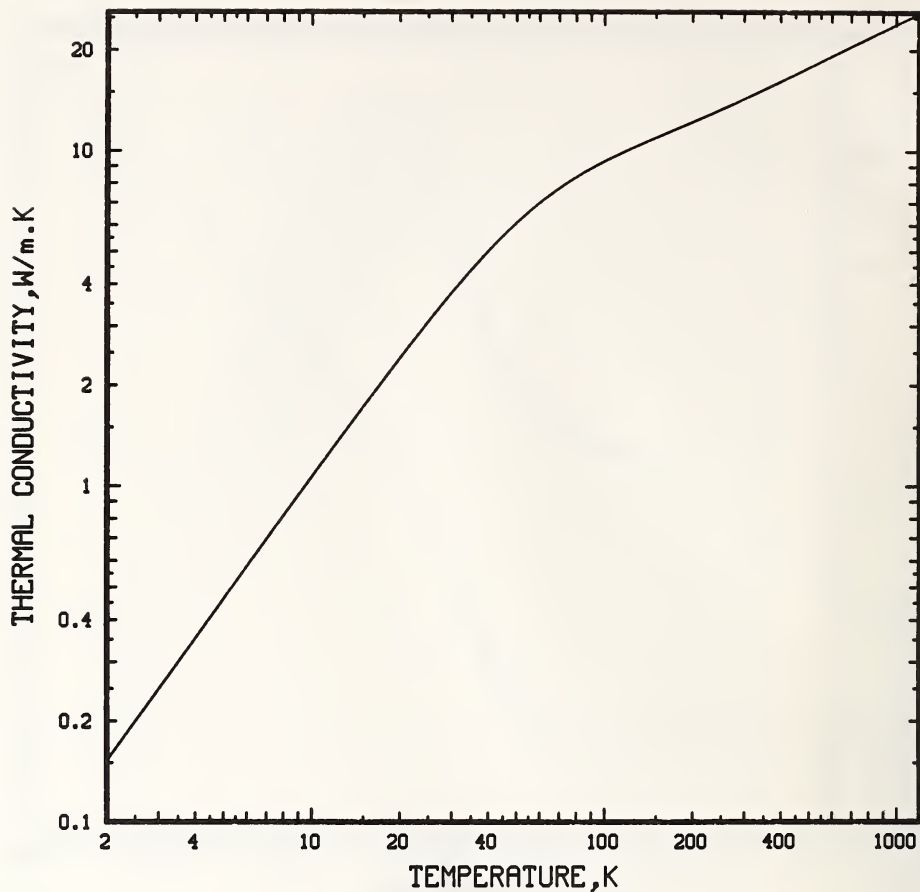


Figure 4.5 Thermal conductivity values for the stainless steel SRM calculated from eq.(3.1)

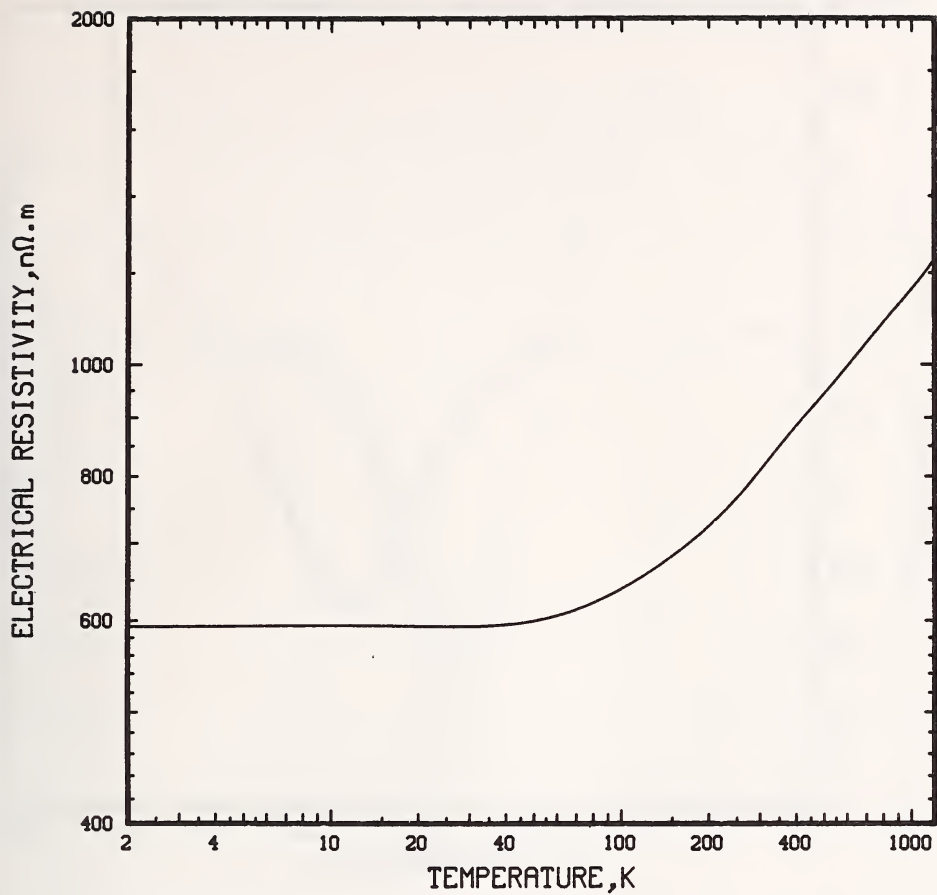


Figure 4.6 Electrical resistivity values for the stainless steel SRM calculated from eq.(3.5)

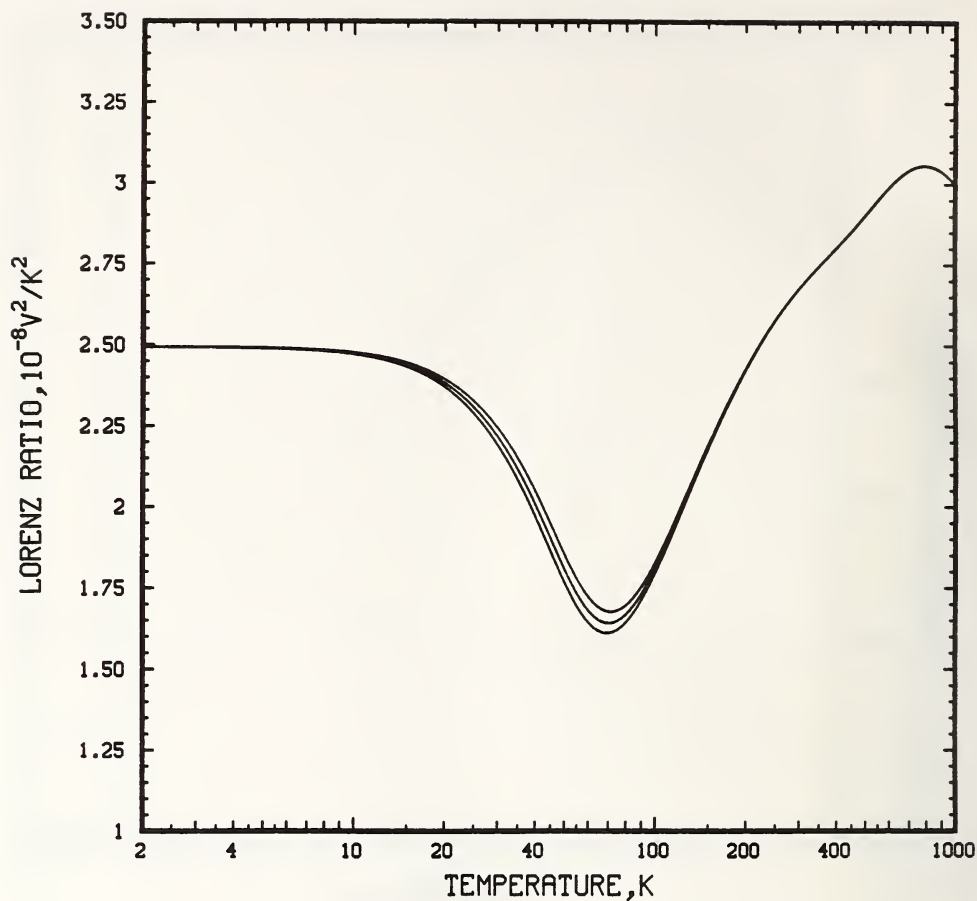


Figure 4.7 Lorenz ratio for the electrolytic iron RM as calculated from eqs. (3.1) and (3.5) at the same residual resistivities as in figs. 4.1 and 4.2

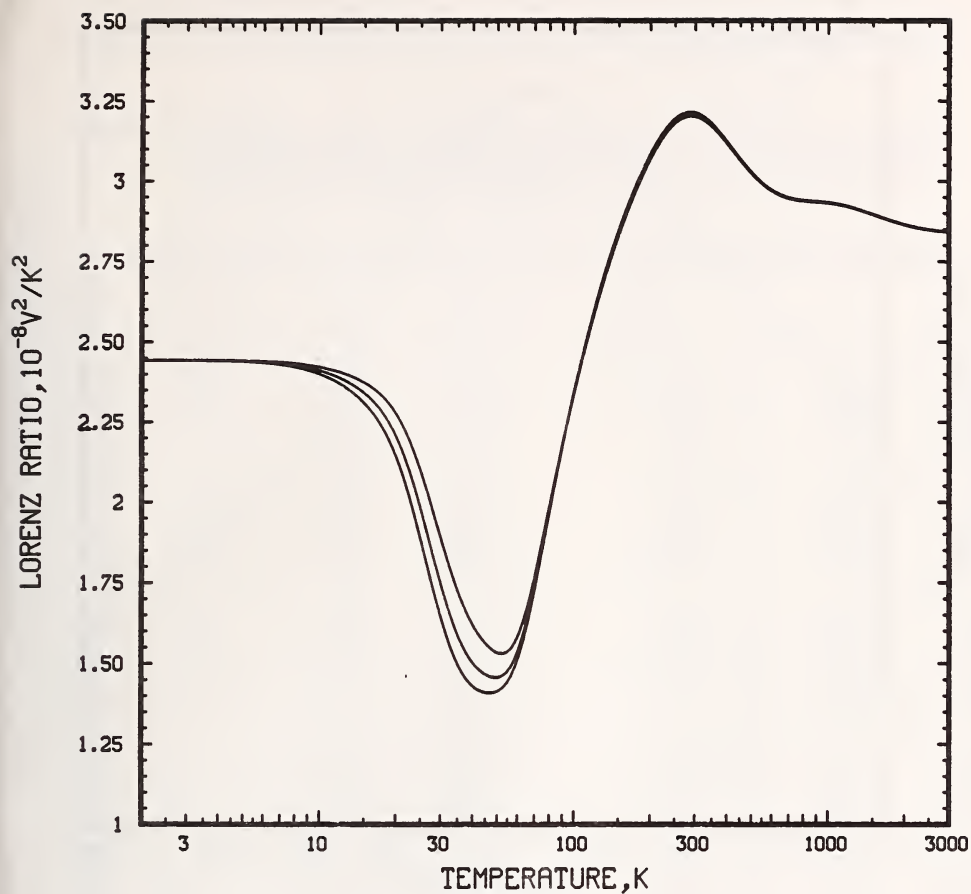


Figure 4.8 Lorenz ratio for the tungsten RM as calculated from eqs. (3.1) and (3.5) at the same residual resistivities as in figs. 4.3 and 4.4

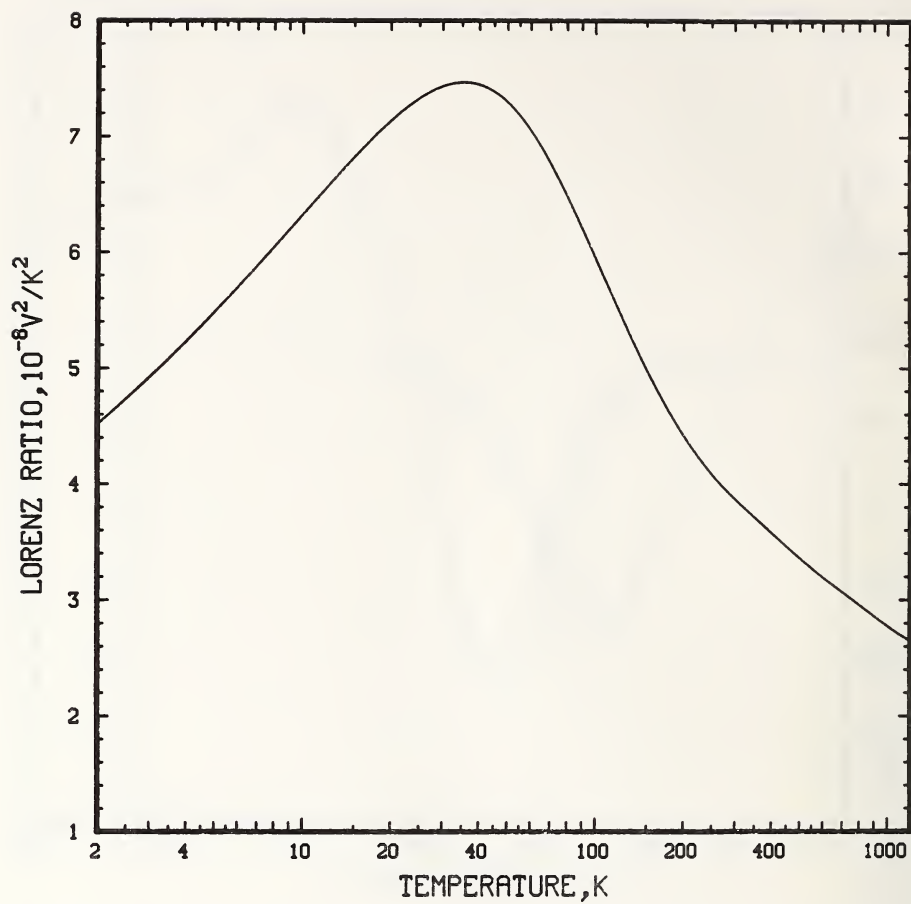


Figure 4.9 Lorenz ratio for the stainless steel SRM as calculated from eqs. (3.1) and (3.5)

Table 4.1. Recommended thermal conductivity and electrical resistivity values for the electrolytic iron RM for RRR values of 20.0, 22.5, and 25.0; and corresponding residual resistivities of 4.579, 4.047, and 3.625 nΩ.m. (Corrected for thermal expansion).

T (K)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)			Electrical Resistivity ($\text{n}\Omega\cdot\text{m}$)		
	RRR = 20.0	= 22.5	= 25.0	RRR = 20.0	= 22.5	= 25.0
2	10.89	12.32	13.75	4.579	4.047	3.625
3	16.33	18.48	20.62	4.579	4.047	3.625
4	21.76	24.62	27.48	4.579	4.047	3.625
5	27.19	30.76	34.33	4.580	4.047	3.626
6	32.60	36.88	41.15	4.580	4.048	3.626
7	37.99	42.97	47.94	4.581	4.049	3.627
8	43.4	49.0	54.7	4.583	4.050	3.629
9	48.7	55.0	61.4	4.585	4.052	3.631
10	54.0	61.0	68.0	4.587	4.054	3.633
12	64.4	72.8	81.1	4.593	4.061	3.639
14	74.6	84.2	93.7	4.602	4.070	3.648
16	84.5	95.2	105.9	4.615	4.082	3.661
18	93.9	105.7	117.4	4.632	4.099	3.678
20	102.9	115.7	128.2	4.653	4.120	3.699
25	123.0	137.4	151.5	4.731	4.199	3.777
30	138.7	153.9	168.5	4.854	4.322	3.900
35	149.5	164.5	178.7	5.03	4.50	4.08
40	155.1	169.1	182.1	5.28	4.75	4.33
45	155.9	168.3	179.7	5.62	5.08	4.66
50	152.9	163.6	173.2	6.06	5.52	5.10
60	141.6	149.1	155.6	7.30	6.76	6.34
70	129.6	134.9	139.5	9.06	8.52	8.09
80	119.9	123.8	127.1	11.32	10.78	10.35
90	112.3	115.4	117.9	14.04	13.50	13.06
100	106.4	108.9	110.9	17.17	16.62	16.18
150	91.5	92.7	93.7	35.93	35.37	34.93
200	85.9	86.7	87.3	56.5	56.0	55.5
250	81.0	81.5	82.0	79.5	79.0	78.5
300	76.0	76.4	76.7	105.6	105.0	104.6
400	67.2	67.5	67.7	166.6	166.1	165.6
500	60.0	60.2	60.3	241.8	241.2	240.7
600	53.5	53.6	53.7	335.1	334.6	334.1
700	47.42	47.49	47.55	449.1	448.5	448.1
800	41.92	41.96	42.00	583.0	583.0	582.0
900	37.09	37.12	37.14	737.0	737.0	736.0
1000	32.95	32.98	33.00	909.0	909.0	908.0

Table 4.2. Recommended thermal conductivity and electrical resistivity values for the tungsten RM for RRR values of 50, 75, and 100; and corresponding residual resistivities of 0.9878, 0.6540, and 0.4889 nΩ·m.

T (K)	Thermal Conductivity ($\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$)			Electrical Resistivity (nΩ·m)		
	RRR = 50	= 75	= 100	RRR = 50	= 75	= 100
2	49.5	74.7	99.9	.988	.654	.489
3	74.2	112.0	149.9	.988	.654	.489
4	98.9	149.3	199.7	.988	.654	.489
5	123.5	186.4	249.3	.988	.654	.489
6	148.1	223.4	298.5	.988	.655	.489
7	172.5	260.0	347.2	.989	.655	.490
8	196.7	296.2	395.1	.989	.655	.490
9	220.7	331.8	442.0	.990	.656	.491
10	244.3	366.7	487.6	.991	.657	.492
12	290.0	434.0	574.0	.994	.661	.496
14	334.0	496.0	651.0	1.000	.666	.501
16	374.0	551.0	718.0	1.008	.674	.509
18	410.0	596.0	768.0	1.019	.686	.521
20	440.0	629.0	799.0	1.035	.701	.536
25	477.0	647.0	786.0	1.099	.766	.601
30	468.0	597.0	692.0	1.212	.879	.714
35	433.0	525.0	586.0	1.392	1.059	.893
40	391.3	454.5	494.4	1.656	1.322	1.157
45	348.3	391.9	418.0	2.017	1.683	1.518
50	308.7	339.0	356.5	2.482	2.148	1.983
60	254.8	271.8	281.0	3.720	3.387	3.221
70	232.1	244.0	250.4	5.31	4.98	4.82
80	221.1	230.5	235.5	7.17	6.83	6.67
90	213.2	220.9	225.0	9.18	8.85	8.68
100	206.9	213.4	216.9	11.29	10.95	10.79
150	191.2	194.9	196.8	22.20	21.87	21.70
200	184.7	187.3	188.6	33.22	32.89	32.73
250	179.0	180.9	181.9	44.42	44.08	43.92
300	171.9	173.4	174.2	55.9	55.5	55.4
400	156.6	157.5	157.9	79.6	79.3	79.1
500	144.3	144.9	145.3	104.7	104.4	104.2
600	135.7	136.2	136.4	131.3	130.9	130.8
700	129.5	129.9	130.1	159.2	158.8	158.7
800	124.9	125.2	125.4	188.1	187.8	187.6
900	121.2	121.5	121.6	217.8	217.5	217.3
1000	118.2	118.4	118.5	248.0	247.7	247.5
1100	115.6	115.7	115.8	278.6	278.3	278.1
1200	113.2	113.4	113.5	309.4	309.1	308.9
1300	111.2	111.3	111.4	340.6	340.3	340.1
1400	109.3	109.4	109.5	372.1	371.8	371.6
1500	107.5	107.6	107.7	404.0	403.7	403.5
1600	105.9	106.0	106.1	436.3	436.0	435.8
1800	103.1	103.1	103.2	502.0	502.0	502.0
2000	100.6	100.6	100.7	570.0	569.0	569.0
2200	98.4	98.4	98.5	639.0	639.0	638.0
2400	96.4	96.5	96.5	710.0	709.0	709.0
2600	94.7	94.7	94.7	782.0	781.0	781.0
2800	93.1	93.1	93.2	855.0	855.0	855.0
3000	91.7	91.7	91.7	930.0	930.0	930.0

Table 4.3. Recommended thermal conductivity values for the stainless steel SRM.

T (K)	Thermal Conductivity (W·m ⁻¹ ·K ⁻¹)	Electrical Resistivity (nΩ·m)
2	.152	593.
3	.249	593.
4	.352	593.
5	.462	594.
6	.575	594.
7	.693	594.
8	.814	594.
9	.938	594.
10	1.064	594.
12	1.323	594.
14	1.588	594.
16	1.858	593.
18	2.132	593.
20	2.407	593.
25	3.092	592.
30	3.763	592.
35	4.404	593.
40	5.01	595.
45	5.57	597.
50	6.08	599.
60	6.98	606.
70	7.72	613.
80	8.34	622.
90	8.85	630.
100	9.30	639.
150	10.94	683.
200	12.20	724.
250	13.31	767.
300	14.32	810.
400	16.16	885.
500	17.78	944.
600	19.23	997.
700	20.54	1045.
800	21.75	1088.
900	22.86	1127.
1000	23.90	1162.
1100	24.86	1197.
1200	25.77	1234.

5. Summary

New data have been obtained from several laboratories throughout the world on previously established NBS SRM's. These data were used to update and extend the recommended values for these materials. Generally the new values are not outside the original uncertainty limits of the previous recommendations. However, this update decreases the uncertainty of the data and in some areas produces significant changes. Although other data are available, this analysis considers only thermal conductivity and electrical resistivity. The study of other properties is part of our future plans. The data presented are uncorrected for thermal expansion below 300 K and corrected for thermal expansion above 300 K.

6. Acknowledgments

The authors wish to thank the numerous experimental contributors to this effort for their cooperation and patience. Most of the work was a direct consequence of the CODATA Task Group on Thermophysical Properties. The leadership and organization of Dr. M. L. Minges is recognized and appreciated. In addition, the coordination and guidance provided by Dr. R. Berman and Dr. G. K. White was of utmost importance to the completion of this effort. Finally, we express our gratitude for the contributions of Dr. Y. S. Touloukian (deceased) as the former chairman of this task group.

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here) An update is given of the thermal conductivity and electrical resistivity of the metals: electrolytic iron, tungsten, and stainless steel. This document describes the measurement effort that has occurred since the establishment of these SRM's. New data are presented and, based on these, changes in the recommended values are described. The new recommended values are presented in the form of equations, graphs, and tables. The temperature ranges included are: 2 to 1000 K for electrolytic iron, 2 to 3000 K for tungsten, and 2 to 1200 K for stainless steel.			
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