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

The National Bureau of Standards[1] was established by an act of Congress on March 3, 1901. The Bureau's overall goal is to strengthen and advance the nation's science and technology and facilitate their effective application for public benefit. To this end, the Bureau conducts research and provides: (1) a basis for the nation's physical measurement system, (2) scientific and technological services for industry and government, (3) a technical basis for equity in trade, and (4) technical services to promote public safety. The Bureau's technical work is performed by the National Measurement Laboratory, the National Engineering Laboratory, the Institute for Computer Sciences and Technology, and the Center for Materials Science.

The National Measurement Laboratory

Provides the national system of physical and chemical measurement; coordinates the system with measurement systems of other nations and furnishes essential services leading to accurate and uniform physical and chemical measurement throughout the Nation's scientific community, industry, and commerce; provides advisory and research services to other Government agencies; conducts physical and chemical research; develops, produces, and distributes Standard Reference Materials; and provides calibration services. The Laboratory consists of the following centers:

- Basic Standards[2]
- Radiation Research
- Chemical Physics
- Analytical Chemistry

The National Engineering Laboratory

Provides technology and technical services to the public and private sectors to address national needs and to solve national problems; conducts research in engineering and applied science in support of these efforts; builds and maintains competence in the necessary disciplines required to carry out this research and technical service; develops engineering data and measurement capabilities; provides engineering measurement traceability services; develops test methods and proposes engineering standards and code changes; develops and proposes new engineering practices; and develops and improves mechanisms to transfer results of its research to the ultimate user. The Laboratory consists of the following centers:

- Applied Mathematics
- Electronics and Electrical Engineering[2]
- Manufacturing Engineering
- Building Technology
- Fire Research
- Chemical Engineering[2]

The Institute for Computer Sciences and Technology

Conducts research and provides scientific and technical services to aid Federal agencies in the selection, acquisition, application, and use of computer technology to improve effectiveness and economy in Government operations in accordance with Public Law 89-306 (40 U.S.C. 759), relevant Executive Orders, and other directives; carries out this mission by managing the Federal Information Processing Standards Program, developing Federal ADP standards guidelines, and managing Federal participation in ADP voluntary standardization activities; provides scientific and technological advisory services and assistance to Federal agencies; and provides the technical foundation for computer-related policies of the Federal Government. The Institute consists of the following centers:

- Programming Science and Technology
- Computer Systems Engineering

The Center for Materials Science

Conducts research and provides measurements, data, standards, reference materials, quantitative understanding and other technical information fundamental to the processing, structure, properties and performance of materials; addresses the scientific basis for new advanced materials technologies; plans research around cross-country scientific themes such as nondestructive evaluation and phase diagram development; oversees Bureau-wide technical programs in nuclear reactor radiation research and nondestructive evaluation; and broadly disseminates generic technical information resulting from its programs. The Center consists of the following Divisions:

- Inorganic Materials
- Fracture and Deformation[3]
- Polymers
- Metallurgy
- Reactor Radiation

[1]Headquarters and Laboratories at Gaithersburg, MD, unless otherwise noted; mailing address Gaithersburg, MD 20899.
[2]Some divisions within the center are located at Boulder, CO 80303.
[3]Located at Boulder, CO, with some elements at Gaithersburg, MD.

Standard Reference Materials:

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

Jerome G. Hust
Alan B. Lankford

Center for Chemical Engineering
National Engineering Laboratory
National Bureau of Standards
Boulder, CO 80303

Sponsored by:
Office of Standard Reference Materials
National Measurement Laboratory
National Bureau of Standards
Gaithersburg, MD 20899

NBS Special publication

U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, Secretary
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, Director

Issued September 1984

Library of Congress Catalog Card Number: 84-601107

National Bureau of Standards Special Publication 260-90
Natl. Bur. Stand. (U.S.), Spec. Publ. 260-90, 71 pages (Sept. 1984)
CODEN: XNBSAV

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 1984

For sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402

PREFACE

Standard Reference Materials (SRM's) as defined by the National Bureau of Standards are "well-characterized materials, produced in quantity, that calibrate a measurement system to assure compatibility of measurement in the Nation." SRM's are widely used as primary standards in many diverse fields of science, industry, and technology, both within the United States and throughout the world. For many of the Nation's scientists and technologists it is of more than passing interest to know the measurements obtained and methods used by the analytical community when analyzing SRM's. An NBS series of papers, of which this publication is a member, called the NBS Special Publication - 260 Series is reserved for this purpose.

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:

Office of Standard Reference Materials
National Bureau of Standards
Gaithersburg, MD 20899

Stanley D. Rasberry, Chief
Office of Standard Reference Materials

OTHER NBS PUBLICATIONS IN THIS SERIES

Catalog of NBS Standard Reference Materials (1981-83 edition), R. W. Seward, ed., NBS Spec. Publ. 260 (November 1981).

Michaelis, R. E., and Wyman, L. L. Standard Reference Materials: Preparation of White Cast Iron Spectrochemical Standards. NBS Misc. Publ. 260-1 (June 1964). COM74-11061**

Michaelis, R. E., Wyman, L. L., and Flitsch, R., Standard Reference Materials: Preparation of NBS Copper-Base Spectrochemical Standards. NBS Misc. Publ. 260-2 (October 1964). COM74-11063**

Michaelis, R. E., Yakowitz, H., and Moore, G. A., Standard Reference Materials: Metallographic Characterization of an NBS Spectrometric Low-Alloy Steel Standard. NBS Misc. Publ. 260-3 (October 1964). COM74-11060**

Hague, J. L. Mears, T. W., and Michaelis, R. E., Standard Reference Materials: Sources of Information, NBS Misc. Publ. 260-4 (February 1965). COM74-11059

Alvarez, R., and Flitsch R., Standard Reference Materials: Accuracy of Solution X-Ray Spectrometric Analysis of Copper-Base Alloys. NBS Misc. Publ. 260-5 (March 1965). PB168068**

Shultz, J. I., Standard Reference Materials: Methods for the Chemical Analysis of White Cast Iron Standards, NBS Misc. Publ. 260-6 (July 1975). COM74-11068**

Bell, R. K., Standard Reference Materials: Methods for the Chemical Analysis of NBS Copper-Base Spectrochemical Standards. NBS Misc. Publ. 260-7 (October 1965). COM74-11067**

Richmond, M.S., Standard Reference Materials: Analysis of Uranium Concentrates at the National Bureau of Standards. NBS Misc. Publ. 260-8 (December 1965). COM74-11066**

Anspach, S. C., Cavallo, L. M. Garfinkel, S. B. Hutchinson, J. M. R., and Smith, C. N., Standard Reference Materials: Half Lives of Materials Used in the Preparation of Standard Reference Materials of Nineteen Radioactive Nuclides Issued by the National Bureau of Standards NBS Misc. Publ. 260-9 (November 1965). COM74-11065**

Yakowitz, H., Vieth, D. L., Heinrich, K. F. J., and Michaelis, R. E., Standard Reference Materials: Homogeneity Characterization on NBS Spectrometric Standards II: Cartridge Brass and Low-Alloy Steel, NBS Misc. Publ. 260-10 (December 1965). COM74-11064**

Napolitano, A., and Hawkins, E. G., Standard Reference Materials: Viscosity of Standard Lead-Silica Glass, NBS Misc. Publ. 260-11 (November 1966). NBS Misc. Publ. 260-11**

Yakowitz, H., Vieth, D. L., and Michaelis, R. E., Standard Reference Materials: Homogeneity Characterization of NBS Spectrometric Standards III: White Cast Iron and Stainless Steel Powder Compact, NBS Misc. Publ. 260-12 (September 1966). NBS Misc. Publ. 260-12**

Spijkerman, J. L., Snediker, D. K., Ruegg, F. C., and DeVoe, J. R., Standard Reference Materials: Mossbauer Spectroscopy Standard for the Chemical Shift of Iron Compounds, NBS Misc. Publ. 260-13 (July 1967). NBS Misc. Publ. 260-13**

Menis, O., and Sterling, J. T., Standard Reference Materials: Determination of Oxygen in Ferrous Materials - SRM 1090, 1091, and 1092, NBS Misc. Publ. 260-14 (September 1966). NBS Misc. Publ. 260-14**

Passaglia, E., and Shouse, P. J. Standard Reference Materials: Recommended Method of Use of Standard Light-Sensitive Paper for Calibrating Carbon Arcs Used in Testing Textiles for Colorfastness to Light, NBS Misc. Publ. 260-15 (June 1967). (Replaced by NBS Spec. Publ. 260-41.)

Yakowitz, H., Michaelis, R. E., and Vieth, D. L., Standard Reference Materials: Homogeneity Characterization of NBS Spectrometric Standards IV: Preparation and Microprobe Characterization of W-20% MO Alloy Fabricated by Powder Metallurgical Methods, NBS Spec. Publ. 260-16 (January 1969). COM74-11062**

Catanzaro, E. J., Champion, C. E., Garner, E. L., Marinenko, G., Sappenfield, K. M., and Shields, W. R. Standard Reference Materials: Boric Acid; Isotopic and Assay Standard Reference Materials, NBS Spec. Publ. 260-17 (February 1970). Out of Print

Geller, S. B., Mantek, P.A., and Cleveland, N. G., Standard Reference Materials: Calibration of NBS Secondary Standard Magnetic Tape (Computer Amplitude Reference) Using the Reference Tape Amplitude Measurement "Process A, "NBS Spec. Publ. 260-18 (November 1969). (See NBS Spec. Publ. 260-29.)

Paule, R. C., and Mandel, J., Standard Reference Materials: Analysis of Interlaboratory Measurements on the Vapor Pressure of Gold (Certification of Standard Reference Material 745). NBS Spec. Publ. 260-19 (January 1970). PB190071**

Paule, R. C., and Mandel, J., Standard Reference Materials: Analysis of Interlaboratory Measurements on the Vapor Pressures of Cadmium and Silver, NBS Spec. Publ. 260-21 (January 1971). COM74-11359**

Yakowitz, H., Fiori, C. E., and Michaelis, R. E., Standard Reference Materials: Homogeneity Characterization of Fe-3 Si Alloy, NBS Spec. Publ. 260-22 (February 1971). COM74-11357**

Napolitano, A., and Hawkins, E. G., Standard Reference Materials: Viscosity of a Standard Borosilicate Glass, NBS Spec. Publ. 260-23 (December 1970). COM71-00157**

Sappenfield, K. M., Marineko, G., and Hague, J. L., Standard Reference Materials: Comparison of Redox Standards, NBS Spec. Publ. 260-24 (January 1972). COM72-50058**

Hicho, G. E., Yakowitz, H., Rasberry, S. D., and Michaelis, R. E., Standard Reference Materials: A Standard Reference Material Containing Nominally Four Percent Austenite, NBS Spec. Publ. 260-25 (February 1971). COM74-11356**

Martin, J. F., Standard Reference Materials: National Bureau of Standards-US Steel Corportion Joint Program for Determining Oxygen and Nitrogen in Steel, NBS Spec. Publ. 260-26 (February 1971). 85 cents* PB 81176620

Garner, E. L., Machlan, L. A., and Shields, W. R., Standard Reference Materials: Uranium Isotopic Standard Reference Materials, NBS Spec. Publ. 260-27 (April 1971). COM74-11358**

Heinrich, K. F. J., Myklebust, R. L., Rasberry, S. D., and Michaelis, R. E., Standard Reference Materials: Preparation and Evaluation of SRM's 481 and 482 Gold-Silver and Gold-Copper Alloys for Microanalysis, NBS Spec. Publ. 260-28 (August 1971). COM71-50365**

Geller, S. B., Standard Reference Materials: Calibration of NBS Secondary Standard Magnetic Tape (Computer Amplitude Reference) Using the Reference Tape Amplitude Measurement "Process A-Model 2," NBS Spec. Publ. 260-29 (June 1971). COM71-50282

Gorozhanina, R. S., Freedman, A. Y., and Shaievitch, A. B. (translated by M. C. Selby), Standard Reference Materials: Standard Samples Issued in the USSR (A Translation from the Russian). NBS Spec. Publ. 260-30 (June 1971). COM71-50283**

Hust, J. G., and Sparks, L. L., Standard Reference Materials: Thermal Conductivity of Electrolytic Iron SRM 734 from 4 to 300 K, NBS Spec. Publ. 260-31 (November 1971). COM71-50563**

Mavrodineanu, R., and Lazar, J. W., Standard Reference Materials: Standard Quartz Cuvettes, for High Accuracy Spectrophotometry, NBS Spec. Publ. 260-32 (December 1973). 55 cents* SN003-003-01213-1

Wagner, H. L., Standard Reference Materials: Comparison of Original and Supplemental SRM 705, Narrow Molecular Weight Distribution Polystyrene, NBS Spec. Publ. 260-33 (May 1972). COM72-50526**

Sparks, L. L., and Hust, J. G., Standard Reference Materials: Thermoelectric Voltage, NBS Spec. Publ. 260-34, (April 1972). COM72-50371**

Sparks, L. L., and Hust, J. G., Standard Reference Materials: Thermal Conductivity of Austenitic Stainless Steel, SRM 735 from 5 to 280 K, NBS Spec. Publ. 260-35 (April 1972.) 35 cents* COM72-50368**

Cali, J. P., Mandel, J., Moore, L. J., and Young, D. S., Standard Reference Materials: A Referee Method for the Determination of Calcium in Serum, NBS SRM 915, NBS Spec. Publ. 260-36 (May 1972). COM72-50527**

Shultz, J. I. Bell., R. K. Rains, T. C., and Menis, O., Standard Reference Materials: Methods of Analysis of NBS Clay Standards, NBS Spec. Publ. 260-37 (June 1972). COM72-50692**

Richmond, J. C., and Hsia, J. J., Standard Reference Materials: Preparation and Calibration of Standards of Spectral Specular Reflectance, NBS Spec. Publ. 260-38 (May 1972). COM72-50528**

Clark, A. F., Denson, V.A., Hust, J. G., and Powell, R. L., Standard Reference Materials The Eddy Current Decay Method for Resistivity Characterization of High-Purity Metals, NBS Spec. Publ. 260-39 (May 1972). COM72-50529**

McAdie, H. G., Garn, P.D., and Menis, O., Standard Reference Materials: Selection of Thermal Analysis Temperature Standards Through a Cooperative Study (SRM 758, 759, 760), NBS Spec. Publ. 260-40 (August 1972.) COM72-50776**

Wood, L. A., and Shouse, P. J., Standard Reference Materials: Use of Standard Light-Sensitive Paper for Calibrating Carbon Arcs Used in Testing Textiles for Colorfastness to Light, NBS Spec. Publ. 260-41 (August 1972) COM72-50775**

Wagner, H. L. and Verdier, P. H., eds., Standard Reference Materials: The Characterization of Linear Polyethylene, SRM 1475, NBS Spec. Publ. 260-42 (September 1972). COM72-50944**

Yakowitz, H., Ruff, A. W., and Michaelis, R. E., Standard Reference Materials: Preparation and Homogeneity Characterization of an Austenitic Iron-Chromium-Nickel Alloy, NBS Spec. Publ. 260-43 (November 1972). COM73-50760**

Schooley, J. F., Soulen, R. J., Jr., and Evans, G. A., Jr., Standard Reference Materials: Preparation and Use of Superconductive Fixed Point Devices, SRM 767, NBS Spec. Publ. 260-44 (December 1972). COM73-50037**

Greifer, B., Maienthal, E. J. Rains, T. C., and Rasberry, S. D., Standard Reference Materials: Powdered Lead-Based Paint, SRM 1579, NBS Spec. Publ. 260-45 (March 1973). COM73-50226**

Hust, J. G., and Giarratano, P. J., Standard Reference Materials: Thermal Conductivity and Electrical Resistivity Standard Reference Materials: Austenitic Stainless Steel, SRM's 735 and 798, from 4 to 1200 k, NBS Spec. Publ. 260-46 (March 1975). SN003-003-01278-5

Hust, J. G., Standard Reference Materials: Electrical Resistivity of Electrolytic Iron, SRM 797, and Austenitic Stainless Steel, SRM 798, from 5 to 280 K, NBS Spec. Publ. 260-47 (February 1974). COM74-50176**

Mangum, B. W., and Wise, J. A., Standard Reference Materials: Description and Use of Precision Thermometers for the Clinical Laboratory, SRM 933 and SRM 934, NBS Spec. Publ. 260-48 (May 1974). 60 cents* SN003-003-01278-5

Carpenter, B. S., and Reimer, G. M., Standard Reference Materials Calibrated Glass Standards for Fission Track Use, NBS Spec. Publ. 260-49 (November 1974). COM74-51185

Hust, J. G., and Giarratano, P. J., Standard Reference Materials: Thermal Conductivity and Electrical Resistivity Standard Reference Materials: Electrolytic Iron, SRM's 734 and 797 from 4 to 1000 K, NBS Spec. Publ. 260-50 (June 1975). $1.00* SN003-003-01425-7

Mavrodineanu, R., and Baldwin, J. R., Standard Reference Materials: Glass Filters As a Standard Reference Material for Spectrophotometry; Selection; Preparation; Certification; Use-SRM 930, NBS Spec. Publ. 260-51 (November 1975). $1.90* SN003-003-01481-8

Hust, J. G., and Giarratano, P. J., Standard Reference Materials: Thermal Conductivity and Electrical Resistivity Standard Reference Materials 730 and 799, from 4 to 3000 K, NBS Spec. Publ. 260-52 (September 1975). $1.05* SN003-003-01464-8

Durst, R. A., Standard Reference Materials: Standardization of pH Measurements, NBS Spec. Publ. 260-53 (December 1975, Revised). $1.05 SN003-003-01551-2

Burke, R. W., and Mavrodineanu, R. Standard Reference Materials: Certification and Use of Acidic Potassium Dichromate Solutions as an Ultraviolet Absorbance Standard, NBS Spec. Publ. 260-54 (August 1977). $3.00* SN003-003-01828-7

Ditmars, D. A., Cezairliyan, A., Ishihara, S., and Douglas, T. B., Standard Reference Materials: Enthalpy and Heat Capacity; Molybdenum SRM 781, from 273 to 2800 K, NBS Spec. Publ. 260-55 (September 1977). $2.20* SN003-003-01836-8

Powell, R. L., Sparks, L. L., and Hust, J. G., Standard Reference Materials: Standard Thermocouple Materials, Pt.67: SRM 1967, NBS Spec. Publ. 260-56 (February 1978). $2.20* SN003-003-018864

Cali, J. P. and Plebanski, T., Guide to United States Reference Materials, NBS Spec. Publ. 260-57 (February 1978). $2.20* PB 277173

Barnes, J. D., and Martin, G. M., Standard Reference Materials: Polyester Film for Oxygen Gas Transmission Measurements SRM 1470, NBS Spec. Publ. 260-58 (June 1979) $2.00* SN003-003-02077

Chang, T., and Kahn, A. H. Standard Reference Materials: Electron Paramagnetic Resonance Intensity Standard; SRM 2601, NBS Spec. Publ. 260-59 (August 1978) $2.30* SN003-003-01975-5

Velapoldi, R. A., Paule, R. C., Schaffer, R., Mandel, J., and Moody, J. R., Standard Reference Materials: A Reference Method for the Determination of Sodium in Serum, NBS Spec. Publ. 260-60 (August 1978). $3.00* SN003-003 01978-0

Verdier, P. H., and Wagner. H. L., Standard Reference Materials: The Characterization of Linear Polyethylene (SRM 1482, 1483, 1484), NBS Spec. Publ. 260-61 (December 1978). $1.70* SN003-003-02006-1

Soulen, R. J., and Dove, R. B., Standard Reference Materials: Temperature Reference Standard for Use Below 0.5 K (SRM 768). NBS Spec. Publ. 260-62 (April 1979). $2.30* SN003-003-02047-8

Velapoldi, R. A., Paule, R. C., Schaffer, R. Mandel, J., Machlan, L. A., and Gramlich, J. W., Standard Reference Materials: A Reference Method for the Determination of Potassium in Serum. NBS Spec. Publ. 260-63 (May 1979). $3.75* SN003-003-02068

Velapoldi, R. A., and Mielenz, K. D., Standard Reference Materials: A Fluorescence Standard Reference Material Quinine Sulfate Dihydrate (SRM 936), NBS Spec. Publ. 260-64 (January 1980). $4.25* SN003-003-02148-2

Marinenko, R. B., Heinrich, K. F. J., and Ruegg, F. C., Standard Reference Materials: Micro-Homogeneity Studies of NBS Standard Reference Materials, NBS Research Materials, and Other Related Samples. NBS Spec. Publ. 260-65 (September 1979). $3.50* SN003-003-02114-1

Venable, W. H., Jr., and Eckerle, K. L., Standard Reference Materials: Didymium Glass Filters for Calibrating the Wavelength Scale of Spectrophotometers (SRM 2009, 2010, 2013). NBS Spec. Publ. 260-66 (October 1979). $3.50* SN003-003-02127-0

Velapoldi, R. A., Paule, R. C., Schaffer, R., Mandel, J., Murphy, T. J., and Gramlich, J. W., Standard Reference Materials: A Reference Method for the Determination of Chloride in Serum, NBS Spec. Publ. 260-67 (November 1979). $3.75* SN003-003-02136-9

Mavrodineanu, R. and Baldwin, J. R., Standard Reference Materials: Metal-On-Quartz Filters as a Standard Reference Material for Spectrophotometry-SRM 2031, NBS Spec. Publ. 260-68 (April 1980). $4.25* SN003-003-02167-9

Velapoldi, R. A., Paule, R. C., Schaffer, R., Mandel, J., Machlan, L. A., Garner, E. L., and Rains, T. C., Standard Reference Materials: A Reference Method for the Determination of Lithium in Serum, NBS Spec. Publ. 260-69 (July) 1980). $4.25* SN003-003-02214-4

Marinenko, R. B., Biancaniello, F., Boyer, P. A., Ruff, A. W., DeRobertis, L., Standard Reference Materials: Preparation and Characterization of an Iron-Chromium-Nickel Alloy for Microanalysis, NBS Spec. Publ. 260-70 (May 1981). $2.50* SN003-003-02328-1

Seward, R. W., and Mavrodineanu, R., Standard Reference Materials: Summary of the Clinical Laboratory Standards Issued by the National Bureau of Standards, NBS Spec. Publ. 260-71 (November 1981). $6.50* SN003-003-02381-7

Reeder, D.J., Coxon, B., Enagonio, D., Christensen, R. G., Schaffer, R., Howell, B. F., Paule, R. C., Mandel, J., Standard Reference Materials: SRM 900, Antiepilepsy Drug Level Assay Standard, NBS Spec. Publ. 260-72 (June 1981). $4.25* SN003-003-02329-9

Interrante, C. G., and Hicho, G. E., Standard Reference Materials: A Standard Reference Material Containing Nominally Fifteen Percent Austenite (SRM 486), NBS Spec. Publ. 260-73 (January 1982). $2.75* SN003-003-02386-8

Marinenko, R. B., Standard Reference Materials: Preparation and Characterization of K-411 and K-414 Mineral Glasses for Microanalysis: SRM 470. NBS Spec. Publ. 260-74 (April 1982). $3.50 SN003-003-023-95-7

Weidner, V. R., Hsia, J. J., Standard Reference Materials: Preparation and Calibration of First Surface Aluminum Mirror Specular Reflectance Standards (SRM 2003a), NBS Spec. Publ. 260-75 (May 1982). $3.75 SN003-003-023-99-0

Hicho, G. E. and Eaton, E. E., Standard Reference Materials: A Standard Reference Material Containing Nominally Five Percent Austenite (SRM 485a), NBS Spec. Publ. 260-76 (August 1982). $3.50 SN003-003-024-33-3

Furukawa, G. T., Riddle, J. L., Bigge, W. G., and Pfieffer, E. R., Standard Reference Materials: Application of Some Metal SRM's as Thermometric Fixed Points, NBS Spec. Publ. 260-77 (August 1982). $6.00 SN003-003-024-34-1

Hicho, G. E. and Eaton, E. E., Standard Reference Materials: Standard Reference Material Containing Nominally Thirty Percent Austenite (SRM) 487), NBS Spec. Publ. 260-78 (September 1982). $3.75 SN003-003-024-35-0

Richmond, J. C., Hsia, J. J. Weidner, V. R., and Wilmering, D. B., Standard Reference Materials: Second Surface Mirror Standards of Specular Spectral Reflectance (SRM's 2023, 2024, 2025), NBS Spec. Publ. 260-79 (October 1982). $4.50 SN003-003-024-47-3

Schaffer, R., Mandel, J., Sun, T., Cohen, A., and Hertz, H. S., Standard Reference Materials: Evaluation by an ID/MS Method of the AACC Reference Method for Serum Glucose, NBS Spec. Publ. 260-80 (October 1982). $4.75 SN003-003-024-43-1

Burke, R. W., Mavrodineanu, R. (NBS retired), Standard Reference Materials: Accuracy in Analytical Spectrophotometry, NBS Spec. Publ. 260-81 (April 1983). $6.00 SN003-003-024-84-8

Weidner, V. R., Standard Reference Materials: White Opal Glass Diffuse Spectral Reflectance Standard for the Visible Spectrum (SRM 2015 and 2016), NBS Spec. Publ. 260-82 (April 1983). $3.75 SN-003-003-024-89-9

Bowers, G. N., Jr., Alvarez, R., Cali, J. P. (NBS retired), Eberhardt, K. R., Reeder, D. J., Schaffer, R., Uriano, G. A., Standard Reference Materials: The Measurement of the Catalytic (Activity) Concentration of Seven Enzymes in NBS Human Serum SRM 909, NBS Spec. Publ. 260-83 (June 1983). $4.50 SN003-003-024-99-6

Gills, T. E., Seward, R. W., Collins, R. J., and Webster, W. C., Standard Reference Materials: Sampling, Materials Handling, Processing, and Packaging of NBS Sulfur in Coal Standard Reference Materials, 2682, 2683, 2684, and 2685, NBS Spec. Publ. 260-84 (August 1983). $4.50 SN003-003-025-20-8

Swyt, D. A., Standard Reference Materials: A Look at Techniques for the Dimensional Calibration of Standard Microscopic Particles, NBS Spec. Publ. 260-85 (September 1983). $5.50 SN003-003-025-21-6

Hicho, G. E. and Eaton, E. E., Standard Reference Materials: A Standard Reference Material Containing Two and One-Half Percent Austenite, SRM 488, NBS Spec. Publ. 260-86 (December 1983). $1.75* SN003-003-025-41-1

Mangum, B. W., Standard Reference Materials: SRM 1969: Rubidium Triple-Point - A Temperature Reference Standard Near 39.30 °C, NBS Spec. Publ. 260-87 (December 1983). $2.25* SN003-003-025-44-5

Gladney, E. S., Burns, C. E., Perrin, D. R., Roelandts, I., and Gills, T. E., 1982 Compilation of Elemental Concentration Data for NBS Biological, Geological, and Environmental Standard Reference Materials. NBS Spec. Publ. 260-88 (March 1984). SN003-003-02565-8

Hust, J. G., A Fine-Grained, Isotropic Graphite for Use as NBS Thermophysical Property RM's from 5 to 2500 K, NBS Spec. Publ. 260-89 (In Press).

Hust, J. G., and Lankford, A. B., Update of Thermal Conductivity and Electrical Resistivity of Electrolytic Iron, Tungsten, and Stainless Steel, NBS Spec. Publ. 260-90 (In Press).

* Send order with remittance to Superintendent of Documents, U.S. Government Printing Office Washington, DC 20402. Remittance from foreign countries should include an additional one-fourth of the purchase price for postage.

** May be ordered from: National Technical Information Services (NTIS). Springfield Virginia 22151.

TABLE OF CONTENTS

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

J. G. Hust and A. B. Lankford

Chemical Engineering Science Division
Center for Chemical Engineering
National Bureau of Standards
Boulder, Colorado 80303

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

$$\lambda = (W_o + W_i + W_{io})^{-1} \tag{3.1}$$

where

$$W_o = \beta/T, \text{ where } \beta = \frac{\rho_o}{L_o} \tag{3.2}$$

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

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

and

$$W_{io} = P_7 W_i W_o/(W_i+W_o) \tag{3.4}$$

The general form of the electrical resistivity equation is given by

$$\rho = \rho_o + \rho_i + \rho_{io} \tag{3.5}$$

where ρ_o = residual electrical resistivity

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

and

$$\rho_{io} = P_7 \rho_i \rho_o/(\rho_i+\rho_o) \tag{3.7}$$

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

$P_1 = 274.6 \times 10^{-8}$ $\quad$ $P_5 = 245.4$

$P_2 = 1.757$ $\quad$ $P_6 = 1.375$

$P_3 = 1.5167 \times 10^5$ $\quad$ $P_7 = 0.0$

$P_4 = -1.22$

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

The residuals were represented by

$$W_c = -0.004 \ \ell n(T/440) \exp(-(\ell n(T/650)/0.8)^2)$$

$$-0.002 \ \ell n(T/90) \exp(-(\ell n(T/90)/0.45)^2) \tag{3.8}$$

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

$P_1 = 42.17 \times 10^{-16}$

$P_2 = 3.243$

$P_3 = 7.638 \times 10^{11}$

$P_4 = 1.95$

$P_5 = 178.5$

$P_6 = 1.98$

$P_7 = 0.05944$

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

The residuals were represented by

$$\rho_c = -\ 3 \times 10^{-8}\ \ell n(T/370)\ \exp(-(\ell n(T/600)/0.6)^2) - 3 \times 10^{-9}\ \ell n(T/105)\ \exp(-(\ell n(T/120)/0.45)^2) \quad (3.9)$$

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.

3.1.1 List of Figures and Tables for Electrolytic Iron

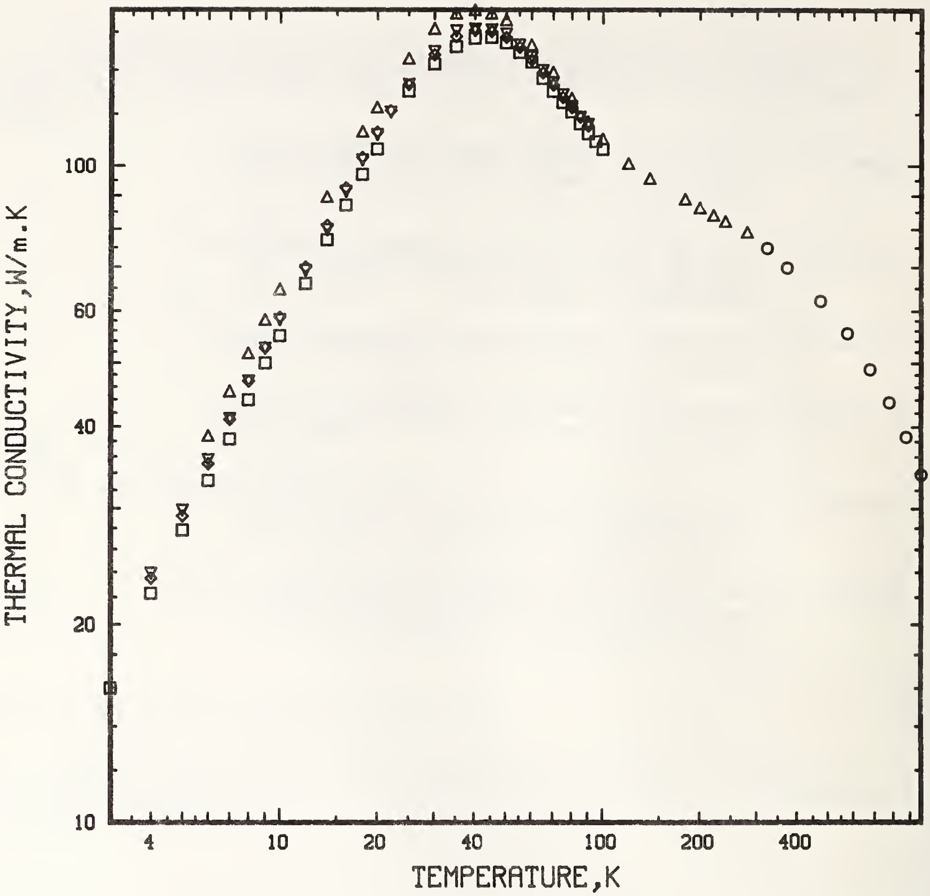

Figure 3.1.1 Experimental thermal conductivity data for the electrolytic iron RM from the following sources: (8,13,26)

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

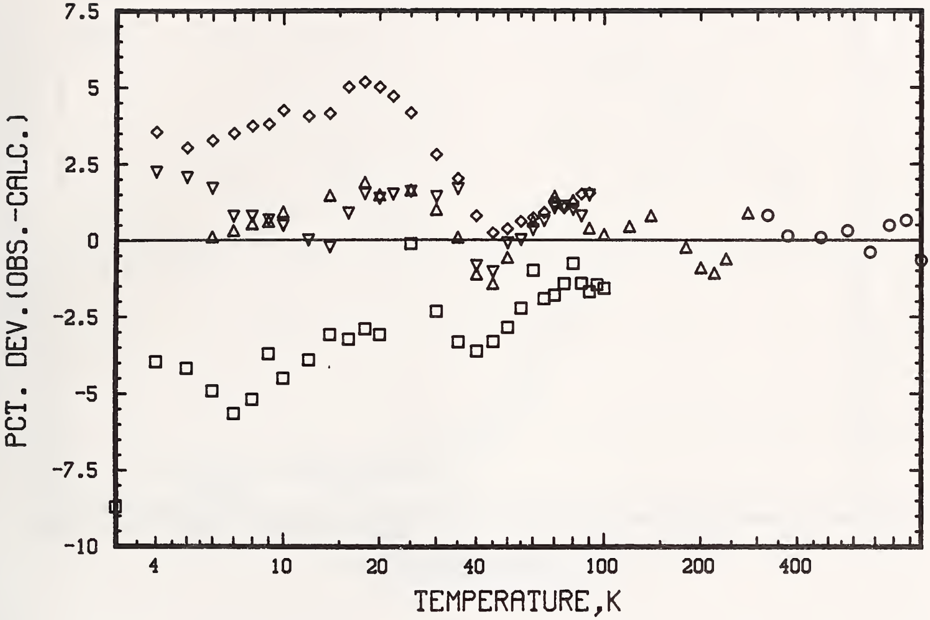

Figure 3.1.2 Thermal conductivity deviations of the electrolytic iron RM data of the following references from eq.(3.1): (8,13,26)

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

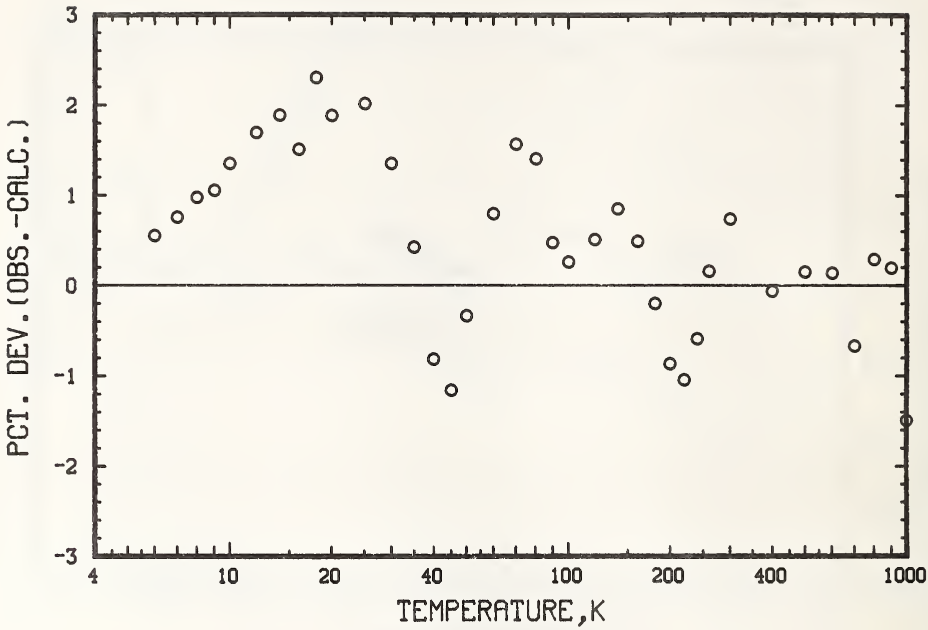

Figure 3.1.3 Deviations of the previously recommended thermal conductivity values (6) from eq.(3.1).

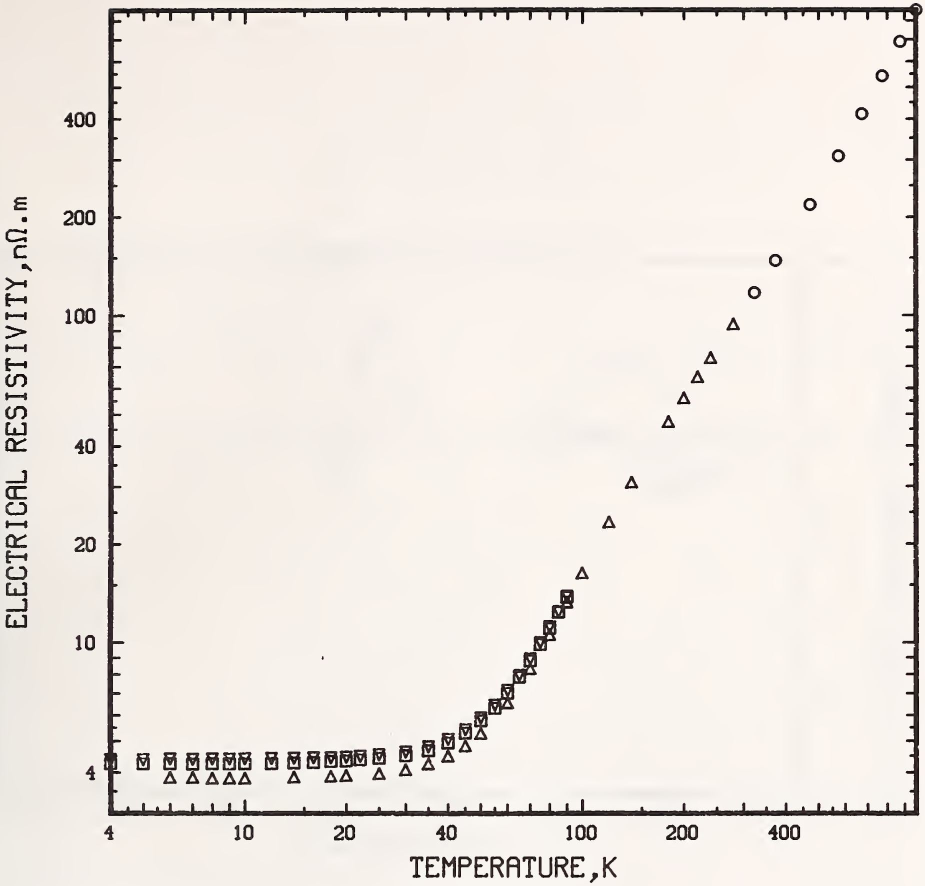

Figure 3.1.4 Experimental electrical resistivity data for the electrolytic iron RM from the following sources:(8,13,26)

○ = (26), △ = (8), □ = (13), ▽ = (13)

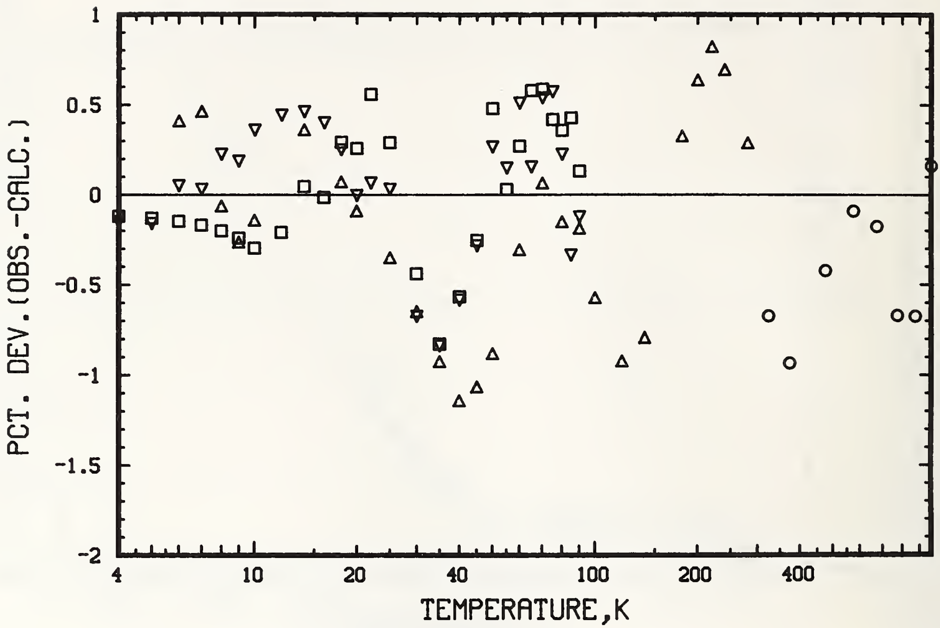

Figure 3.1.5 Electrical resistivity deviations of the electrolytic iron RM data of the following references from eq.(3.5): (8,13,26)

○ - (26), △ - (8), □ - (13), ▽ - (13)

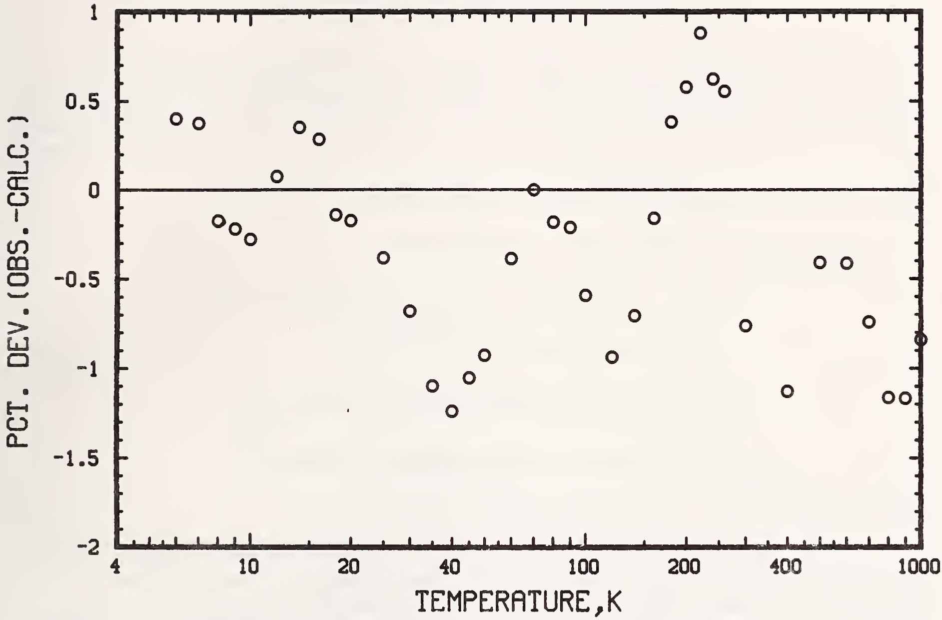

Figure 3.1.6 Deviations of the previously recommended electrical resistivity values (6) from eq.(3.5).

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

$$P_1 = 16.4 \times 10^{-8} \qquad P_5 = 69.21$$

$$P_2 = 2.449 \qquad P_6 = 3.986$$

$$P_3 = 541.3 \qquad P_7 = 0.1$$

$$P_4 = -0.22$$

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

The systematic residuals were represented by

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

where W_c and T are in m•K•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:

$$P_1 = 4.801 \times 10^{-16} \qquad P_5 = 55.63$$

$$P_2 = 3.839 \qquad P_6 = 2.391$$

$$P_3 = 1.88 \times 10^{10} \qquad P_7 = 0.0$$

$$P_4 = 1.22$$

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

The systematic residuals were represented by

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

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.

3.2.1 List of Figures and Tables for Tungsten

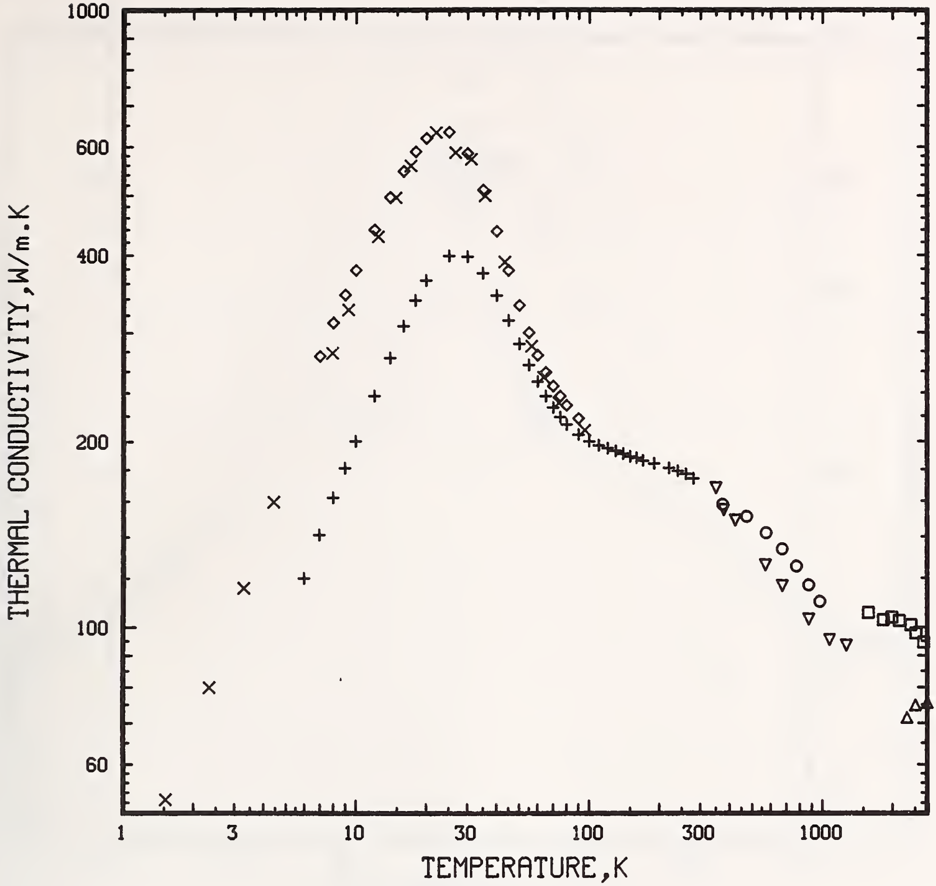

Figure 3.2.1 Experimental thermal conductivity data for the tungsten RM from the following sources: (11,13,19,27)

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

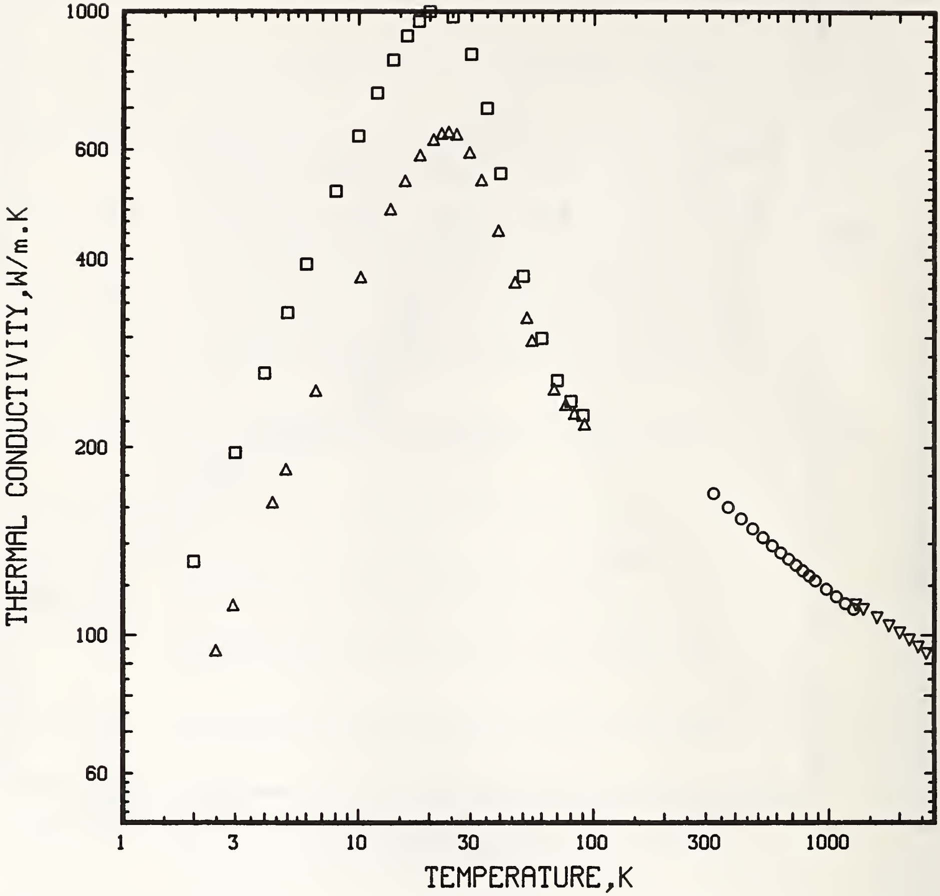

Figure 3.2.2 Experimental thermal conductivity data for the tungsten RM from the following sources: (13,22,28)

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

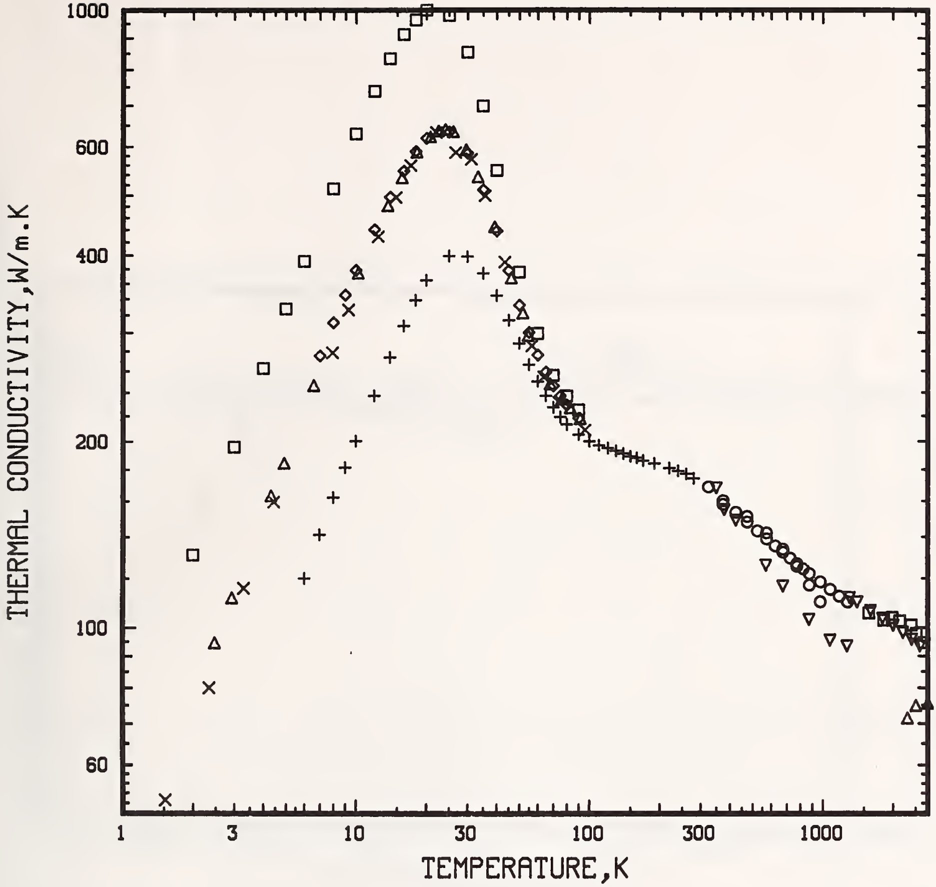

Figure 3.2.3 Composite of the data in figs. 3.2.1 and 3.2.2

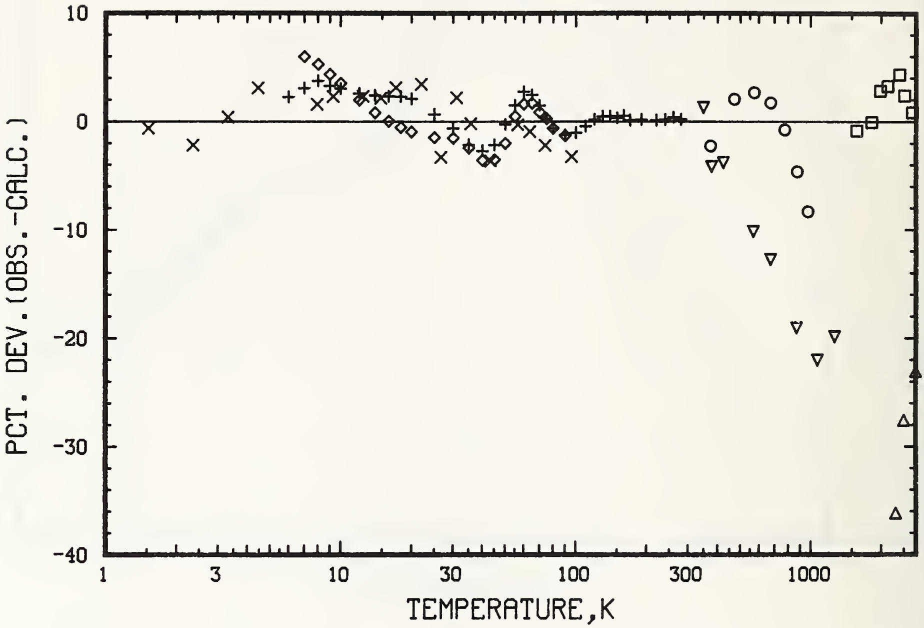

Figure 3.2.4 Thermal conductivity deviations of the tungsten RM data of the following references from eq.(3.1): (11,13,19,27)

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

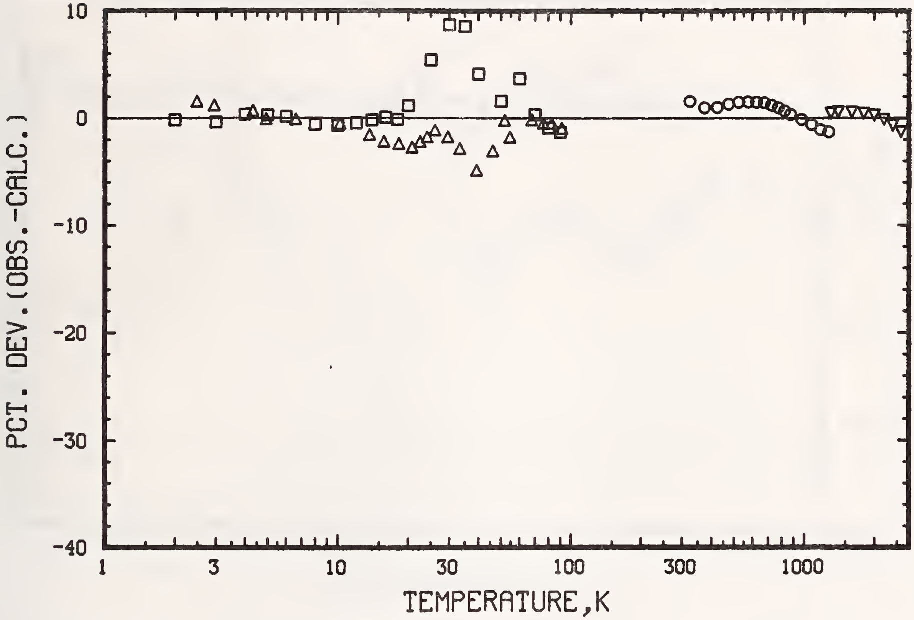

Figure 3.2.5 Thermal conductivity deviations of the tungsten RM data of the following references from eq.(3.1): (13,22,28)

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

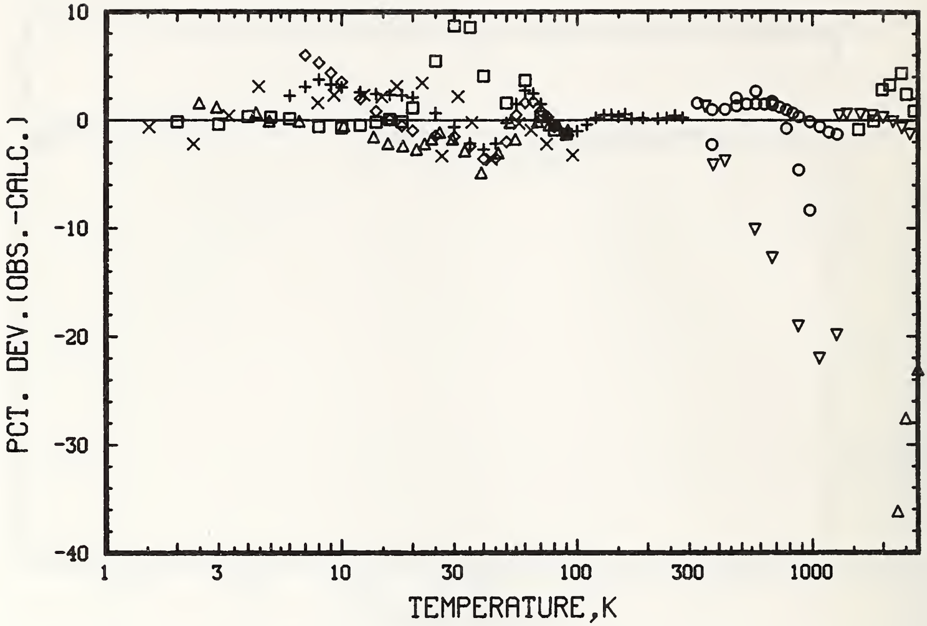

Figure 3.2.6 Composite of the data in figs. 3.2.4 and 3.2.5

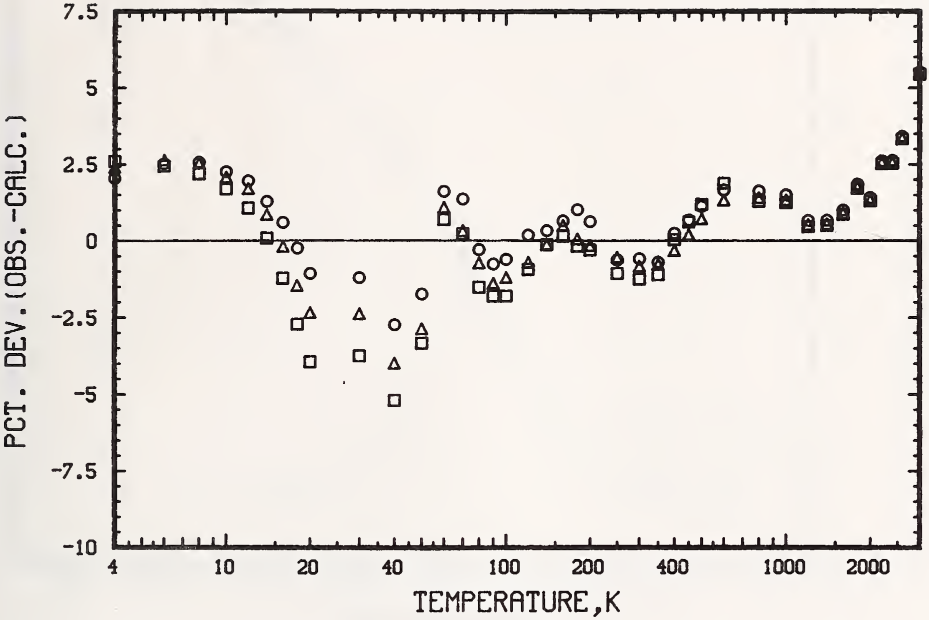

Figure 3.2.7 Deviations of the previously recommended thermal conductivity values (5) from eq.(3.1).

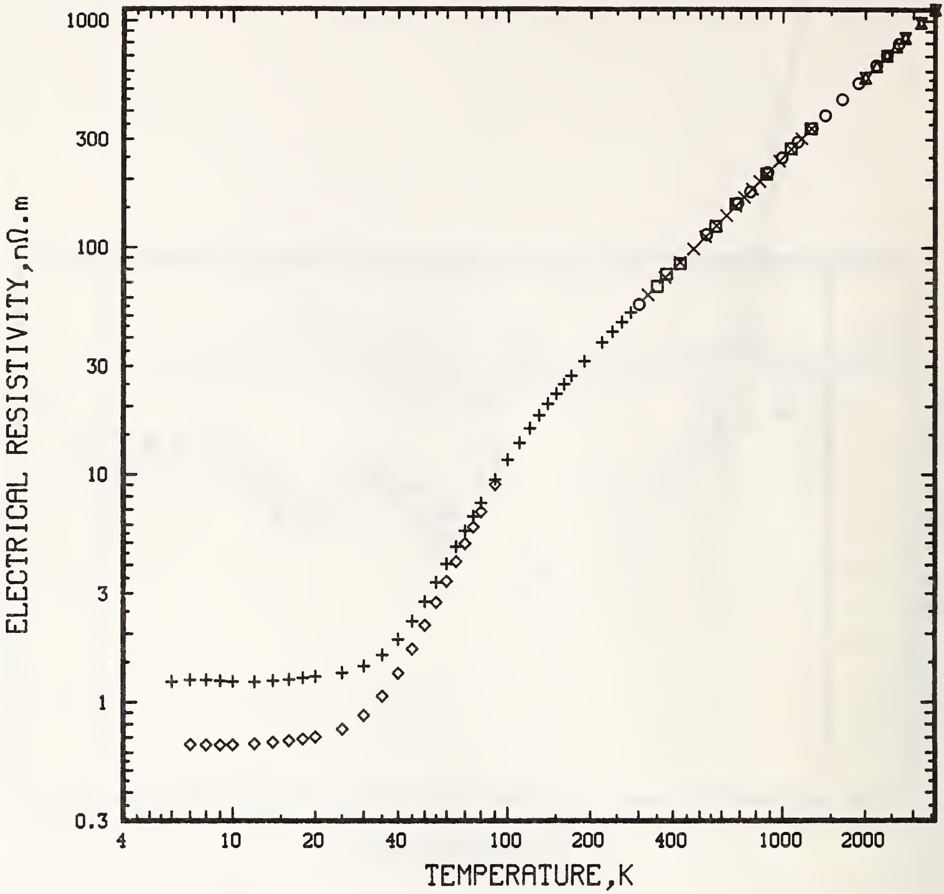

Figure 3.2.8 Experimental electrical resistivity data for the tungsten RM from the following sources: (11,18,19,27,28)

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

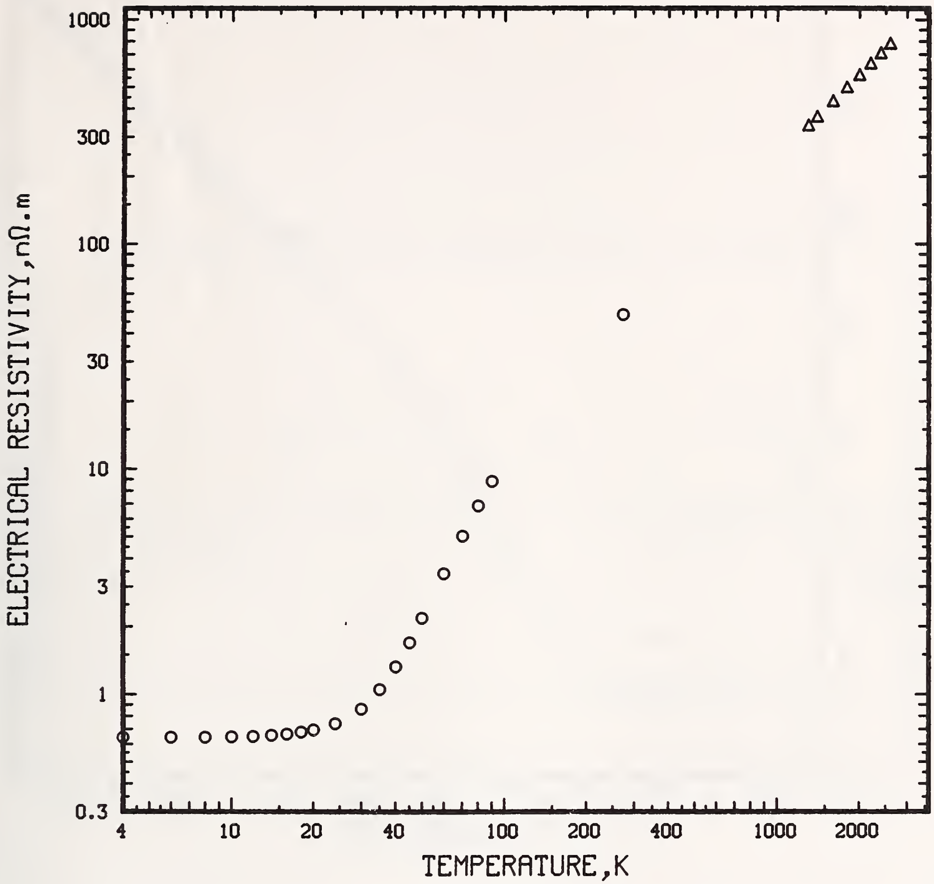

Figure 3.2.9 Experimental electrical resistivity data for the tungsten RM from the following sources: (13,22)

O - (13), Δ - (22)

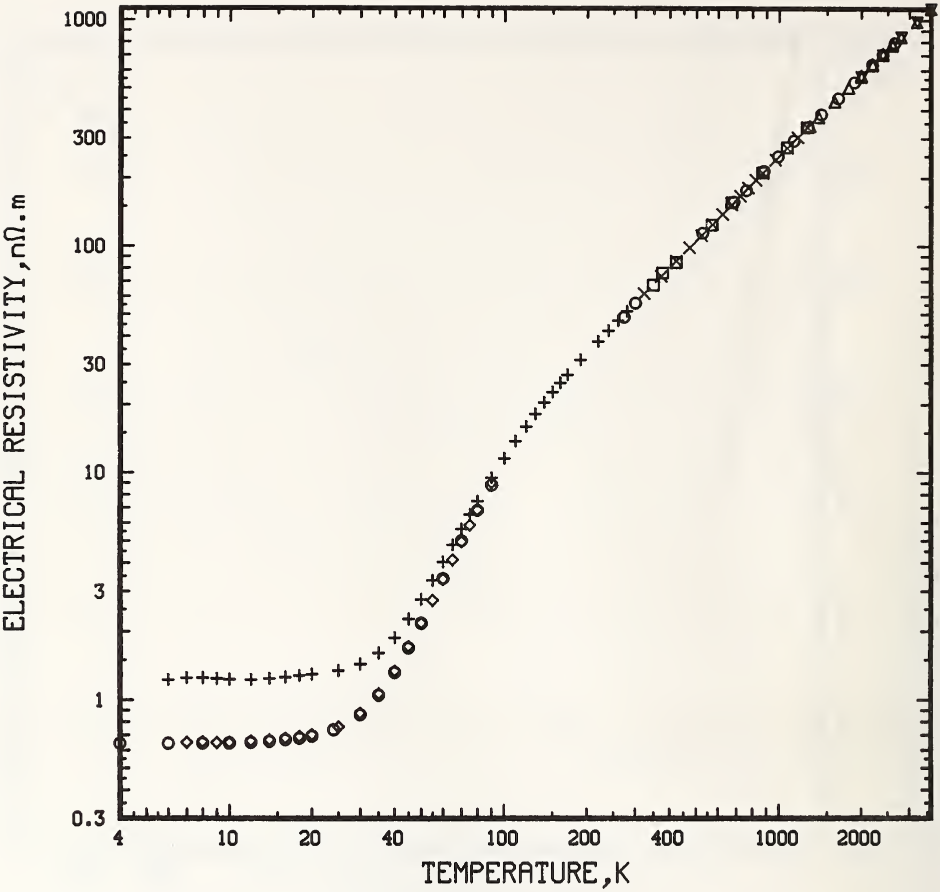

Figure 3.2.10 Composite of data in figs. 3.2.8 and 3.2.9

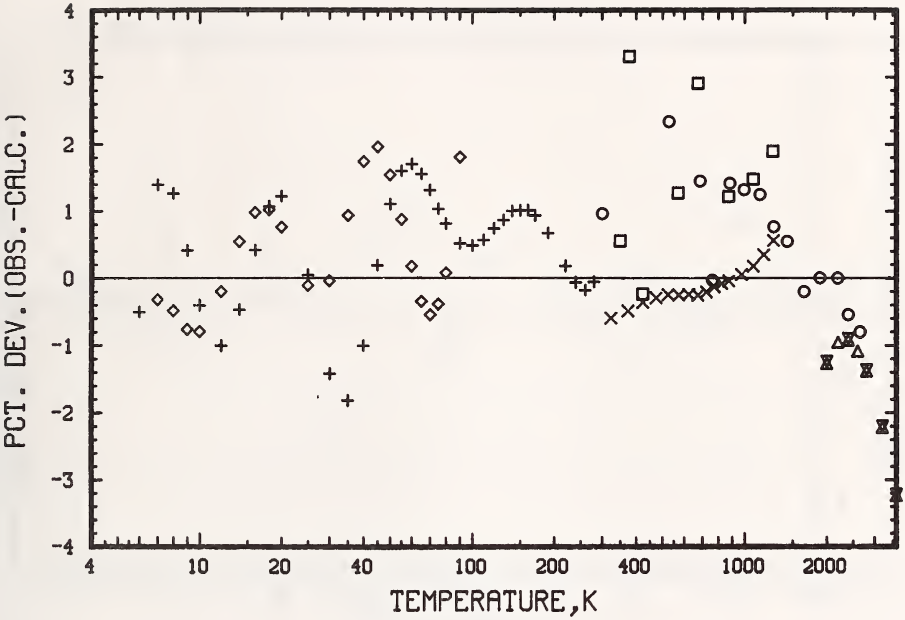

Figure 3.2.11 Electrical resistivity deviations of the tungsten RM data of the following references from eq.(3.5): (11,18,19,27,28)

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

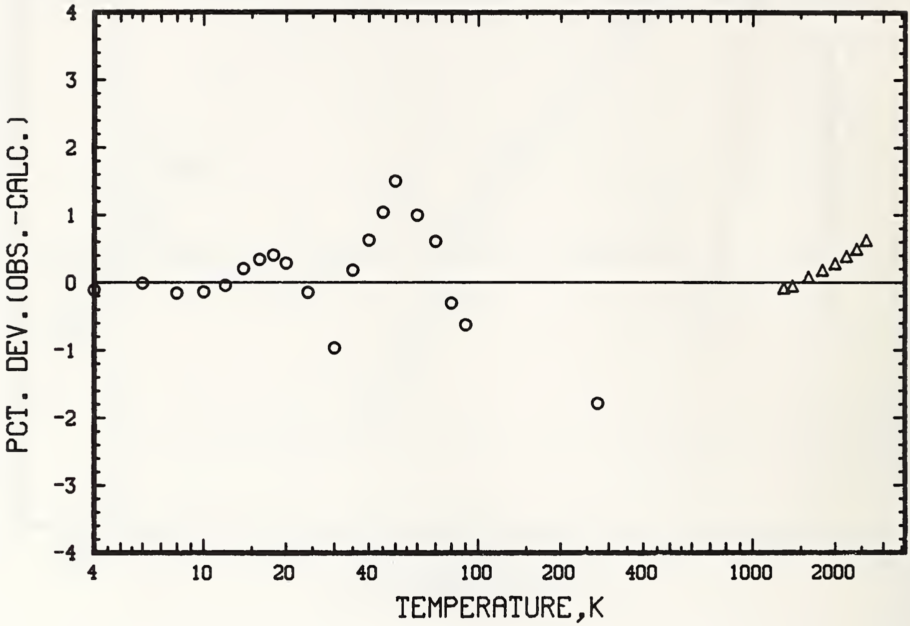

Figure 3.2.12 Electrical resistivity deviations of the tungsten RM data of the following references from eq.(3.5): (13,22)

O - (13), Δ - (22)

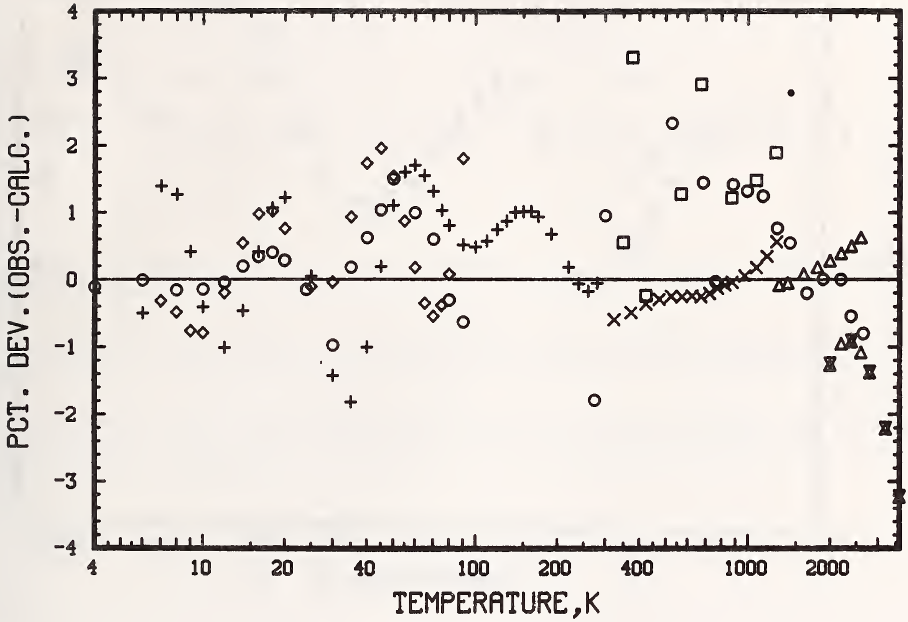

Figure 3.2.13 Composite of the data in figs. 3.2.11 and 3.2.12

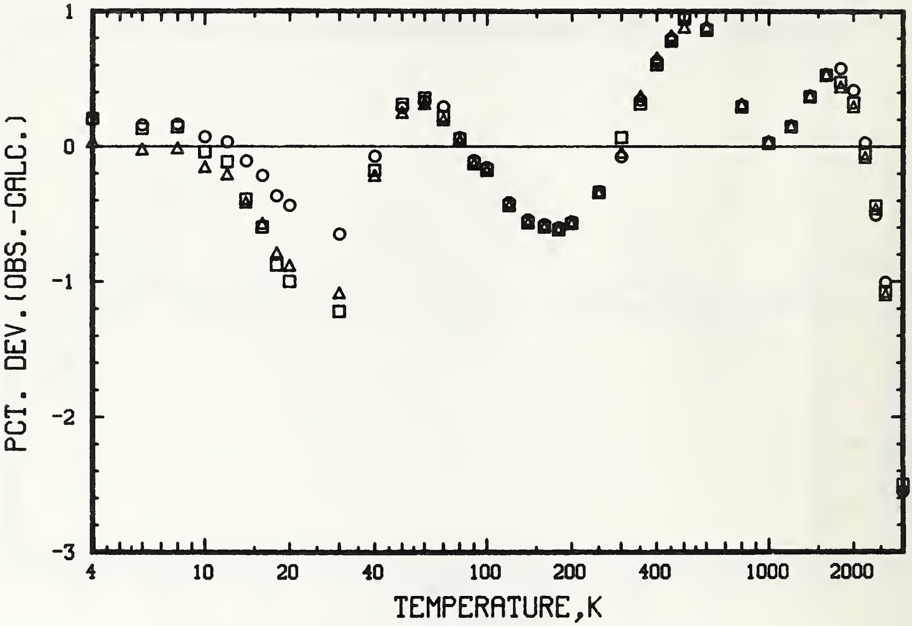

Figure 3.2.14 Deviations of the previously recommended electrical resistivity values(5) from eq.(3.5).

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 β/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

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

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

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

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

The systematic residuals were represented by

$$\rho_c = 2.5 \times 10^{-8}\ \ell n(T/135)\ \ell n(T/270)\ \ell n(T/530)\ \exp(-(\ell n(T/350)/1.4)^2)$$

$$-5.5 \times 10^{-8}\ \exp(-(\ell n(T/1300)/0.4)^2)$$

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.

3.3.1 List of Figures and Tables for Stainless Steel

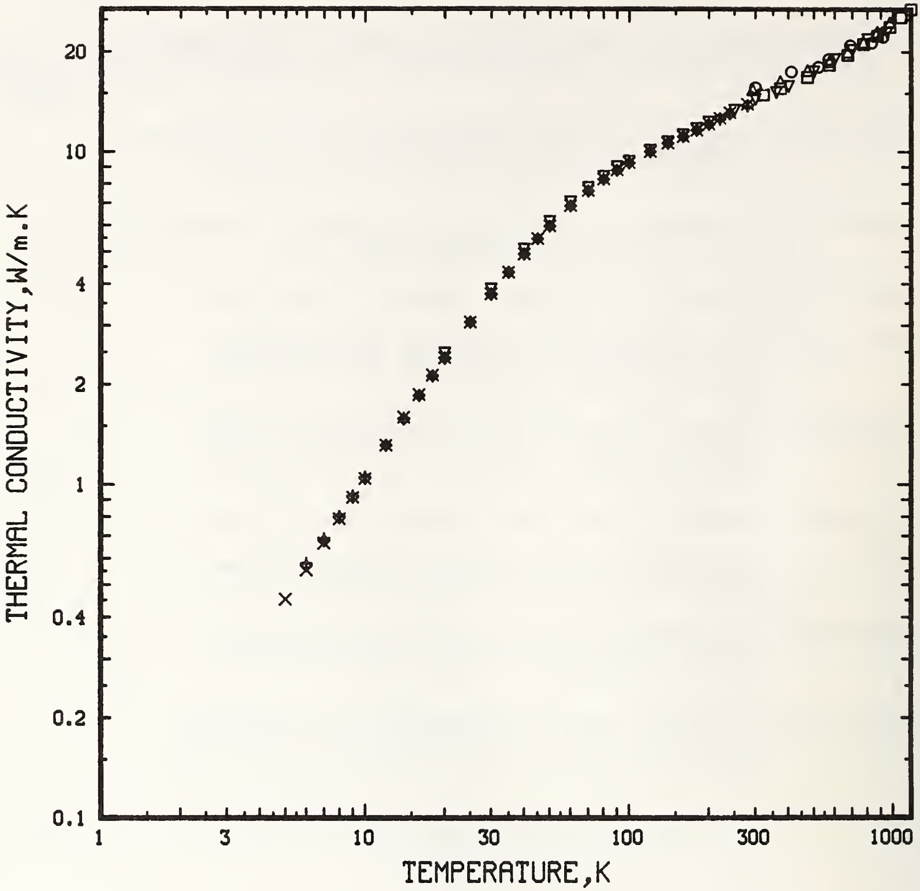

Figure 3.3.1 Experimental thermal conductivity data for the stainless steel SRM from the following sources: (9,10,16,21,27)

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

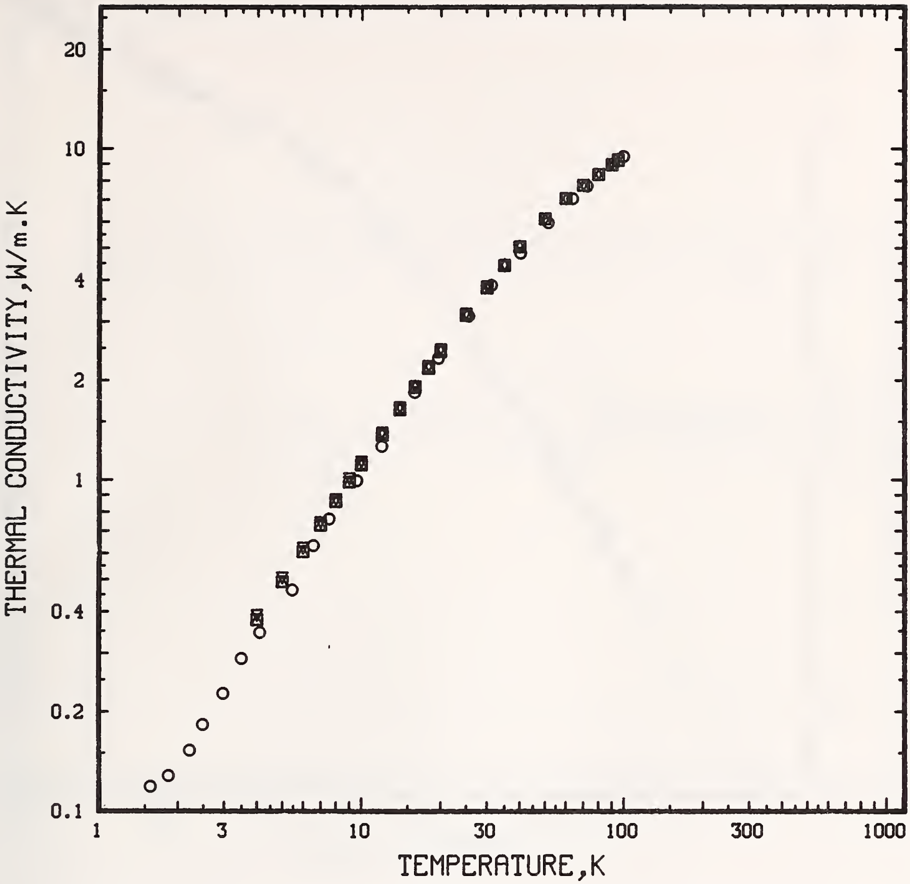

Figure 3.3.2 Experimental thermal conductivity data for the stainless steel SRM from the following sources: (13)

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

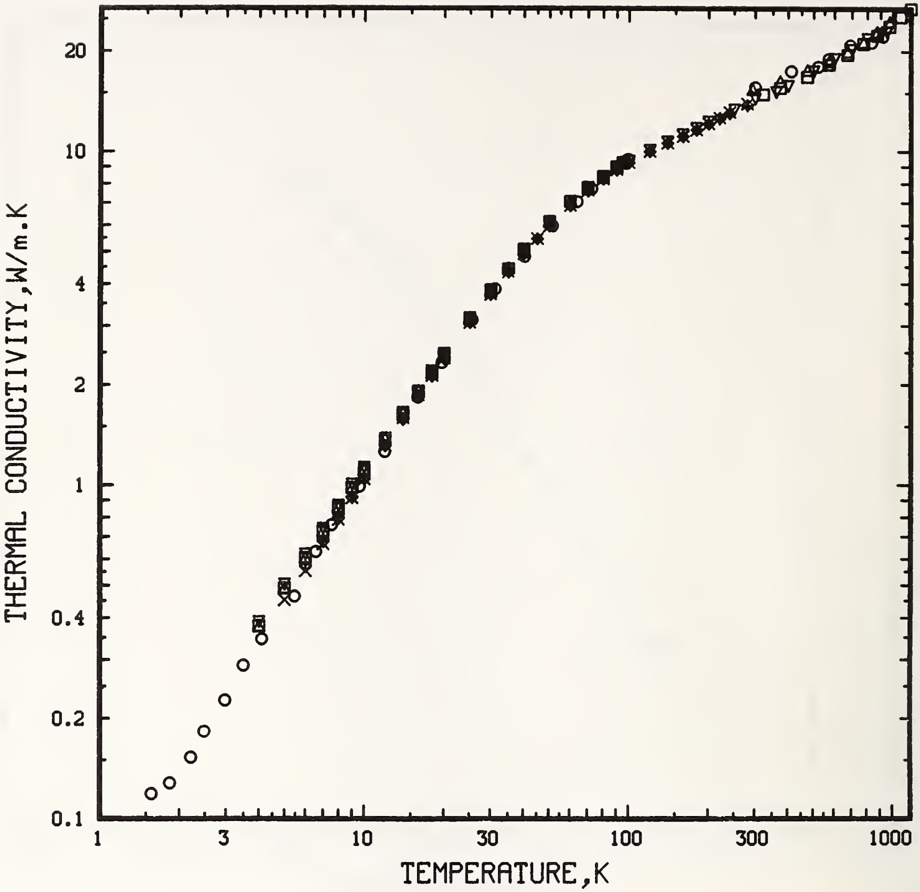

Figure 3.3.3 Composite of the data in figs. 3.3.1 and 3.3.2

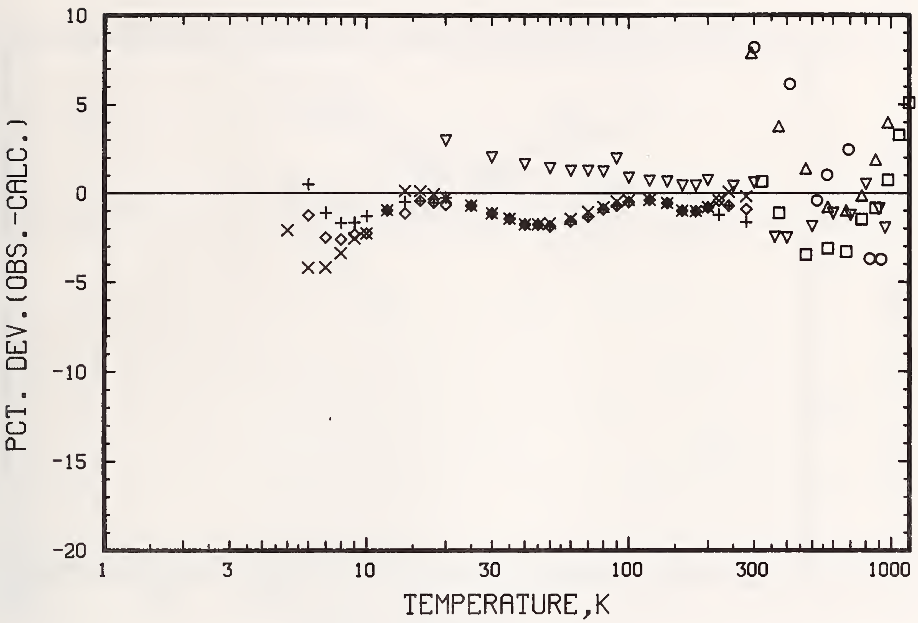

Figure 3.3.4 Thermal conductivity deviations of the stainless steel SRM data of the following references from eq.(3.1): (9,10,16,21,27)

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

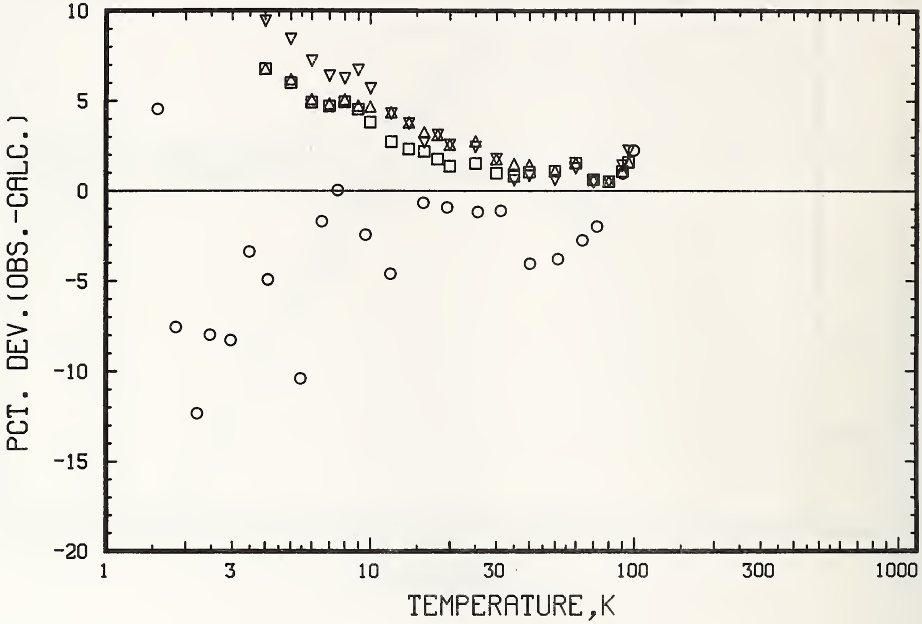

Figure 3.3.5 Thermal conductivity deviations of the stainless steel SRM data of the following references from eq.(3.1): (13)

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

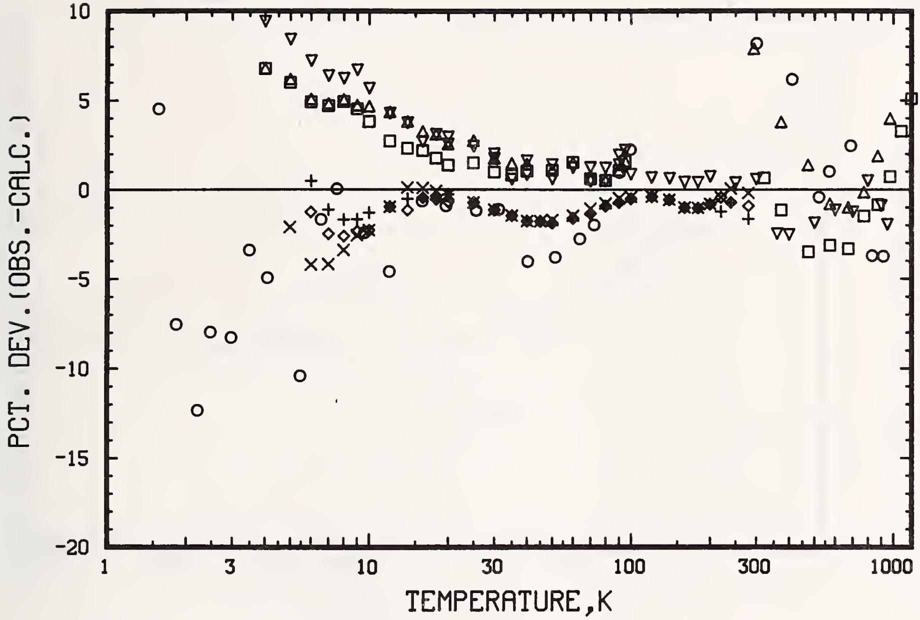

Figure 3.3.6 Composite of the data in figs. 3.3.4 and 3.3.5

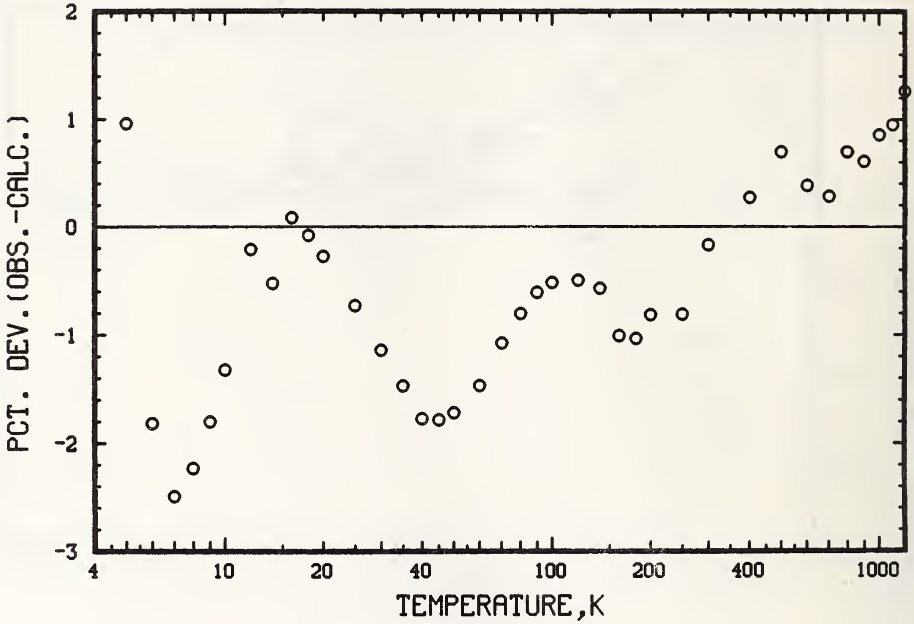

Figure 3.3.7 Deviations of the previously recommended thermal conductivity values (6) from eq.(3.1).

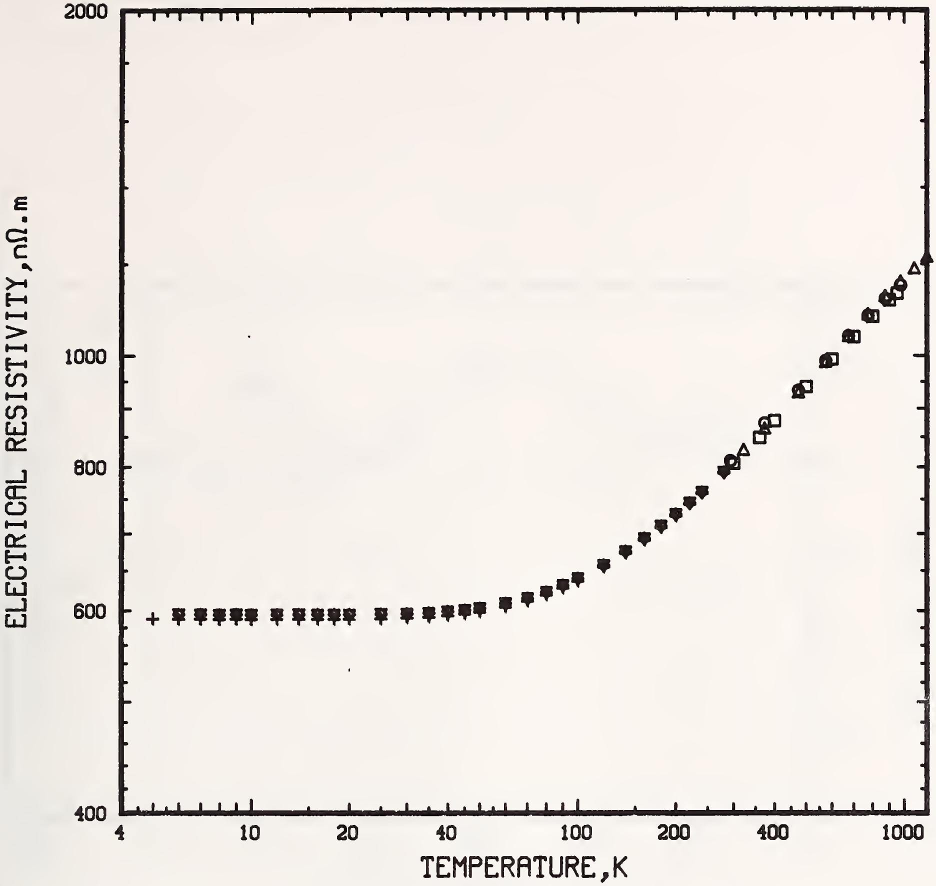

Figure 3.3.8 Experimental electrical resistivisty data for the stainless steel SRM from the following sources: (9,10,16,21,27)

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

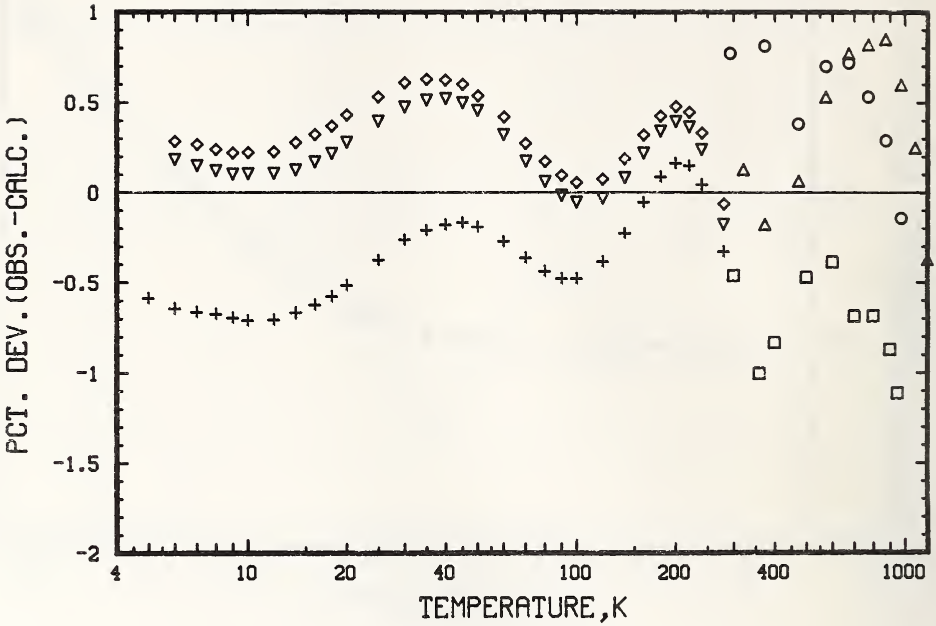

Figure 3.3.9 Electrical resistivity deviations of the stainless steel SRM data of the following references from eq.(3.5): (9,10,16,21,27)

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

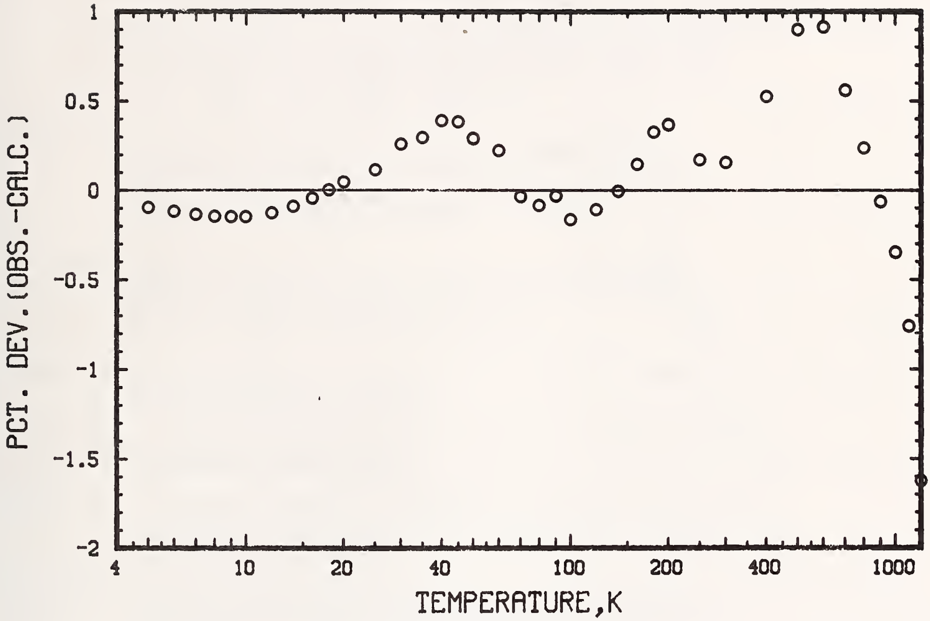

Figure 3.3.10 Deviations of the previously recommended electrical resistivity values (6) from eq.(3.5).

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.

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

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

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

4.1 List of Figures and Tables

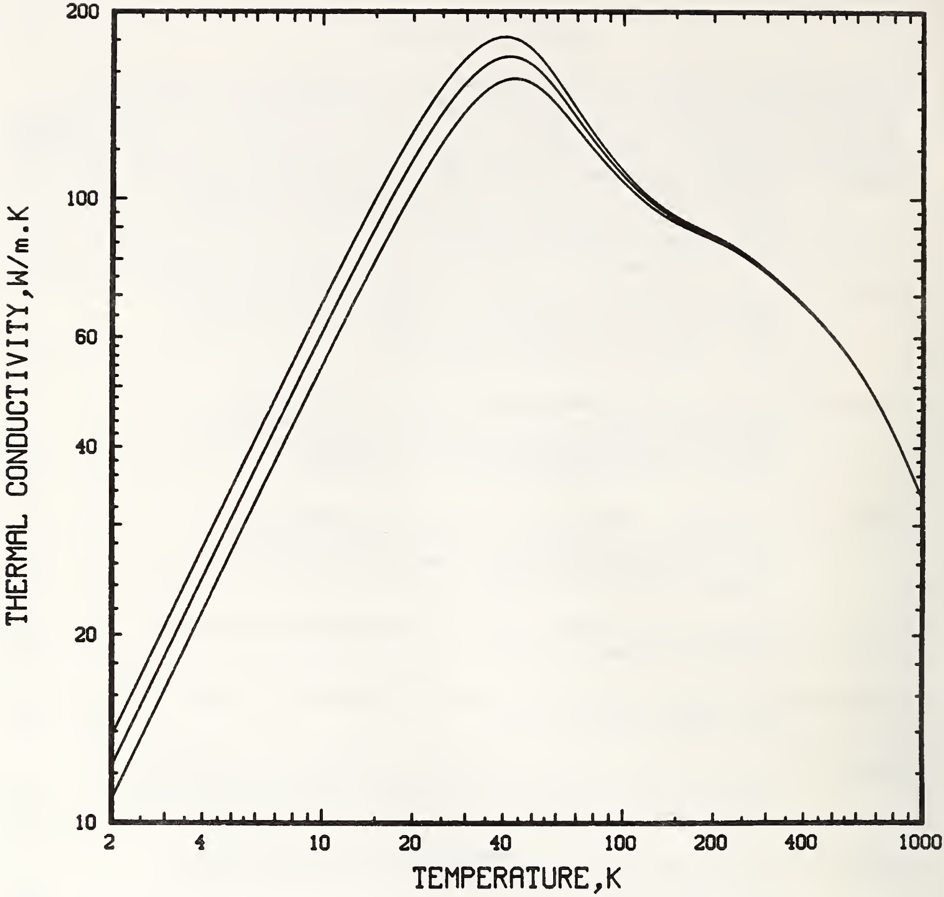

Figure 4.1 Thermal conductivity values for the electrolytic iron RM calculated from eq.(3.1) at RRR=20.0, 22.5, and 25.0 (the corresponding values of residual resistivity are: 4.579, 4.046, and 3.625 nΩ.m)

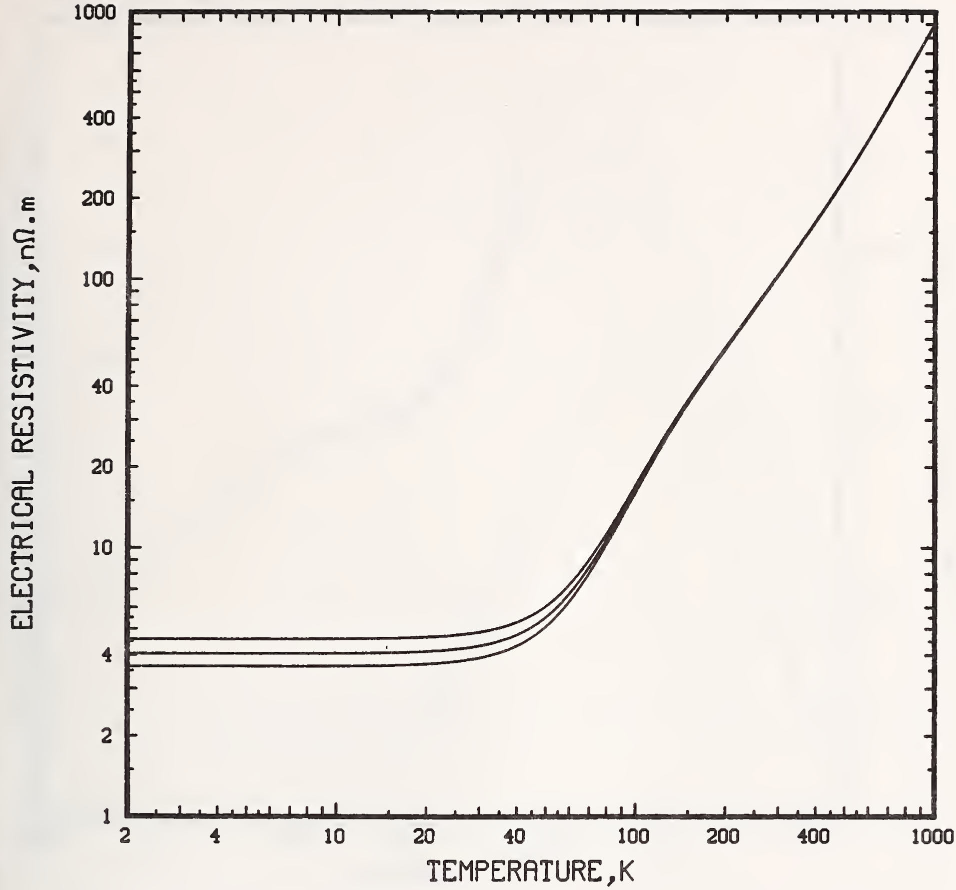

Figure 4.2 Electrical resistivity values for the electrolytic iron RM calculated from eq.(3.5) at RRR=20.0, 22.5, and 25.0 (the corresponding values of residual resistivity are: 4.579, 4.046, and 3.625 nΩ.m)

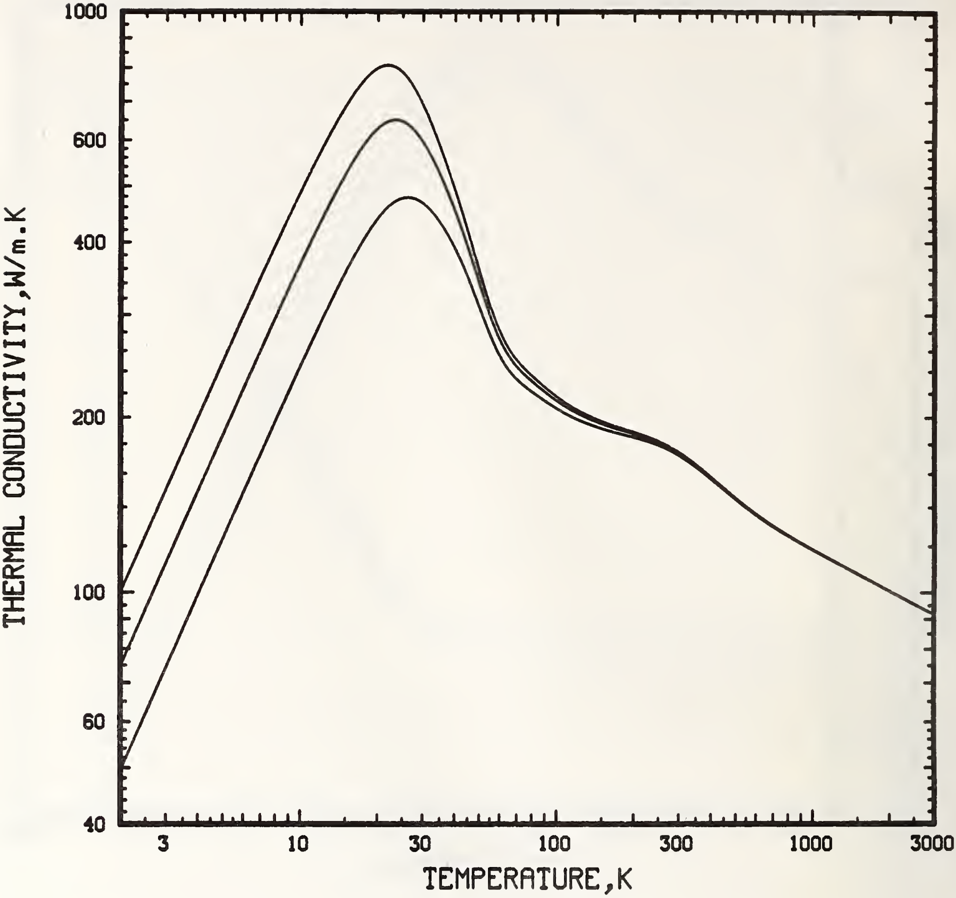

Figure 4.3 Thermal conductivity values for the tungsten RM calculated from eq.(3.1) at RRR=50, 75, and 100 (the corresponding values of residual resistivity are: 0.9878, 0.6540, and 0.4889 nΩ.m)

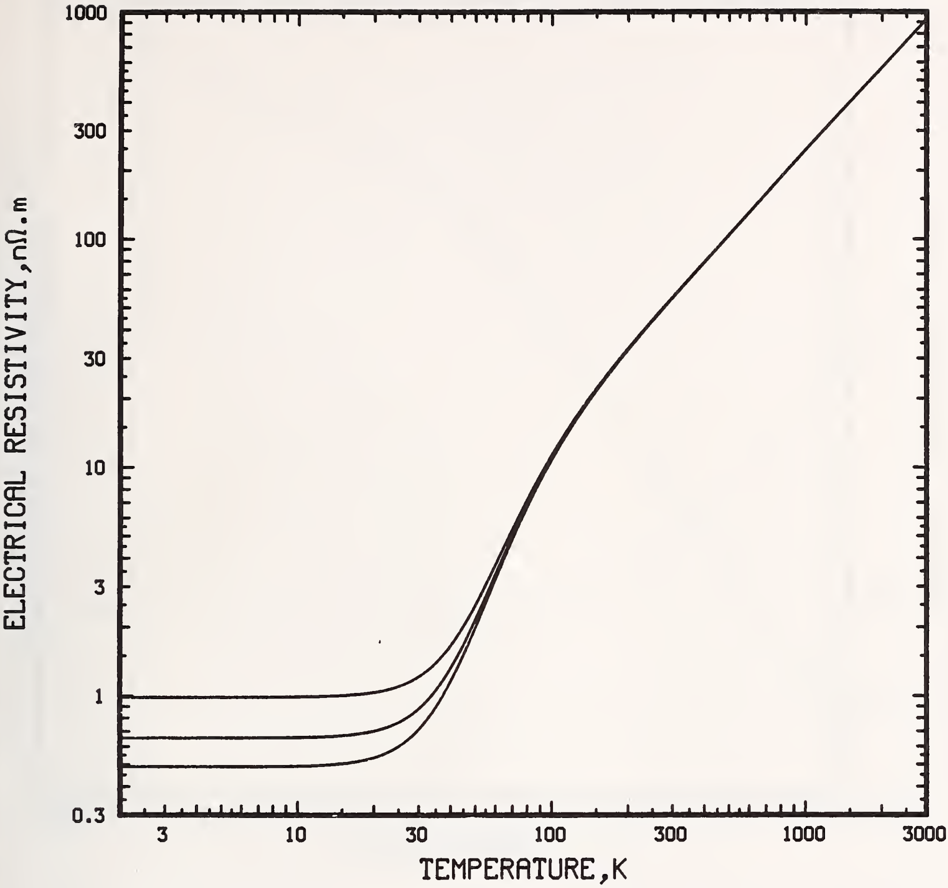

Figure 4.4 Electrical resistivity values for the tungsten RM calculated from eq.(3.5) at RRR=50, 75, and 100 (the corresponding values of residual resistivity are: 0.9878, 0.6540, and 0.4889 nΩ.m)

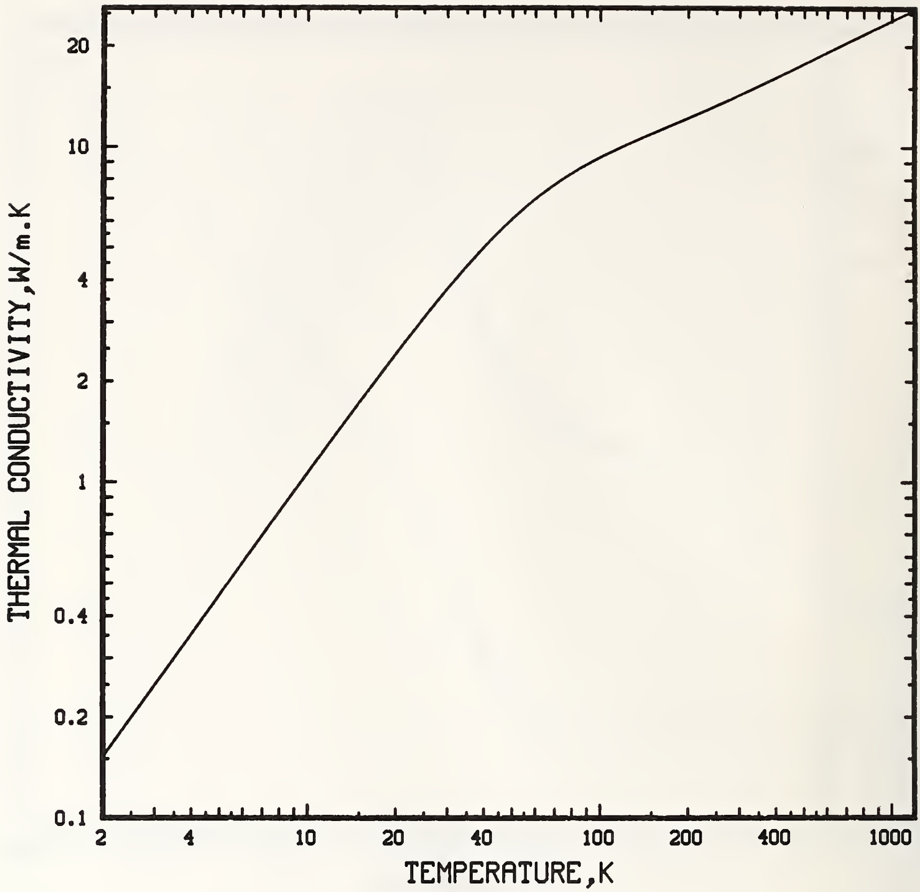

Figure 4.5 Thermal conductivity values for the stainless steel SRM calculated from eq.(3.1)

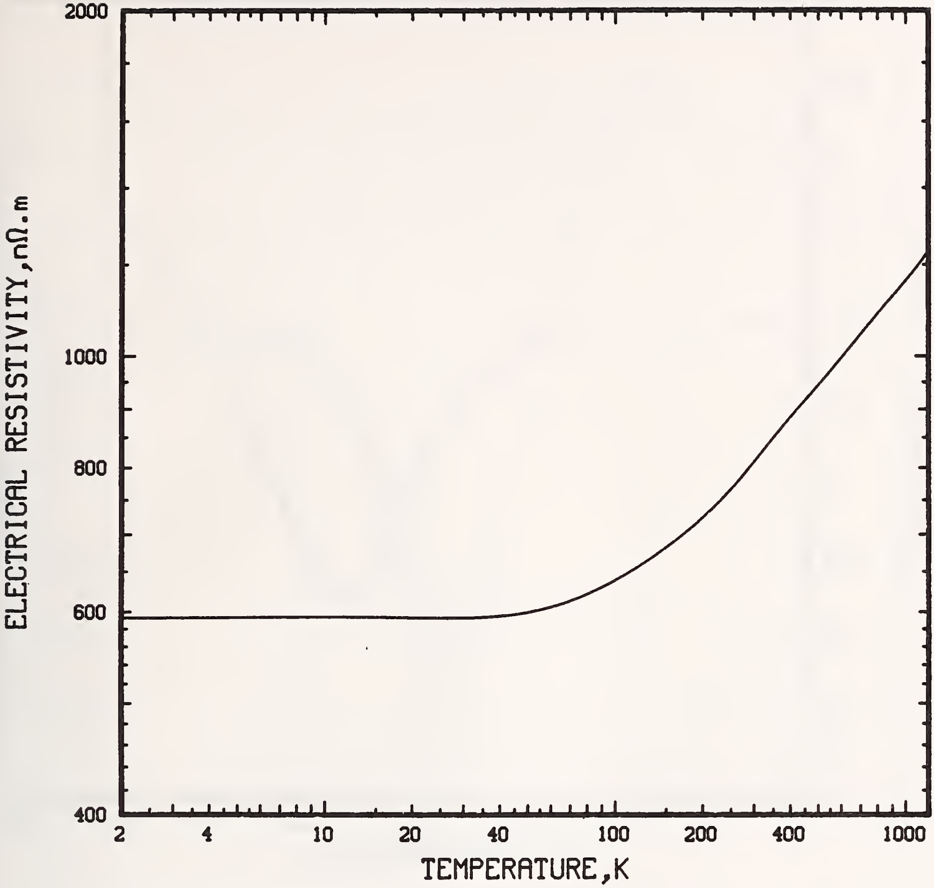

Figure 4.6 Electrical resistivity values for the stainless steel SRM calculated from eq.(3.5)

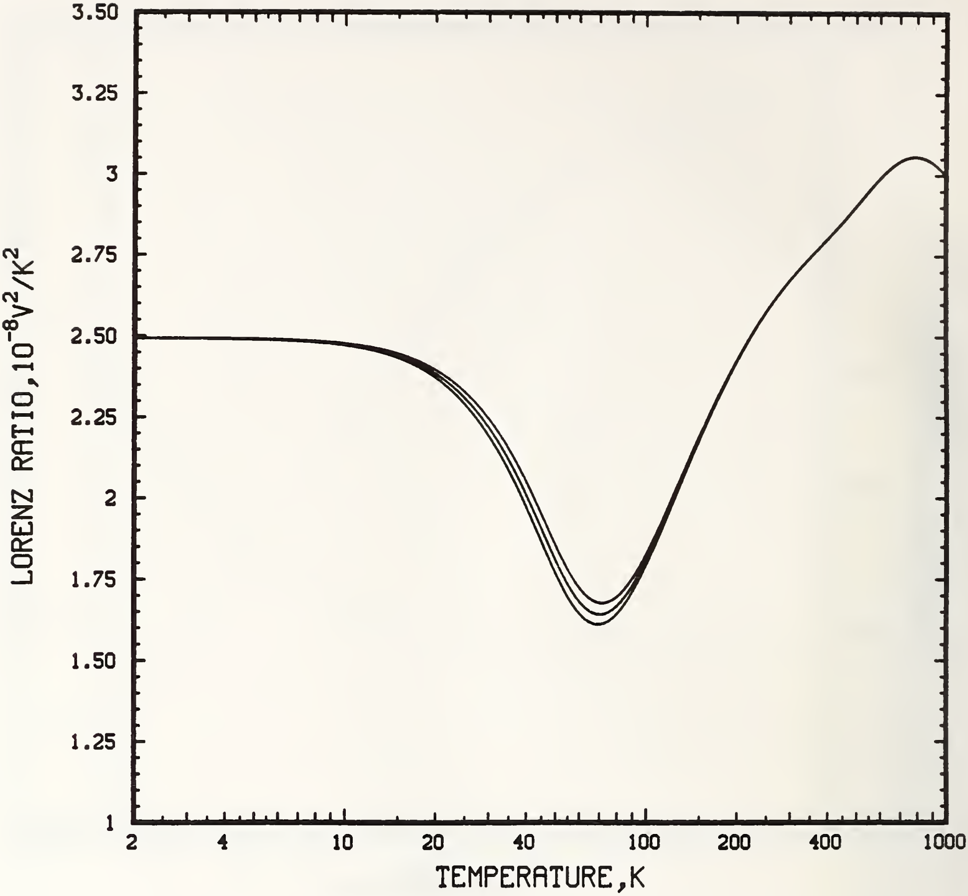

Figure 4.7 Lorenz ratio for the electrolytic iron RM as calculated from eqs. (3.1) and (3.5) at the same residual resistivities as in figs. 4.1 and 4.2

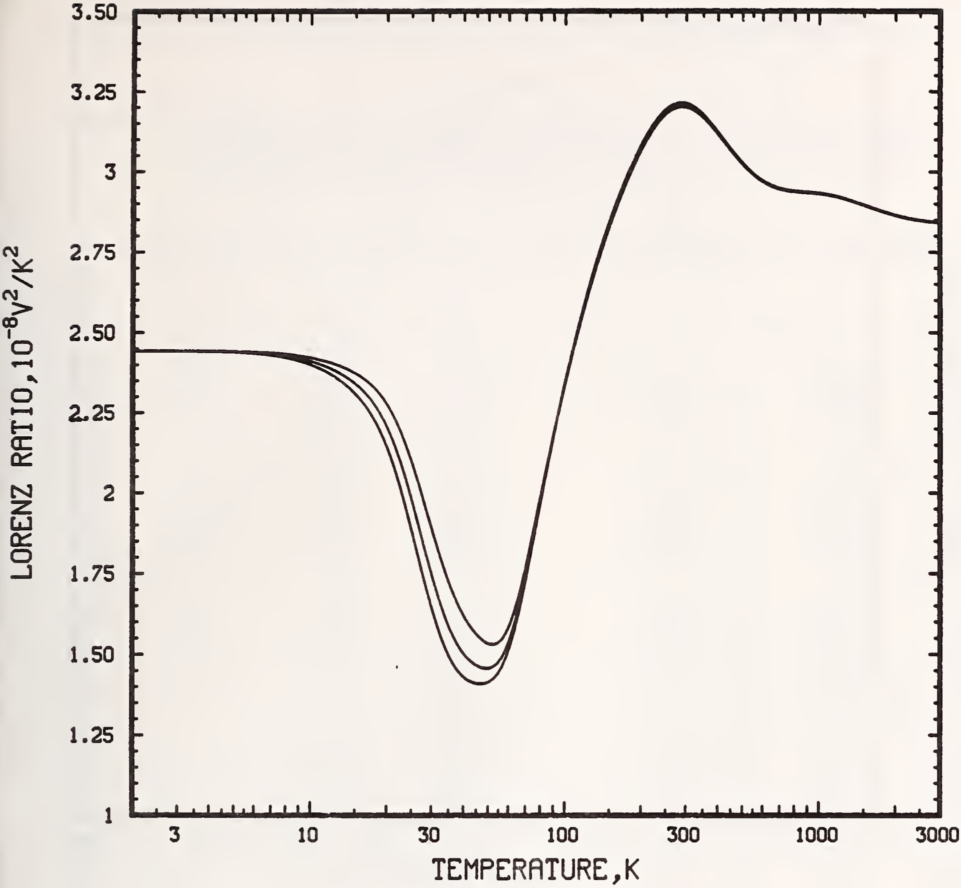

Figure 4.8 Lorenz ratio for the tungsten RM as calculated from eqs. (3.1) and (3.5) at the same residual resistivities as in figs. 4.3 and 4.4

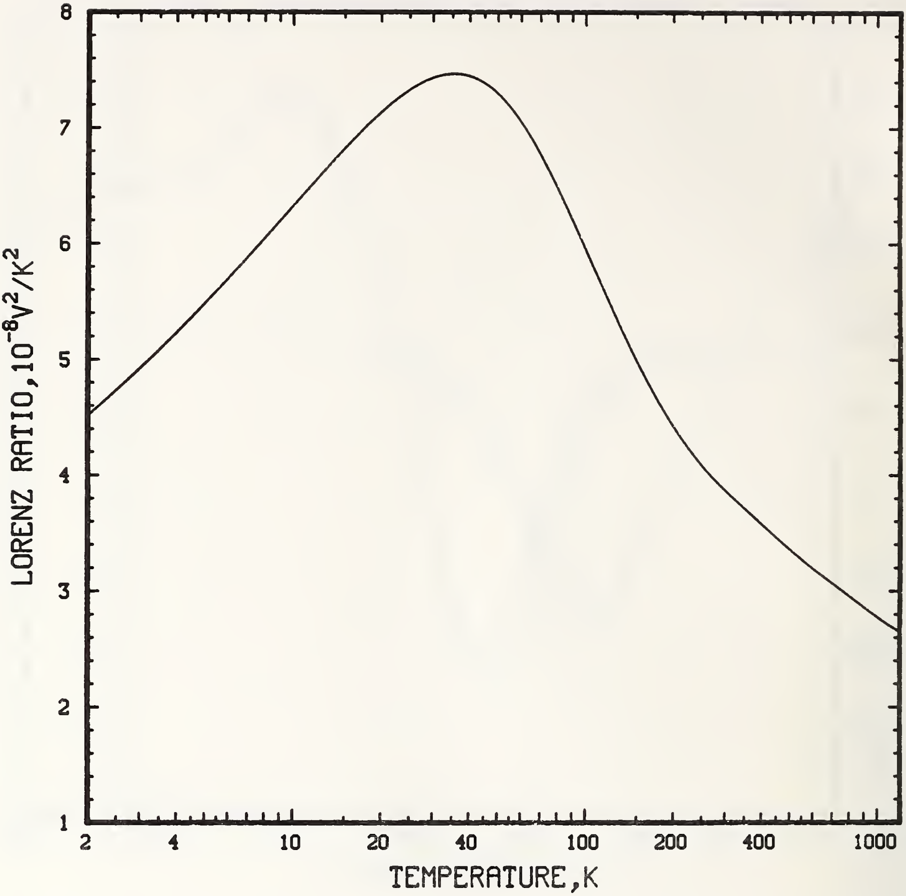

Figure 4.9 Lorenz ratio for the stainless steel SRM as calculated from eqs. (3.1) and (3.5)

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).

	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)			Electrical Resistivity (nΩ·m)		
T (K)	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.

	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)			Electrical Resistivity (nΩ·m)		
T (K)	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 ($W \cdot m^{-1} \cdot K^{-1}$)	Electrical Resistivity ($n\Omega \cdot m$)
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.

7. References

[1] Hust, J. G.; Sparks, L. L. Thermal conductivity of electrolytic iron, SRM-734, from 4 to 300 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-31; 1971.

[2] Hust, J. G.; Sparks, L. L. Standard reference materials: thermal conductivity of austenitic stainless steel, SRM-735, from 5 to 280 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-35; 1972.

[3] Hust, J. G. Electrical resistivity of electrolytic iron, SRM-797, and austenitic stainless steels, SRM-798, from 5 to 280 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-47; 1974.

[4] Hust, J. G.; Giarratano, P. J. Thermal conductivity and electrical resistivity standard reference materials: austenitic stainless steel, SRM's 735 and 798, from 4 to 1200 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-46; 1974.

[5] Hust, J. G.; Giarratano, P. J. Thermal conductivity and electrical resistivity standard reference materials: arc cast and sintered tungsten, SRM's 730 and 799, from 4 to 3000 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-52; 1975.

[6] Hust, J. G.; Giarratano, P. J. Thermal conductivity and electrical resistivity standard reference materials: electrolytic iron, SRM's 734 and 797, from 4 to 1000 K. Nat. Bur. Stand. (U.S.) Spec. Publ. 260-50; 1975.

[7] Hust, J. G. Thermal conductivity standard reference materials from 4 to 300 K. I. Armco Iron. Nat. Bur. Stand. (U.S.) NBS Report 9740; 1969.

[8] Hust, J. G.; Sparks, L. L. Thermal conductivity standard reference materials from 4 to 300 K. II. OSRM iron 1265. Nat. Bur. Stand. (U.S.) NBS Report 9771; 1970.

[9] Hust, J. G.; Sparks, L. L. Thermal conductivity standard reference materials from 4 to 300 K. III. AGARD stainless steel. Nat. Bur. Stand. (U.S.) NBS Report 9786; 1971.

[10] Hust, J. G.; Sparks, L. L. Thermal conductivity standard reference materials from 4 to 300 K. V. AGARD stainless steel. Nat. Bur. Stand. (U.S.) NBS Report 10710; 1971.

[11] Hust, J. G. Thermal conductivity standard reference materials from 6 to 280 K. VI. NBS sintered tungsten. Nat. Bur. Stand. (U.S.) NBSIR 73-351; 1974.

[12] Minges, M. L. The standard reference materials and data programs of the CODATA task group on thermophysical properties. Hust, J. G., ed. Proceedings of the 17th international thermal conductivity conference; Plenum Press, New York; 1983. 73 p.

[13] Berman, R.; Hardy, N. D.; Sahota, M.; Hust, J. G.; Tainsh, R. J. Standard reference materials for thermal conductivity below 100 K. Hust, J. G., ed. Proceedings of the 17th international thermal conductivity conference; Plenum Press, New York; 1983. 105 p.

[14] Brandt, R.; Neuer, G. Thermal diffusivity measurements on reference materials. Nat. Bur. Stand. (U.S.) NBS Report 9740; 1969.

[15] Maglic, K.; Perovic, N.; Zivotic, Z. Thermal diffusivity of candidate standard reference materials. Nat. Bur. Stand. (U.S.) NBS Report 9740; 1969. 163 p.

[16] Graves, R. S.; Williams, R. K.; Moore, J. P. The thermal conductivity, electrical resistivity, and Seebeck coefficient of SRM-735. Larsen, D. C., ed. Proceedings of the 16th international thermal conductivity conference; Plenum Press, New York; 1983. 343 p.

[17] Taylor, Roy. Thermal diffusivity of POCO graphite and stainless steel, SRM-735 S. Nat. Bur. Stand. (U.S.) NBS Report 9740; 1969. 753 p.

[18] Cezairliyan, A.; McClure, J. L. High-speed (subsecond) measurement of heat capacity, electrical resistivity, and thermal radiation properties of tungsten in the range 2000 to 3600 K. J. Res. Nat. Bur. Stand. (U.S.). 75A(4): 283-290; 1971.

[19] Binkele, L; Zur frage der hochtemperatur-Lorenzzahl bei wolfram — eine analyse neuer messwerte der thermischen und elektrischen leitfahigkeit im temperatur bereich 300 bis 1300 K. Submitted for publication in High Temperature-High Pressure; 1982.

[20] Bode, K. H. Results of thermal conductivity measurements on tungsten between 20 and 500 °C. To be submitted to Int. J. Heat and Mass Transfer; 1982. Data not available at this time.

[21] Binkele, L. Private communication on measurements of λ and ρ for stainless steel; 1982.

[22] Taylor, R. E. Thermal properties of tungsten SRM's 730 and 799. J. of Heat Transfer, Vol. 100, No. 2, 330-333; 1978.

[23] Graves, G. A. (UDRI) private communication; 1983.

[24] Callanan, J. E. (NBS) private communication; 1983.

[25] Atalla, S. R. Thermal properties of stainless steel and graphite specimens in the temperature range 400-1000 K. Proceedings of the eighth european thermophysical conference; Baden-Baden, Germany. Paper No. 004, Session No. 10; 1982.

[26] Fulkerson, W.; Moore, J. P.; McElroy, D. L. Comparison of the thermal conductivity, electrical resistivity, and Seebeck coefficient of a high-purity iron and an Armco iron to 1000 °C. J. Appl. Phys., Vol. 37, No. 7, 2639-2653; 1966.

[27] Fitzer, E., Thermophysical properties of solid materials. Project Section II. Cooperative measurements on heat transport phenomena of solid materials at high temperature, AGARD Report No. 606, 1973.

[28] Moore, J. P., Graves, R. S., Fulkerson, W., and McElroy, D. L., The thermal properties of tungsten, Proceedings of the fifth thermal conductivity conference, Univ. of Denver, Vol. 2, V-G-1 - V-G-35 (1965).

☆U.S. GOVERNMENT PRINTING OFFICE: 1984 420 997 10043

NBS-114A (REV. 2-80)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** *(See instructions)*	1. PUBLICATION OR REPORT NO. NBS/SP-260/90	2. Performing Organ. Report No.	3. Publication Date September 1984

4. TITLE AND SUBTITLE

Standard Reference Materials:
Update of Thermal Conductivity and Electrical Resistivity of Electrolytic Iron, Tungsten, and Stainless Steel

5. AUTHOR(S)

Jerome G. Hust and Alan B. Lankford

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
BOULDER, CO 80303

7. Contract/Grant No.

8. Type of Report & Period Covered

Final

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

Office of Standard Reference Materials
National Measurement Laboratory
National Bureau of Standards
Gaithersburg, MD 20899

10. SUPPLEMENTARY NOTES

Library of Congress Catalog Card Number: 84-601107

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

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

13. AVAILABILITY

☒ Unlimited
☐ For Official Distribution. Do Not Release to NTIS
☒ Order From Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402.
☐ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

14. NO. OF PRINTED PAGES

71

15. Price

NBS Technical Publications

Periodicals

Journal of Research—The Journal of Research of the National Bureau of Standards reports NBS research and development in those disciplines of the physical and engineering sciences in which the Bureau is active. These include physics, chemistry, engineering, mathematics, and computer sciences. Papers cover a broad range of subjects, with major emphasis on measurement methodology and the basic technology underlying standardization. Also included from time to time are survey articles on topics closely related to the Bureau's technical and scientific programs. As a special service to subscribers each issue contains complete citations to all recent Bureau publications in both NBS and non-NBS media. Issued six times a year.

Nonperiodicals

Monographs—Major contributions to the technical literature on various subjects related to the Bureau's scientific and technical activities.

Handbooks—Recommended codes of engineering and industrial practice (including safety codes) developed in cooperation with interested industries, professional organizations, and regulatory bodies.

Special Publications—Include proceedings of conferences sponsored by NBS, NBS annual reports, and other special publications appropriate to this grouping such as wall charts, pocket cards, and bibliographies.

Applied Mathematics Series—Mathematical tables, manuals, and studies of special interest to physicists, engineers, chemists, biologists, mathematicians, computer programmers, and others engaged in scientific and technical work.

National Standard Reference Data Series—Provides quantitative data on the physical and chemical properties of materials, compiled from the world's literature and critically evaluated. Developed under a worldwide program coordinated by NBS under the authority of the National Standard Data Act (Public Law 90-396).
NOTE: The Journal of Physical and Chemical Reference Data (JPCRD) is published quarterly for NBS by the American Chemical Society (ACS) and the American Institute of Physics (AIP). Subscriptions, reprints, and supplements are available from ACS, 1155 Sixteenth St., NW, Washington, DC 20056.

Building Science Series—Disseminates technical information developed at the Bureau on building materials, components, systems, and whole structures. The series presents research results, test methods, and performance criteria related to the structural and environmental functions and the durability and safety characteristics of building elements and systems.

Technical Notes—Studies or reports which are complete in themselves but restrictive in their treatment of a subject. Analogous to monographs but not so comprehensive in scope or definitive in treatment of the subject area. Often serve as a vehicle for final reports of work performed at NBS under the sponsorship of other government agencies.

Voluntary Product Standards—Developed under procedures published by the Department of Commerce in Part 10, Title 15, of the Code of Federal Regulations. The standards establish nationally recognized requirements for products, and provide all concerned interests with a basis for common understanding of the characteristics of the products. NBS administers this program as a supplement to the activities of the private sector standardizing organizations.

Consumer Information Series—Practical information, based on NBS research and experience, covering areas of interest to the consumer. Easily understandable language and illustrations provide useful background knowledge for shopping in today's technological marketplace.
Order the **above** *NBS publications from: Superintendent of Documents, Government Printing Office, Washington, DC 20402.*
Order the **following** *NBS publications—FIPS and NBSIR's—from the National Technical Information Service, Springfield, VA 22161.*

Federal Information Processing Standards Publications (FIPS PUB)—Publications in this series collectively constitute the Federal Information Processing Standards Register. The Register serves as the official source of information in the Federal Government regarding standards issued by NBS pursuant to the Federal Property and Administrative Services Act of 1949 as amended, Public Law 89-306 (79 Stat. 1127), and as implemented by Executive Order 11717 (38 FR 12315, dated May 11, 1973) and Part 6 of Title 15 CFR (Code of Federal Regulations).

NBS Interagency Reports (NBSIR)—A special series of interim or final reports on work performed by NBS for outside sponsors (both government and non-government). In general, initial distribution is handled by the sponsor; public distribution is by the National Technical Information Service, Springfield, VA 22161, in paper copy or microfiche form.

U.S. Department of Commerce
National Bureau of Standards
Gaithersburg, MD 20899