Journal of Physical and Chemical Reference Data

Volume 3, 1974
Supplement No. 1

Thermal Conductivity of the Elements: A Comprehensive Review

C. Y. Ho
R. W. Powell
P. E. Liley

Published by the **American Chemical Society** and the **American Institute of Physics** for the **National Bureau of Standards**

Journal of
Physical and Chemical Reference Data

David R. Lide, Jr., Editor

The ***Journal of Physical and Chemical Reference Data*** is published quarterly by the American Chemical Society and the American Institute of Physics for the National Bureau of Standards. The objective of the Journal is to provide critically evaluated physical and chemical property data, fully documented as to the original sources and the criteria used for evaluation. Critical reviews of measurement techniques, whose aim is to assess the accuracy of available data in a given technical area, are also included. One of the principal sources for the Journal is the National Standard Reference Data System (NSRDS), which is described more fully below. The Journal is not intended as a publication outlet for original experimental measurements such as are normally reported in the primary research literature, nor for review articles of a descriptive or primarily theoretical nature.

Supplements to the Journal are published at irregular intervals and are not included in subscriptions to the Journal. They contain compilations which are too lengthy for a journal format.

The Editor welcomes appropriate contributions from individuals or groups for consideration by the Editorial Board. Potential contributors are invited to submit an outline of the nature and scope of the proposed compilation, with criteria for evaluation of the data and other pertinent factors to:

David R. Lide, Jr., Editor
J. Phys. Chem. Ref. Data
National Bureau of Standards
Washington, D.C. 20234

The National Standard Reference Data System was established in 1963 as a means of coordinating on a national scale the production and dissemination of critically evaluated reference data in the physical sciences. Under the Standard Reference Data Act (Public Law 90-396) the National Bureau of Standards of the U.S. Department of Commerce has the primary responsibility in the Federal Government for providing reliable scientific and technical reference data. The Office of Standard Reference Data of NBS coordinates a complex of data evaluation centers, located in university, industrial, and other Government laboratories as well as within the National Bureau of Standards, which are engaged in the compilation and critical evaluation of numerical data on physical and chemical properties retrieved from the world scientific literature. The participants in this NBS-sponsored program, together with similar groups under private or other Government support which are pursuing the same ends, comprise the National Standard Reference Data System.

The primary focus of the NSRDS is on well-defined physical and chemical properties of well-characterized materials or systems. An effort is made to assess the accuracy of data reported in the primary research literature and to prepare compilations of critically evaluated data which will serve as reliable and convenient reference sources for the scientific and technical community.

Information for Contributors

All mathematical expressions and formulas, insofar as possible, should be typed, with unavailable Greek letters or symbols inserted neatly in ink. Distinguish between capitals and small letters. Avoid complicated superscripts and subscripts. Avoid repetition of a complicated expression by representing it by a symbol. Identify in the margin handwritten Greek letters and unusual symbols. Use fractional exponents instead of root signs, and use the solidus (/) for fractions whereever its use will save vertical space.

Literature references are to be numbered consecutively in brackets. They are to be placed at the end of the paper. A footnote appears after the first reference stating: Figures in brackets indicate literature references at the end of this paper. Literature citations of technical journals should be in the form indicated in the *Style Manual* of the American Institute of Physics (price $2.50 prepaid from American Institute of Physics, Dept. BN, 335 East 45 St., New York, N.Y. 10017).

Tables may be typewritten on sheets from the running text. Each table must have a caption that will make the data in the table intelligible without reference to the text. Avoid complicated column headings.

Figures should, whenever practicable, be planned for reproduction in one-column width (8.7 cm). Line drawings should be India ink on white paper or tracing cloth. The original drawing or a high-quality glossy print should be submitted. To facilitate mailing and handling, original drawings should not exceed 22 by 28 cm in size. Lettering, preferably drawn with a mechanical set, should be of a size so that when reduced the smallest lower-case letters will not be less than about 1.5mm. Avoid gross disparities in lettering size on a drawing. Consult the *Style Manual* of the American Institute of Physics for further discussion of figures. Type figure captions on a separate sheet of paper. Number figures consecutively. Identify each original drawing or photograph with the figure number and authors names, written where they will not be reproduced.

Subscriptions, renewals, address changes, single-copy and reprint orders, and orders for supplements should be addressed to: Subscription Service Department, American Chemical Society, 1155 Sixteenth Street, NW, Washington, D.C. 20056. Members of AIP member and affiliated societies requesting Member subscription rates should renew subscriptions and direct orders to American Institute of Physics, Dept. S/F, 335 East 45 Street, New York, N.Y. 10017. Allow at least six weeks advance notice. For address changes please send both old and new addresses, and, if possible, include an address-stencil imprint from the mailing wrapper of a recent issue. Prices for reprints and supplements are listed on the last page.

Subscription Prices *(not incl. supplements)*	*U.S.A., Canada, and Mexico*	*Elsewhere*
Members (affiliated and member societies)	$20	$23
All others	$60	$63

The *Journal of Physical and Chemical Reference Data* appears in Sect. 1 of *Current Physics Microform* (CPM) along with 18 other primary journals published by the American Institute of Physics. CPM Sect. 1 is available on an annual subscription for $1600.

Journal of
Physical and Chemical Reference Data

Volume 3, 1974
Supplement No. 1

Thermal Conductivity of the Elements: A Comprehensive Review

C. Y. Ho
R. W. Powell
P. E. Liley

Thermophysical Properties Research Center
Purdue University
West Lafayette, Indiana 47906

Published by the **American Chemical Society** and the **American Institute of Physics** for the **National Bureau of Standards**

Library of Congress Catalog Card Number 75-4440

International Standard Book Numbers
0-88318-216-5 (Paper cover)

American Institute of Physics, Inc.
335 East 45 Street
New York, New York 10017

Printed in the United States of America

Foreword

The *Journal of Physical and Chemical Reference Data* is published jointly by the American Institute of Physics and the American Chemical Society for the National Bureau of Standards. Its objective is to provide critically evaluated physical and chemical property data, fully documented as to the original sources and the criteria used for evaluation. One of the principal sources of material for the journal is the National Standard Reference Data System (NSRDS), a program coordinated by NBS for the purpose of promoting the compilation and critical evaluation of property data.

The regular issues of the *Journal of Physical and Chemical Reference Data* are published quarterly and contain compilations and critical data reviews of moderate length. Longer monographs, volumes of collected tables, and other material unsuited to a periodical format are published separately as *Supplements* to the *Journal*. This monograph, "Thermal Conductivity of the Elements: A Comprehensive Review," by C. Y. Ho, R. W. Powell, and P. E. Liley, is presented as Supplement No. 1 to Volume 3 of the *Journal of Physical and Chemical Reference Data.*

David R. Lide, Jr., Editor
Journal of Physical and Chemical Reference Data

Thermal conductivity of the elements: a comprehensive review

C. Y. Ho, R. W. Powell, and P. E. Liley

Thermophysical Properties Research Center,
Purdue University, West Lafayette, Indiana 47906

This work presents and discusses the available data and information on the thermal conductivity of the elements and contains the recommended reference values resulting from critical evaluation, analysis and synthesis of the available data and information. It also gives estimated values, at least for normal temperature, for all those elements for which no thermal conductivity information is available. Experimental thermal conductivity data are available in the world literature for 82 elements and estimated values for four other elements. Estimated values for the remaining 19 elements are given here, although only rough estimates are given for the trans-plutonium elements. Thus, this work provides recommended or estimated thermal conductivity values for all the 105 elements. This work is published in two companion versions: this comprehensive volume and an abridged version. In addition to the recommended and estimated thermal conductivity values for elements, the comprehensive volume presents the original data, specimen characterization, and measurement information for the 5200 sets of raw data compiled; contains a detailed discussion for every element reviewing the individual pieces of available data and information together with the considerations involved in arriving at the final assessment and recommendations, and with the theoretical guidelines or semi-empirical correlations on which the critical evaluation, analysis, and synthesis are based; and includes also the complete bibliographic citations for the 1658 references. The abridged version contains only the recommended and estimated thermal conductivity values.

Key words: Conductivity; critical evaluation; data analysis; data compilation; data synthesis; elements; gases; liquid metals; liquids; metallic elements; metals; molten metals; most probable values; nonmetallic elements; recommended reference values; reference data; solids; standard reference data; thermal conductivity.

Preface

Thermal Conductivity of the Elements: A Comprehensive Review is the result of many years of effort by the Thermophysical Properties Reseach Center (TPRC) as part of an overall program to generate tables of numerical data for science and technology. The property, thermal conductivity, was selected as a priority task because of its scientific and technical importance and because of TPRC's extensive bibliographic coverage of the literature on this property.

This volume can serve many purposes. It provides engineering and design data for those elements such as tungsten, molybdenum, carbon (graphite), aluminum, copper, germanium, silicon, liquid sodium, mercury, etc. which are used in nearly pure form as engineering materials. It provides reliable data for those elements that can be used as reference materials to check apparatus for thermal conductivity measurements or as standards in comparative thermal conductivity measurements. It provides data against which theoreticians can test their theories. Furthermore, the knowledge of the thermal conductivity of the elements is essential for the estimation and prediction of this property for the more complex engineering alloys. Since precise measurement of thermal conductivity is very difficult, a capability for the estimation and prediction of this property within confidence levels acceptable to technological requirements would be very valuable. A knowledge of the thermal conductivity of the elements is an essential requirement for the development of such a capability.

Thermal Conductivity of the Elements: A Comprehensive Review has been published in two companion versions. This *comprehensive* volume makes it possible for serious students of the subject to have access to the original data without having to duplicate the laborious and costly process of literature search and data extraction. It is quite appropriate at this point to mention that only original sources have been used for the critique of the data and that all cited documents are available at TPRC in standard microfiche format. Also, for the active researchers in the field, a detailed discussion is presented for each element reviewing the available experimental data and the considerations by which the authors arrived at their final assessment and recommended values.

Since the comprehensive version is voluminous and perhaps somewhat cumbersome for frequent use as a reference, an *abridged* version has been published (Journal of Physical and Chemical Reference Data, **1,** 279, 1972) which gives the recommended values with minimal discussion. Reprints of the abridged version should provide inexpensive, personal, desk-top reference sources for designers, engineers, students and scientists who have a need for ready access to these data.

The input of data to *Thermal Conductivity of the Elements: A Comprehensive Review* has a cut-off date of January 1971; works published subsequent to this date have not been considered. However, TPRC monitors and retrieves the world literature on a continuing basis and our state of knowledge on the thermal conductivity of the elements is being kept on a current basis, and the recommendations are being constantly evaluated and revised if and when deemed necessary.

While this volume is primarily intended as a reference work for the designer, researcher, experimentalist, and theoretician, the teacher at the graduate level may also use it as a teaching tool to point out to his students the topography of the state of knowledge on the thermal conductivity of the elements. We believe the contents of the volume also provide ample ground for reflection by the specialist and the academician regarding the meaning of *original* data and their *information content.*

The authors are keenly aware of the possibility of omissions or errors which may be encountered in a work of this scope. We hope that these faults will not be judged too harshly and that we will receive the benefit of suggestions regarding references omitted, improvements in presentation, and, most important, any inadvertent errors.

This volume is primarily the result of financial support and interest of the Office of Standard Reference Data of the National Bureau of Standards. The support of the extensive documentary work necessary for the preparation of this volume was made possible through the support received from the Air Force Materials Laboratory of the Air Force Systems Command.

While the preparation and continued maintenance of this work is the responsibility of TPRC's Data Tables Division, this work would not have been possible without the direct input of TPRC's Scientific Documentation Division and, to a lesser degree, the Theoretical and Experimental Research Divisions. It should be clearly understood, however, that many have contributed over the years within and outside of TPRC, and their contributions are hereby acknowledged.

In order to give a greater degree of confidence to the recommendations set forth in this work, preliminary sections of this volume have been submitted to some 70 international expert workers in this field for their comments and critique. The authors wish to express their appreciation and gratitude to all who responded. Particular acknowledgement is made for the valuable contributions made by the following individuals:

Dr. A. R. Adams, University of Surrey, London, England.
Dr. N. Bäcklund, The Royal Institute of Technology, Stockholm, Sweden.
Dr. R. Berman, University of Oxord, Oxford, England.
Prof. C. F. Bonilla, Columbia University, New York, New York.
Dr. R. I. Boughton, The Ohio State University, Columbus, Ohio.
Dr. A. Cezairliyan, National Bureau of Standards, Washington, D.C.
Dr. L. J. Challis, University of Nottingham, Nottingham, England.
Dr. J. G. Cook, National Research Council, Ottawa, Canada.
Dr. M. J. Duggin, CSIRO, National Standards Laboratory, Chippendale, N.S.W., Australia.
Prof. L. P. Filippov, Moscow State University, Moscow, U.S.S.R.
Mr. D. R. Flynn, National Bureau of Standards, Washington, D.C.
Prof. A. V. Grosse, Research Institute of Temple University, Philadelphia, Pennsylvania.
Dr. H. J. Hanley, National Bureau of Standards, Boulder, Colorado.
Dr. M. G. Holland, Raytheon Company, Waltham, Massachusetts.
Prof. J. J. Jackson, Howard University, Washington, D.C.
Dr. D. T. Jamieson, National Engineering Laboratory, Glasgow, Scotland.
Dr. J. Kaspar, Aerospace Corporation, El Segundo, California.
Dr. B. T. Kelly, United Kingdom Atomic Energy Authority, Reactor Materials Laboratory, Warrington, Lancs, England.
Prof. J. Kestin, Brown University, Providence, Rhode Island.
Prof. P. G. Klemens, The University of Connecticut, Storrs, Connecticut.
Dr. M. J. Laubitz, National Research Council of Canada, Ottawa, Canada.
Prof. S Legvold, Iowa State University, Ames, Iowa.
Dr. W. W. Lozier, Union Carbide Corporation, Cleveland, Ohio.
Prof. A. V. Luikov, Heat and Mass Transfer Institute, Minsk, U.S.S.R.
Mr. I. B. Mason, Atomic Energy Research Establishment, Harwell, England.
Mr. J. D. McClelland, Aerospace Corporation, El Segundo, California.
Dr. D. L. McElroy, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
Dr. E. McLaughlin, Imperial College, London, England (now at Louisiana State University, Baton Rouge, Louisiana).
Prof. G. T. Meaden, Dalhousie University, Halifax, Nova Scotia, Canada.
Prof. A. Missenard, Société Française des Thermiciens, Paris, France.
Mr. J. P. Moore, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
Dr. Ya. M. Naziev, Esman Baku Institute of Power Engineering, Baku, Azerbaidzhan, U.S.S.R.
Dr. H. Poltz, Physikalisch-Technische Bundesanstalt, Braunschweig, West Germany.
Dr. R. L. Powell, National Bureau of Standards, Boulder, Colorado.

Dr. F. Richter, Thyssen Röhrenwerke Aktiengesellschaft, Düsseldorf, West Germany.
Prof. B. H. Sage, California Institute of Technology, Pasadena, California.
Prof. G. Samsonov, Institute of Problems of Material Science, Kiev, U.S.S.R.
Dr. N. H. Saunders, University College of Swansea, Swansea, Wales.
Dr. J. T. Schriempf, Naval Research Laboratory, Washington, D.C.
Prof. A. E. Sheindlin, Director of Scientific Research, Institute of High Temperature, Moscow, U.S.S.R.
Prof. E. E. Shpil'rain, Institute of High Temperature, Moscow, U.S.S.R.
Dr. G. A. Slack, General Electric Research Laboratory, Schenectady, New York.
Dr. I. A. Smirnov, Institute of Semiconductors, Leningrad, U.S.S.R.
Prof. N. B. Vargaftik, Moskovskii Aviatsionnyi Institut, Moscow, U.S.S.R.
Dr. P. Wagner, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.
Dr. G. K. White, CSIRO, National Standards Laboratory, Chippendale, N.S.W., Australia.
Prof. S. B. Woods, University of Alberta, Edmonton, Alberta, Canada.
Prof. M. Yaqub, The Ohio State University, Columbus, Ohio.

It goes without saying that while the individuals mentioned above have read selected parts of the preliminary version of this work and have given helpful comments and criticisms, this in no way commits them to the views and judgments expressed in this volume for which the authors assume complete responsibility. In this connection, Drs. C. Y. Ho and R. W. Powell have jointly performed the analysis of the data for the elements which are solid at normal temperature and pressure (N.T.P.) and Dr. P. E. Liley has performed the analysis for those elements which are in the liquid or gaseous state at N.T.P.

Y. S. Touloukian
Director, Thermophysical Properties Research Center
Distinguished Atkins Professor of Engineering

Purdue University
West Lafayette, Indiana
June 1972

Contents

Periodic Table Showing Thermal Conductivities of the Elements at 300 K and at the Debye Temperature

1. Atomic number
2. Symbol
3. Thermal conductivity at 300 K (W cm^{-1} K^{-1})
4. Thermal conductivity at the Debye temperature (W cm^{-1} K^{-1})
5. Debye temperature at 298 K

1. Atomic number	2. Symbol	3. Thermal conductivity at 300 K	4. Thermal conductivity at the Debye temperature	5. Debye temperature
1	H	0.001815 (G)	0.000707 (G)	(105K) ‡
2	He	0.00152 (G)	0.000333 (G)	(30K) ‡
3	Li	0.847	0.775	(448K)
4	Be	2.00	0.887	(1031K)
5	B	0.270		(1362K)
6	C	1.29	0.464	(1550K)
7	N	0.0002598 (G)		(70K) ‡
8	O	0.0002674 (G)	0.000412 (G)	(500K) ‡
9	F	0.000279 (G)		
10	Ne	0.000493 (G)	0.000148 (G)	(60K) ‡
11	Na	1.41	1.40	(155K)
12	Mg	1.56	1.55	(330K)
13	Al	2.37	2.40	(390K)
14	Si	1.48	0.516	(692K)
15	P	0.121 (B) 0.00235 (W)	0.00160 (W)	(576K) (W)
16	S	0.00269	0.00163 (L)	(527K)
17	Cl	0.000089 (G)		(115K) ‡
18	Ar	0.0001772 (G)	0.0000587 (G)	(90K) ‡
19	K	1.024	1.07	(100K)
20	Ca	2.00*	2.14*	(230K)
21	Sc	0.158		(476K)
22	Ti	0.219	0.206	(380K)
23	V	0.307	0.312	(390K)
24	Cr	0.937	0.898	(424K)
25	Mn	0.0782		(363K)
26	Fe	0.802	0.720	(373K)
27	Co	1.00	0.873	(386K)
28	Ni	0.907	0.856	(345K)
29	Cu	4.01	4.00	(310K)
30	Zn	1.16	1.18	(237K)
31	Ga	0.406	0.415	(240K)
32	Ge	0.599	0.429	(403K)
33	As	0.500	0.536	(275K)
34	Se	0.0204	0.0343	(150K) ‡
35	Br	0.00122 (L)		
36	Kr	0.0000949 (G)		(60K) ‡
37	Rb	0.582	0.621	(59K)
38	Sr	0.353*	0.446*	(148K)
39	Y	0.172	0.167	(214K)
40	Zr	0.227	0.237	(250K)
41	Nb	0.537	0.531	(260K)
42	Mo	1.38	1.35	(377K)
43	Tc	0.506	0.499	(422K)
44	Ru	1.17	1.14	(415K)
45	Rh	1.50	1.48	(350K)
46	Pd	0.718	0.716	(275K)
47	Ag	4.29	4.29	(221K)
48	Cd	0.968	0.983	(221K)
49	In	0.816	0.954	(129K)
50	Sn	0.666	0.694	(254K)
51	Sb	0.243	0.302	(200K)
52	Te	0.0235	0.0428	(141K) ‡
53	I	0.00449		(105K) ‡
54	Xe	0.0000569 (G)	0.00971	(76.1K) ‡
55	Cs	0.359	0.462	(43K)
56	Ba	0.184*		(116K)
57	La	0.135	0.106	(135K)
72	Hf	0.230	0.242	(213K)
73	Ta	0.575	0.574	(225K)
74	W	1.74	1.72	(312K)
75	Re	0.479	0.486	(275K)
76	Os	0.876	0.869	(400K)
77	Ir	1.47	1.51	(228K)
78	Pt	0.716	0.721	(225K)
79	Au	3.17	3.24	(178K)
80	Hg	0.0834(L)	0.323	(92K)
81	Tl	0.461	0.560	(96K)
82	Pb	0.353	0.405	(87K)
83	Bi	0.0787	0.146	(116K)
84	Po	0.20*		
85	At	0.017*		
86	Rn	0.0000364 (G)*	0.0000480 (G)*	(400K) ‡
87	Fr	0.15*		
88	Ra	0.186*		(87K) ‡
89	Ac	0.12*		(100K) ‡
104		0.23*		
105		0.58*		
106		1.9*		
118		0.000023 (G)*		
58	Ce	0.114	0.0727	(138K)
59	Pr	0.125	0.0889	(138K)
60	Nd	0.165		(148K)
61	Pm	0.179*		
62	Sm	0.133	0.106	(184K)
63	Eu	0.139*	0.180*	(127K) ‡
64	Gd	0.106	0.128	(155K)
65	Tb	0.111	0.117	(158K)
66	Dy	0.107	0.0898	(158K)
67	Ho	0.162	0.137	(161K)
68	Er	0.143	0.140	(163K)
69	Tm	0.168	0.156	(167K)
70	Yb	0.349	0.459	(118K) ‡
71	Lu	0.164	0.188	(116K)
90	Th	0.540	0.598	(100K)
91	Pa	0.47*		(262K)
92	U	0.276	0.276	(300K)
93	Np	0.063		(163K)
94	Pu	0.0674	0.0437	(176K)
95	Am	0.1*		
96	Cm	0.1*		
97	Bk	0.1*		
98	Cf	0.1*		
99	Es	0.1*		
100	Fm	0.1*		
101	Md	0.1*		
102	No	0.1*		
103	Lw	0.1*		

Note: The thermal conductivity values for those elements of non-cubic crystal structure are for polycrystalline samples. Those suffixed with (L) or (G) are for liquid or gaseous state, respectively. The asterisked values are estimated for the elements for which no experimental data are available. The values given for carbon are for ATJ graphite in the direction perpendicular to the molding pressure. For diamond at 300 K the values range from 8.95 W cm^{-1} K^{-1} for Type I to 23.0 W cm^{-1} K^{-1} for Type IIa. The Debye temperature of diamond is 1874 K but no experimental data above 320 K are available. The values for phosphorus suffixed with (B) or (W) are for black or white phosphorus, respectively. The values of the Debye temperature are for 298 K except for those marked with ‡ which are for a temperature below 298 K.

1. Introduction

The purpose of this work is to present and review the available data and information on the thermal conductivity of each element of the periodic table, to critically evaluate, analyze, and synthesize the data, and to make recommendations for the most probable values of its thermal conductivity.

The recommended (or provisional) thermal conductivity values generated cover the widest possible temperature ranges and are for the purest form of each element for which measurements have been made. In the one instance of iron, values for Armco iron, a form of lower purity much used as a thermal conductivity reference material, have also been included.

Experimental thermal conductivity data are available in the world literature for 82 of the 105 elements known to exist and estimated values for four other elements. The 23 elements for which experimental data are lacking comprise all elements having an atomic number above 94 and twelve others: namely, actinium, astatine, barium, calcium, europium, francium, polonium, promethium, protactinium, radium, radon, and strontium. For these 23 elements estimated values have been given in this work at least for normal temperature. Thus, this work provides recommended (or provisional) thermal conductivity values for all 105 elements.

This work is organized in three distinct sections: namely, an introductory text, the body of information and data, and the source references. The introductory text describes the general procedures and methods for the evaluation, correlation, and synthesis of the available thermal conductivity data and for the generation of recommended or provisional thermal conductivity values. It also discusses the presentation of data and other considerations concerning the body of data. This is followed by the body of information and data, treating each element separately, reviewing the individual pieces of available data and information, and describing the considerations involved in arriving at the final assessment and recommendation and the theoretical guidelines or semi-empirical correlations on which the data analysis and synthesis are based. Figures and tables following the discussions present the recommended (or provisional) values, in addition to the original data, specimen characterization, and measurement information for the 5200 sets of raw data extracted from the primary literature. The last section consists of the 1658 references used in the extraction of data and/or information. Only original sources have been used for this purpose and the effective cut-off date for literature inclusion in this work was January 1971.

Inherent in the character of this work is the fact that we have drawn most heavily upon the scientific literature and feel a debt of gratitude to the authors whose results have been used. While their often discordant results have caused us much difficulty in reconciling their findings, we consider this to be our challenge and our contribution to the negative entropy of information as an effort is made to create from the randomly distributed data a condensed, more orderly state.

An abridged version of this work, which contains only the recommended (or provisional) thermal conductivity values, has been published in the Journal of Physical and Chemical Reference Data [608a]. It should be noted that, while the thermal conductivity values presented here for most of the elements are identical with those published in the Journal [608a], minor improvements in data smoothing have been made for several elements, which result in some small differences in a few values for several of the elements between the present values and those in the Journal. Therefore, wherever there is a difference, the value given here is preferred.

2. General Procedures and Methods for the Evaluation, Correlation, and Synthesis of Thermal Conductivity Data

In this section it is proposed to outline the general procedures and some of the methods for the evaluation, correlation, and synthesis of the available thermal conductivity data and for the generation of recommended (or provisional) values and to group together the resulting thermal conductivity values with a view to revealing any general trends which might be of assistance in the prediction of values or in data extrapolation.

2.1. Theoretical Background

In metals the principal carriers of heat are electrons and lattice waves, and it is commonly assumed that the total thermal conductivity

$$k = k_e + k_g, \tag{1}$$

where k_e and k_g are the thermal conductivity components due to the transport of heat respectively by the electrons and by the phonons or lattice waves. In a very pure metal, k_g is extremely small compared with k_e and in the majority of cases it can practically be neglected.

The electronic component is given by

$$k_e = W_e^{-1} = (W_o + W_i)^{-1}, \tag{2}$$

where W_e is the electronic thermal resistivity, W_o is the residual electronic thermal resistivity due to scattering of electrons by static imperfections and W_i the intrinsic electronic thermal resistivity due to electron-phonon interactions.

The electrical resistivity is likewise composed of a residual and an intrinsic component (Matthiessen's Rule)

$$\rho = \rho_o + \rho_i,$$

where ρ_o is temperature independent but depends on the type and concentration of imperfections, whereas ρ_i is temperature dependent but is independent of the imperfections. The residual thermal and electrical resistivities are related by the Wiedemann-Franz-Lorenz law

$$\frac{\rho_0}{W_0 T} = L_0,$$

hence

$$W_0 = (\rho_0/L_0)\, T^{-1} = \frac{\beta}{T}, \tag{3}$$

where $\beta = \rho_0/L_0$, L_0 is the theoretical Lorenz number ($L_0 = 2.443 \times 10^{-8}\ V^2\ K^{-2}$) and T is the absolute temperature. The intrinsic thermal and electrical resistivities are related by the Wiedemann-Franz-Lorenz law only in the high-temperature limit, while at lower temperatures

$$\frac{\rho_i}{W_i T} = L_i$$

is generally less than L_0. In the limit of low temperatures

$$L_i = \delta\, (T/\theta)^2,$$

where θ is the Debye temperature and the coefficient δ depends on the topology of the Fermi surface.

The derivation of theoretical expressions for W_i and ρ_i involves the solution of the Bloch integral equation [169a] which is very complicated. Explicit expressions have been obtained only for the very simplest model, first by Wilson [1568] and later by several others [875, 789a, 773a, 773b, 1448a, 1342a, 1342b, 1342c, 1612a, 770a]. The general form of their results is the same. In the low-temperature limit

$$\rho_i \propto T^5$$
$$W_i \propto T^2, \tag{4}$$

and

$$L_i = \rho_i/W_i T = 7.8\, N_a^{-2/3}\, (T/\theta)^2,$$

where N_a is the number of conduction electrons per atom. From equations (2–4), the low-temperature electronic thermal resistivity can therefore be written in the form

$$W_e = aT^2 + \beta/T.$$

Thus, at low temperatures

$$k_e = \frac{1}{aT^2 + \beta/T}. \tag{5}$$

Equation (5) has been extensively compared with low-temperature experimental data for high-purity metals whose k_g is negligibly small, and disagreements have been found [248–250] in that the power of T for most metals is not 2 but greater and the coefficient a is not a constant for a metal. Considering the temperature dependence of the coefficient a and the interaction between intrinsic and residual thermal resistivities, Cezairliyan [248], and Cezairliyan and Touloukian [249, 250] have modified equation (5) to become

$$k_e = \frac{1}{a'T^n + \beta/T}, \tag{6}$$

or, assuming k_g being negligible, simply

$$k = \frac{1}{a'T^n + \beta/T}, \tag{7}$$

where

$$a' = a''\left(\frac{\beta}{na''}\right)^{(m-n)/(m+1)}, \tag{8}$$

and a'', m, and n are constants for a metal. The value of n lies between 2 and 3 for most metals.

Figure 1 shows a family of thermal conductivity curves at low temperatures according to the theoretical equation (7) for samples of a typical metallic element. The curves with different values of β and ρ_0 are for different samples with different amounts of impurities and imperfections. Each thermal conductivity curve has a maximum value k_m at a corresponding temperature T_m. The purer the sample (the smaller the β and ρ_0), the higher is the maximum conductivity and the lower is the temperature T_m at which the maximum occurs. The locus of the thermal conductivity maxima is also shown in figure 1 which is a straight line in a logarithmic plot. Physically, the constant m in equation (8) is the absolute value of the slope of this straight line.

Figure 2, reproduced from Cezairliyan's treatise, shows how, by plotting a reduced thermal conductivity k/k_m (denoted by k^*) against the corresponding reduced temperature T/T_m (denoted by T^*), the data then (1962) available for 22 metals (some 1000 data points for 83 samples) were found to approximate a single curve

$$k^* = \left[\frac{1}{3}(T^*)^2 + \frac{2}{3T^*}\right]^{-1}, \tag{9}$$

which may be derived from equation (7) for the limiting case $n = 2$. The standard deviation of points from this curve was calculated as 0.032.

In this work for most of the metallic elements whose k_g is negligibly small, equations (7) and (8) have been used to fit experimental data for deriving recommended thermal conductivity values at temperatures below about 1.5 T_m. For a number of metallic elements the values of the constants m, n, and a'' to be used in equations (7) and (8) for low-temperature thermal conductivity calculations are given in table 1.

In equations (7) and (8), the only parameter is β (since a'', m, n are constants for a metal), and each low-temperature thermal conductivity curve is uniquely determined by its value. An experimental value of β is obtainable by fitting equations (7) and (8) to the measured thermal conductivity data at temperatures below T_m. Using equations (7) and (8) and the constants for each of the metallic elements given in table 1, the low-temperature thermal conductivity of a particular sample can be calculated when the appropriate value of β is used. Different values of β give a family of thermal conductivity curves for each metallic element and a family of recommended curves could have been generated in this way for each metallic element as shown in figure 1.

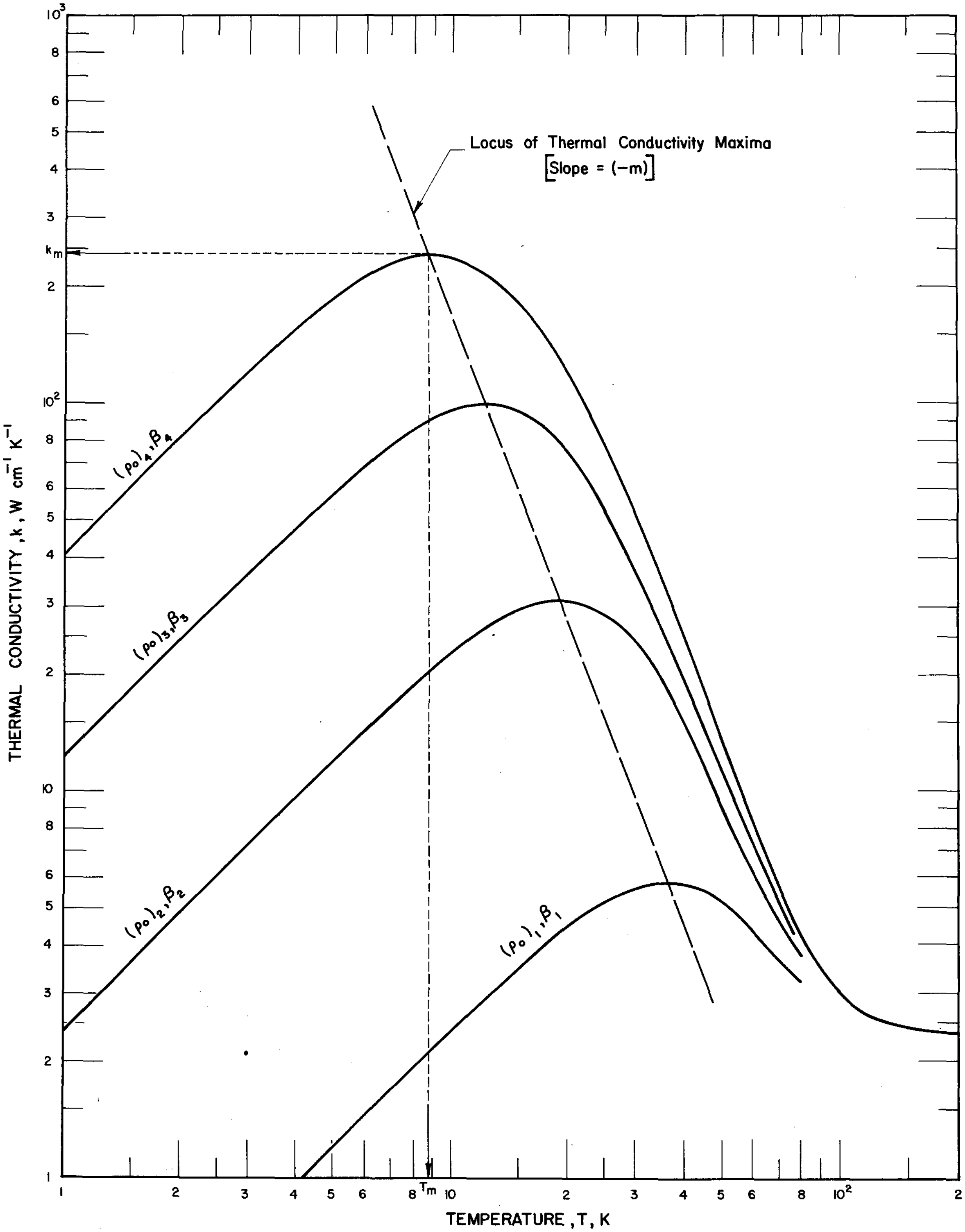


FIGURE 1. LOW-TEMPERATURE THERMAL CONDUCTIVITY OF DIFFERENT SAMPLES OF A METALLIC ELEMENT WITH DIFFERENT IMPURITY AND IMPERFECTION CONTENT

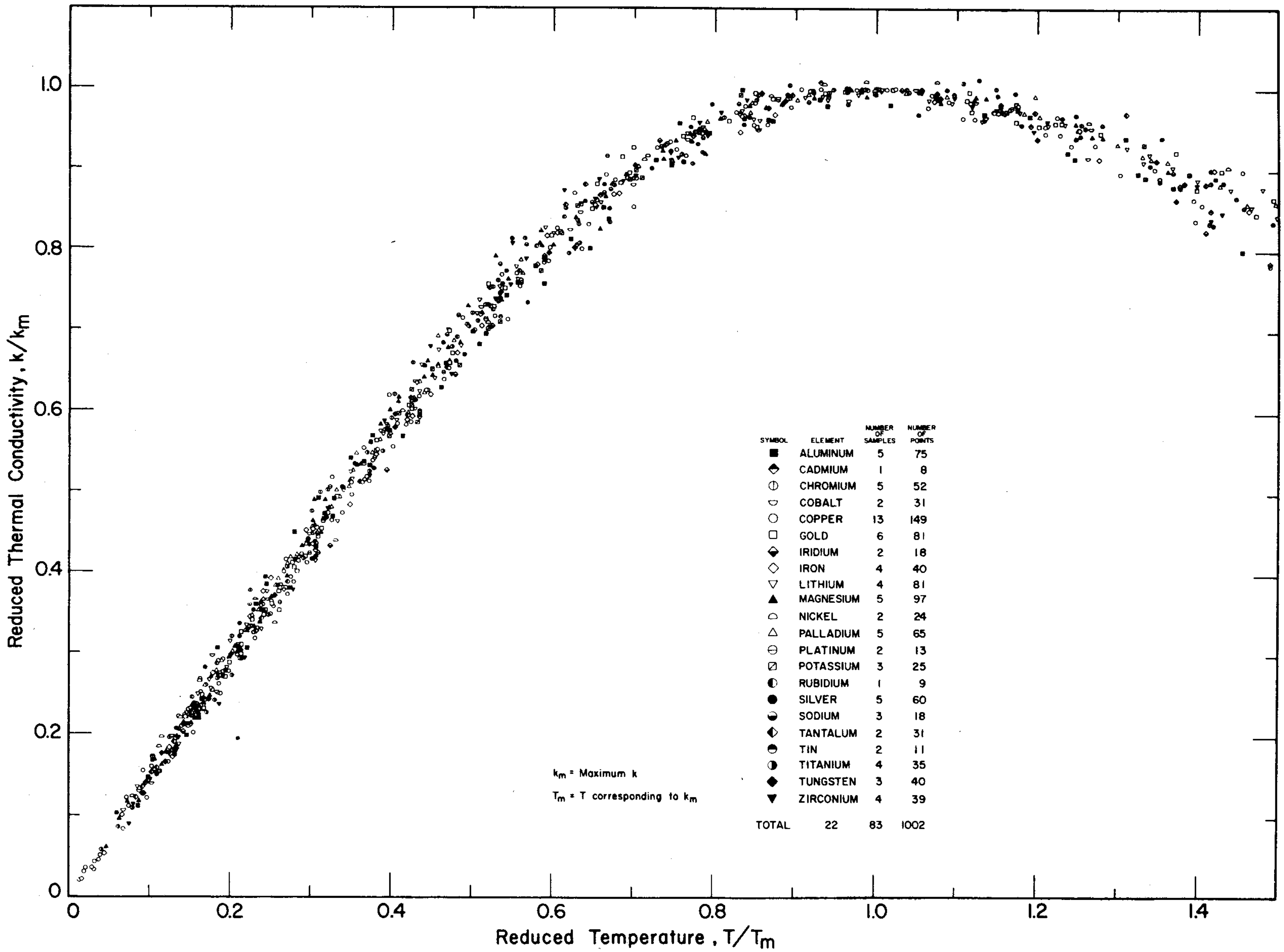


FIGURE 2. REDUCED THERMAL CONDUCTIVITY AS A FUNCTION OF REDUCED TEMPERATURE FOR TWENTY-TWO METALS AT CRYOGENIC TEMPERATURES

In this work, at low temperatures only one recommended curve for one particular sample has been generated and this usually relates to the lowest value of β for the purest sample for which a thermal conductivity measurement has been made. For generating other curves for other samples equations (7) and (8) and the recommended constants of table 1 may be used. It often happens that electrical resistivity investigations have included purer samples yielding much lower values for β, but to use these values seems unwise at present as some doubt exists as to the validity of this simple treatment for samples of much greater purity, especially for transition metals. There is some evidence [600, 1193, 1275] that electron-electron scattering may become important for exceedingly high-purity samples and necessitate one additional term γT such that

$$k=[\alpha T^n+\beta T^{-1}+\gamma T]^{-1}. \quad (10)$$

Also, for many of the elements available data are insufficient to determine the constants m, n, and α'' of equation (8).

TABLE 1. Constants for low-temperature thermal conductivity calculations using equations (7) and (8)

Element	m	n	$\alpha''\times 10^4$
Aluminum	2.62	2.00	0.0479
Cadmium			
(∥ to c-axis)	5.00	4.50	0.0468
(⊥ to c-axis)	5.00	4.50	0.0468
(polycrystalline)	5.00	4.50	0.0468
Chromium	2.20	2.00	0.592
Cobalt	2.20	2.10	0.540
Copper	2.63	2.21	0.0423
Gallium			
(∥ to a-axis)	2.78	2.00	2.04
(∥ to b-axis)	2.78	2.00	0.806
(∥ to c-axis)	2.78	2.00	6.57
Gold	2.46	2.00	0.460
Indium	3.00	2.00	3.50
Iridium	4.40	3.00	0.000272
Iron	2.20	2.00	0.517
Lead	3.50	3.00	4.12
Lithium	2.25	2.00	0.774
Magnesium	2.10	2.00	0.627
Molybdenum	3.20	2.60	0.00967
Nickel	2.60	2.00	0.192
Niobium	2.00	2.00	6.21
Osmium	5.80	3.00	0.00000379
Palladium	2.40	2.00	1.54
Potassium	2.10	2.00	18.0
Rhenium	3.30	2.20	0.0656
Rhodium	3.00	2.80	0.0132
Ruthenium	5.80	2.60	0.00000321
Silver	2.75	2.20	0.0730
Sodium	2.13	2.00	2.89
Tantalum	2.54	2.00	1.39
Thallium	2.80	2.00	26.2
Thorium	2.80	2.79	1.75
Titanium	2.90	2.30	0.188
Tungsten	2.80	2.40	0.0539
Zinc	3.40	3.00	0.0750
Zirconium	2.40	2.00	3.99

A further complication may arise with metallic samples of very high purity in that boundary scattering can become important and render the thermal conductivity at very low temperatures dependent on the size of sample or on that of the individual crystallites of which it is composed. Since the 1930's, see for instance the work of Casimir [243], size dependence has been known for the thermal conductivity of nonmetallic crystals, but measurements by Olsen and Wyder [1053] and by Boughton and Yaqub [185] have more recently directed attention to the influence of crystal size on the electronic thermal conductivity of a metal of sufficiently high purity and perfection. Isotopic content is another factor that has been shown to influence the thermal conductivity at low temperatures; see for instance the work on an isotopically enriched germanium by Geballe and Hull [480], on tellurium by Oskotskii, et al. [1057], and on solid helium by Berman, et al. [141] (see also [143]).

As the temperature rises from the liquid-helium temperature region, the value of the Lorenz function falls quite appreciably to a minimum, but near the Debye temperature it again tends asymptotically towards the theoretical value (see, e.g. Wilson [1569], Makinson [875]). For some metals, including the transition metals, definitely higher values of the Lorenz function may be attained, but the excess seldom exceeds about 30 percent. It follows that in the region from about normal to high temperatures the Lorenz function is generally reasonably close to the theoretical value, and for a particular metal follows a fairly predictable departure curve. Thermal conductivity values can then be calculated from the derived, assumed, or experimentally determined Lorenz function values as a function of temperature and from the measured electrical resistivity data. Considerable use of the Lorenz relationship has therefore been made in this work, both when analyzing thermal conductivity data in the above-normal temperature region and when attempting to make estimations or extrapolations in this range.

For elements such as gallium and yttrium, whose transport properties are strongly anisotropic, uncertainties are associated with the derivation of values from single crystal data that would apply to a polycrystalline sample.

Consider an orthorhombic crystal, such as that of gallium, for which k_a, k_b, and k_c are the thermal conductivity values for the three main crystal axes a, b, and c, and k_p is the thermal conductivity of the polycrystal. By considering the conductivities to be additive, Voigt [1487] showed that

$$k_p=\frac{1}{3}(k_a+k_b+k_c). \quad (11)$$

If however the thermal resistivities are considered to be additive, which Hall, Legvold, and Spedding [577] regarded to be preferable in the case of rods of yttrium, then

$$\frac{1}{k_p}=\frac{1}{3}\left(\frac{1}{k_a}+\frac{1}{k_b}+\frac{1}{k_c}\right), \quad (12)$$

or

$$k_p = \frac{3k_a k_b k_c}{k_a k_b + k_a k_c + k_b k_c}. \quad (13)$$

For gallium at 300 K, $k_a = 0.406$, $k_b = 0.883$, and $k_c = 0.159$ W cm^{-1} K^{-1}. Hence the values of k_p according to equations (11) and (12) are respectively 0.483 and 0.304 W cm^{-1} K^{-1}, and differ by some ± 25 percent from the mean value of 0.393 W cm^{-1} K^{-1}. A more recent treatment, in which Hashin and Shtrikman [592] used a variational method, shows that for the case where $k_c < k_a < k_b$

$$\frac{k_b\,(4k_b^2 + 8k_b k_a + 8k_c k_b + 7k_a k_c)}{16k_b^2 + 5k_b k_a + 5k_c k_b + k_a k_c} > k_p > \frac{k_c\,(4k_c^2 + 8k_c k_a + 8k_c k_b + 7k_a k_b)}{16k_c^2 + 5k_c k_a + 5k_c k_b + k_a k_b}, \quad (14)$$

which leads to extreme values of 0.444 and 0.377 W cm^{-1} K^{-1} for k_p in the case of gallium at 300 K. The treatment embraces a narrower ($\pm 8\%$) range of values and gives a mean of 0.410 W cm^{-1} K^{-1} which happens to be only about 1 percent greater than k_a. In this instance the value of k_a has been taken as representing approximately the thermal conductivity of polycrystalline gallium, but it is clear that more attention could well be devoted both experimentally and theoretically to this problem. Electrical conductivity would behave similarly and this property is likely to be measurable with greater accuracy, although high accuracy would not be so necessary with the large differences indicated for gallium. A practical difficulty could however arise in this instance from the ease with which gallium solidifies in the single crystal form, and the difficulty experienced so far in preparing truly polycrystalline samples of this metal.

In this work, the average of the values given by equations (11) and (12) has been adopted as the estimated value for a polycrystalline sample of an element of large anisotropy if experimental data are not available.

In connection with the thermal conductivity of molten metals, reference will frequently be made to estimated values that are due to Grosse [546, 548]. These values have been derived from the melting to the critical points using the equation $k = L_0 \sigma T$ with derived values for the electrical conductivity, σ, and usually assuming the theoretical Lorenz number, L_0, to hold throughout the range. To derive an expression for the electrical conductivity, Grosse has proposed an equation of the form of a simple equilateral hyperbola [545]

$$(\sigma' + b)\;(T' + b) = a, \quad (15)$$

where the reduced electrical conductivity $\sigma' = \sigma_T/\sigma_f$, the reduced temperature $T' = (T - T_f)/(T_c - T_f)$, σ_f is the electrical conductivity of the molten metal at the melting point, and σ_T is the electrical conductivity at a temperature T between T_f, the melting point, and T_c, the critical temperature. The quantities a and b are constants. At T_c both σ and k are assumed to be zero.

Since these predictions were made, increasing uncertainty has developed as to the Lorenz function of molten metals and its variation with temperature. Previous work, for instance of Powell [1120], had indicated the Lorenz function to approximate the theoretical value, as was assumed by Grosse [546, 548], but according to the work of Filippov [435] on tin and lead and some other recent measurements [884, 1593] the Lorenz function continues to decrease with increase in temperature to values that are well below L_0. This uncertainty needs resolving and, pending confirmation and theoretical support for the lower values, values closer to those of Grosse have provisionally been adopted in the present work.

2.2. Data Evaluation, Correlation, Analysis, and Synthesis

Data analysis and synthesis involve critical evaluation of the validity and accuracy of available data and related information, resolution and reconciliation of disagreement in conflicting data, correlation of data in terms of various controlling parameters (sometimes in reduced forms using the principle of corresponding states), curve fitting with theoretical or empirical equations, comparison of resulting data with theoretical predictions or with results derived from semitheoretical relationships or from generalized empirical correlations, etc. Besides critical evaluation and analysis of the existing data, thermodynamic, kinetic, or statistical mechanical principles and semiempirical techniques are employed to fill gaps and to extrapolate existing data so that the resulting recommended values are internally consistent and cover as wide a range of each of the controlling parameters as possible.

In the critical evaluation of the validity and uncertainty of a particular set of data, say, the thermal conductivity of a solid, the temperature dependence of the thermal conductivity was examined and any unusual dependence or anomaly carefully investigated, the experimental technique reviewed to see whether the actual boundary conditions in the experiment agreed with those assumed in the theory and all the stray heat flows and losses were prevented or minimized and evaluated, the reduction of data examined to see whether all the necessary corrections had been applied, and the estimation of uncertainties checked to ensure that all the possible sources of errors had been considered.

For a steady-state absolute measurement of the thermal conductivity of a solid specimen, for example, the sources of errors may include the uncertainty in the measurements of specimen dimensions and of the distances between points of temperature measurements; the uncertainty in determining the necessary correction to the thermal conductivity value due to the effect of thermal expansion; the uncertainty in determining the power input to the specimen heater; the uncertainty in determining the heat gains or losses to or from the specimen due to direct radiation interchange or to conduction through the surrounding insulation, along the electric leads, and along the thermocouple wires and the ceramic insulating tubings or beads; the uncertainty in temperature measurements due to poor thermocouple calibration, poor thermocouple contact, poor sensitivity of the measuring circuits, and temperature drift; the uncertainty due to the effect of thermal contact resistance; the uncertainty for measurements at elevated temperatures due to thermocouple contamination, specimen oxidation, and reaction of specimen with apparatus components, etc. In a comparative measurement, additional uncertainties may come from the conductivity mismatch between the specimen and the reference sample(s), from the additional interfacial thermal contact resistance, and from the additional uncertainty in the conductivity of the reference sample (especially if the conductivity values of the "reference" sample are blindly taken from the literature). For a nonsteady-state measurement, large uncertainty may result if the density and specific heat values are taken from the literature and not directly measured on the specimen for which the thermal diffusivity data are obtained. The above-mentioned and other possible sources of errors have been carefully considered in critical evaluation of experimental data in this work.

Many authors have included detailed error estimates in their published papers, and from these it is possible to evaluate the uncertainty for a particular method. However, experience has shown that the uncertainty estimates of most authors are unreliable. In many cases the difference between the results of two sets of data is much larger than that given by the sum of their stated uncertainties. Cases even occur where measurements reported to be accurate to within 1 or 2 percent differ from each other by more than 100 percent. In these cases either the actual error must greatly exceed its estimated value, or the author was unaware of the sources of systematic errors, or there must be essential unrecorded sample differences. Therefore, although one has to assume that the author's error estimate bears some relationship to the truth, the exact functional relationship depends on the author himself and on other factors, e.g., was he a new investigator or an experienced worker? was the paper a rushed project to meet a conference or contract deadline? etc.

Besides evaluating and analyzing individual data sets, correlation of data in terms of various controlling parameters is a valuable technique that is frequently used in data analysis. These parameters may include purity, composition, residual electrical resistivity or electrical resistivity ratio (if a metal), density or porosity, hardness, crystal axis orientation, degree of cold working, degree of heat treatment, etc. Applying the principle of corresponding states, reduced property values may be correlated with reduced temperature and other reduced parameters. Certain properties of the elements may also be correlated with the atomic numbers of the elements in the periodic system; examples are critical temperatures, critical pressures, critical volumes, and atomic volumes at 0 K. Wherever appropripate, such correlation techniques have been applied to the thermal conductivity of the elements in the present work.

Several properties of the same material can also be cross-correlated. For example, thermal conductivity, specific heat, and density can be correlated with thermal diffusivity, and viscosity and specific heat of a gas can be correlated with thermal conductivity through the Chapman-Enskog theory or through the experimental Prandtl number. For a fluid, the property of the saturated liquid can also be correlated with that of the saturated vapor.

For meaningful data correlation, the information on specimen characterization is very important especially for solid specimens. A full description of a solid specimen should include, whenever applicable, the following: purity or chemical composition, carrier concentration; type and concentration of lattice defects; type of crystal, crystal axis orientation for a single crystal; microstructure, grain size, preferred grain orientation, pore size and shape and orientation, inhomogeneity, and additional phases for a polycrystalline specimen; specimen shape and dimensions, method and procedure of fabrication; thermal history and cold work history, heat treatment, mechanical, irradiative, and other treatments; manufacturer and supplier, stock number, and catalog number; test environment, degree of vacuum or pressure, heat flow direction, strength and orientation of an applied magnetic field; pertinent physical properties such as density, porosity, hardness, electrical resistivity (residual, ratio, and temperature variations), Lorenz function, transition temperature, etc.; and reference material and its property values for a comparative method of measurement. Data (no matter how accurate) on poorly characterized materials can hardly be analyzed or used for data correlation. It has been found in this and other studies that the specimen purity or composition reported by the author is often unreliable. This is because in many cases the stated purity or composition is the result of ladle analysis which the author obtained from the company who supplied the specimen and it can at best represent only the nominal purity or composition (the actual purity or composition varies from sample to sample). In other cases there is a strong tendency for only certain elements to be covered by a particular chemical analysis, which could miss other quite important constituents.

Besides specimen characterization, a full description of experimental details should, of course, be given by the author in order that his data can be meaningfully evaluated and fully utilized. Sometimes, as an initial method of evaluating the quality of a paper, consideration may be given to the amount of experimental details reported in the paper. Lack of experimental details could lead to the results being given less weight. However, it should be emphasized again that the real enemy of reliable data is the systematic measurement error, whose existence in his measurement is usually unknown to the author. As the author was unaware of it, he provided little information about it in his paper. Therefore, in data evaluation one should not only try to find out what was wrong with a measurement according to the author's description, but also try to detect with reasonable suspicion any possible sources of systematic error unknown to the author in his measurement.

It is apparent that any data that can be considered reliable must be free of systematic error. In practice, for example, if several sets of data that agree with one another were produced by different authors using different absolute experimental methods, these data can usually be considered reliable. However, if they were produced by the same experimental method, the agreement may be spurious and there still exists a probability that they may all suffer from a common, but unknown, systematic error.

In estimating the degree of uncertainty of our recommended values for the various ranges of temperature, it is clear from the above discussion that only for the thermal conductivity of the few much studied materials has it been possible to place close error limits that can be considered reliable. For the less well studied materials, wider limits of uncertainty are generally given; these are based also on other factors and considerations such as general knowledge of the worker, the accuracy of measurements of other materials using the same or similar apparatus, etc. The estimated uncertainty also takes into consideration the behavior of the material itself. For a well-behaved material narrower limits are given when the temperature dependence of its thermal conductivity is predictable from theoretical considerations or from empirical correlations. For an ill-behaved material or a material with phase and/or magnetic transformations, such as the rare earths, the estimated uncertainties are greater. For the recommended values of the thermal conductivity of fluids, the uncertainty estimation is sometimes based on the degree of agreement of our values with those proposed by other experimental or analysis specialists, coupled with a more personal opinion of the experimental accuracy of the existing state-of-the-art of the measurement techniques. At other times, the scatter around the recommended values of those experimental data considered reliable forms the basis of uncertainty estimation.

2.3. Summary Graphs

With a view to bringing out any similarities or differences between the recommended values for the elements of a particular group of the periodic table, these values for all the elements of each group have been plotted in figures 3 to 14, which show some of the generalizations for the property of thermal conductivity that were mentioned at the beginning of this section. These figures may prove helpful when making estimations to temperatures not covered in the sections which follow.

In figure 15 the thermal conductivity of each element at 300 K is plotted against the atomic number of the element. A fairly definite pattern can be traced, and this has been of assistance in deriving estimated values for certain elements for which no information is available. These include actinium, francium, and the trans-plutonium elements. The thermal conductivities of the elements at 300 K and at the Debye temperature are further tabulated in a periodic table appearing on page I–10. This table shows more clearly the variations of the thermal conductivity values of the elements within each group.

Figure 15a is a plot of the thermal conductivities of a number of solid nonmetallic elements at 300 K against the melting temperatures of the elements. A reasonable curve can be drawn through the points to indicate roughly the thermal conductivity at 300 K as a function of the melting temperature. This information was used to obtain an estimated value for the thermal conductivity of astatine as shown in the figure.

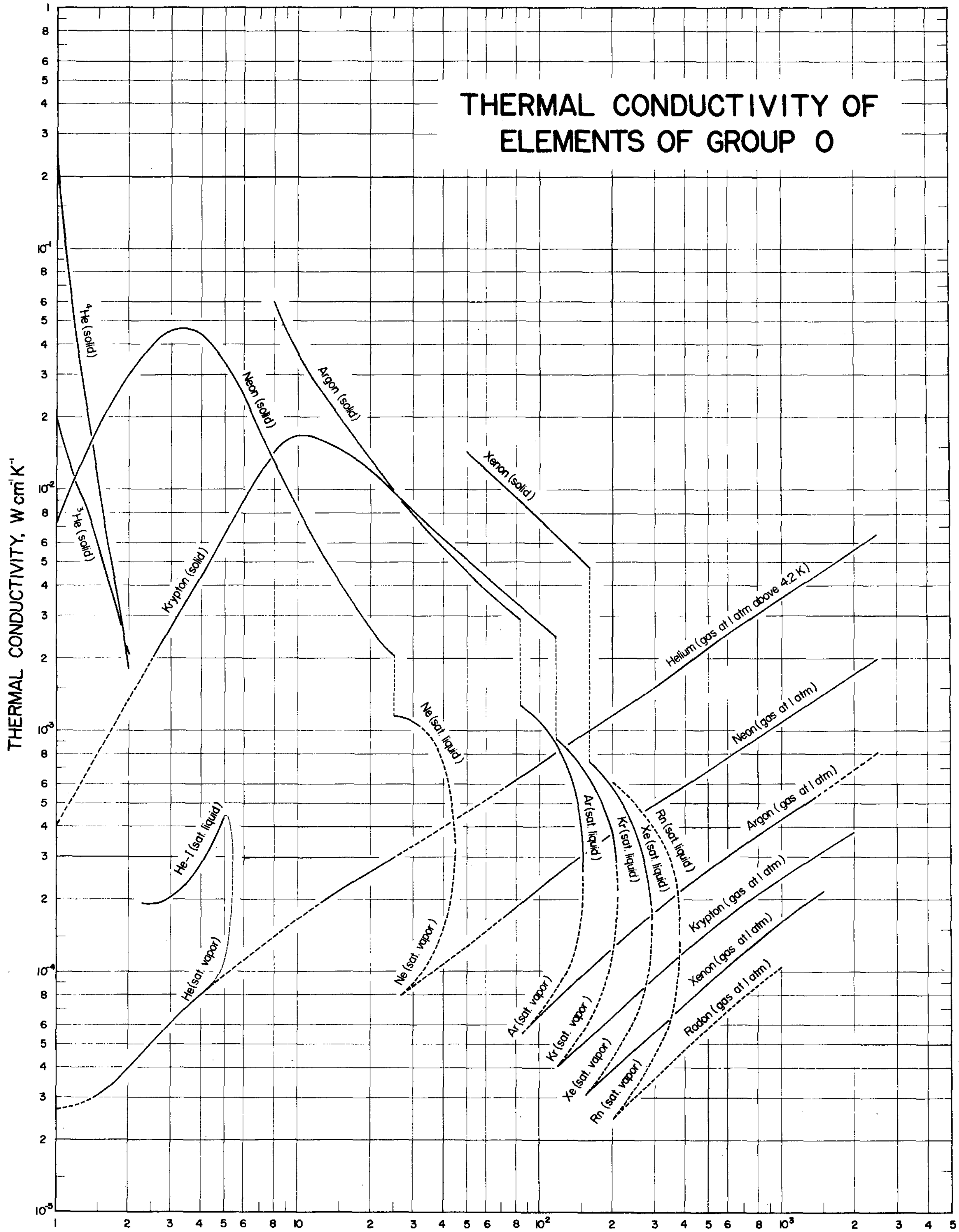
In the other estimations, estimated thermal conductivity values for barium, calcium, europium, polonium, protactinium, and strontium have been based on electrical resistivity data, and those for radon are based mainly on a generalized correlation by Owens and Thodos [1058]. The value for radium comes from collected data by Samsonov [1239], and is attributed to Chirkin [274], but no detail is given.

3. Specific Considerations Concerning the Body of Data

This compilation contains a large number of graphs and tables of thermal conductivity as a function of temperature. The conventions used in this presentation and special comments on the interpretation and use of the data are given below.

The thermal conductivities of the elements are presented alphabetically by the names of the elements, but it should be noted that where information is given for different forms of a particular element, these follow that element. Thus, entries for amorphous carbon, diamond, and for several types of graphite come in the entry for carbon, and those for deuterium and tritium are found after the entry for hydrogen. For most of the nonmetallic elements which are liquid or gaseous at normal temperature and pressure (N.T.P.) and for iodine, thermal conductivity values are given for the solid, saturated liquid, saturated vapor, and gas. For the other elements, values are given only for the solid state or for both the solid and liquid states.

In all figures containing experimental data, a data set consisting of a single point is denoted by a number enclosed by a square and a curve that connects a set of data points is denoted by a ringed number. These numbers correspond to those given in the accompanying tables on specimen characterization and measurement information. When several sets of data are too close together to be distinguishable, some of the data sets, though listed in the table, are omitted from the figure for the sake of clarity. For those omitted curves, one is referred to the TPRC Data Series, Volumes 1 and 2 [1421, 1422], in which numerical data tables are also given. The much heavier curves drawn in the figures represent the proposed values of the thermal conductivity. These heavy curves may be continuous, short-dashed, or long-dashed. Heavy continuous (solid) curves properly labeled represent recommended reference values or provisional values. Accompanying sections of short-dashed curves represent values in the



TPRC FIGURE 3

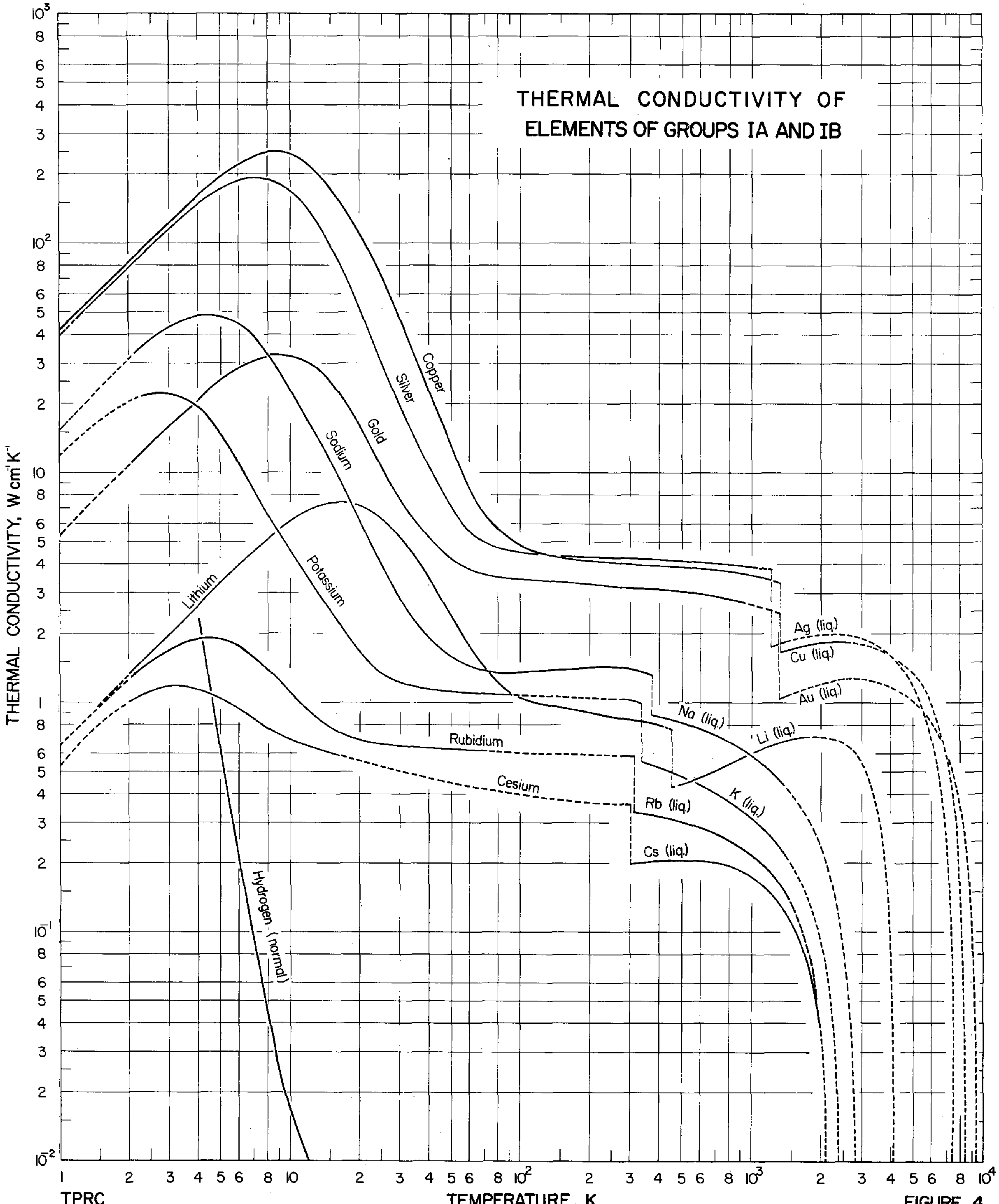

THERMAL CONDUCTIVITY OF
ELEMENTS OF GROUPS IA AND IB
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Copper
Silver
Gold
Sodium
Potassium
Lithium
Rubidium
Cesium
Hydrogen (normal)
Ag (liq.)
Cu (liq.)
Au (liq.)
Na (liq.)
Li (liq.)
K (liq.)
Rb (liq.)
Cs (liq.)
TPRC

FIGURE 4

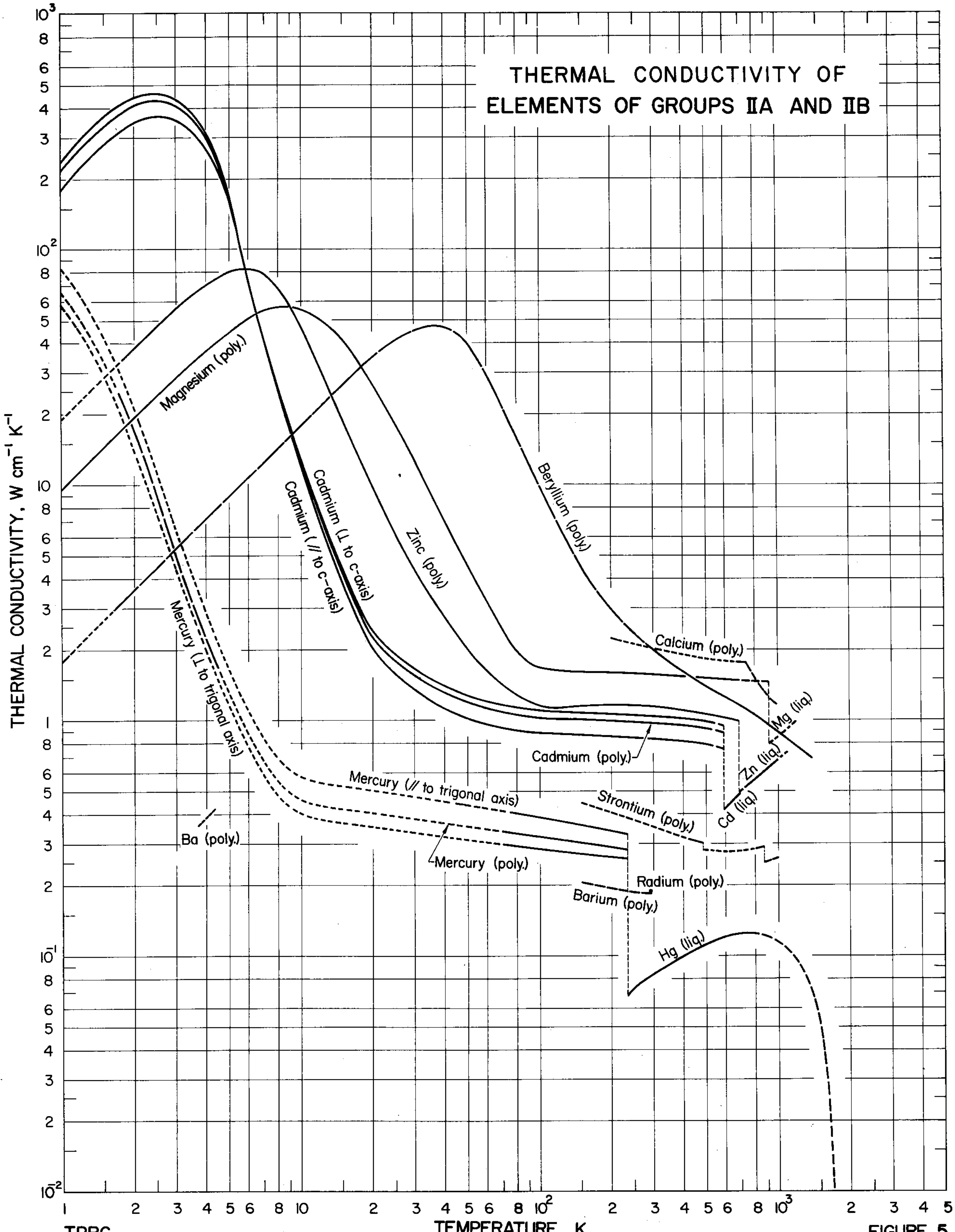

THERMAL CONDUCTIVITY OF
ELEMENTS OF GROUPS IIA AND IIB
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Magnesium (poly.)
Cadmium (⊥ to c-axis)
Cadmium (// to c-axis)
Zinc (poly.)
Beryllium (poly.)
Calcium (poly.)
Mg (liq.)
Zn (liq.)
Cd (liq.)
Cadmium (poly.)
Mercury (⊥ to trigonal axis)
Mercury (// to trigonal axis)
Mercury (poly.)
Strontium (poly.)
Ba (poly.)
Radium (poly.)
Barium (poly.)
Hg (liq.)
TPRC

FIGURE 5

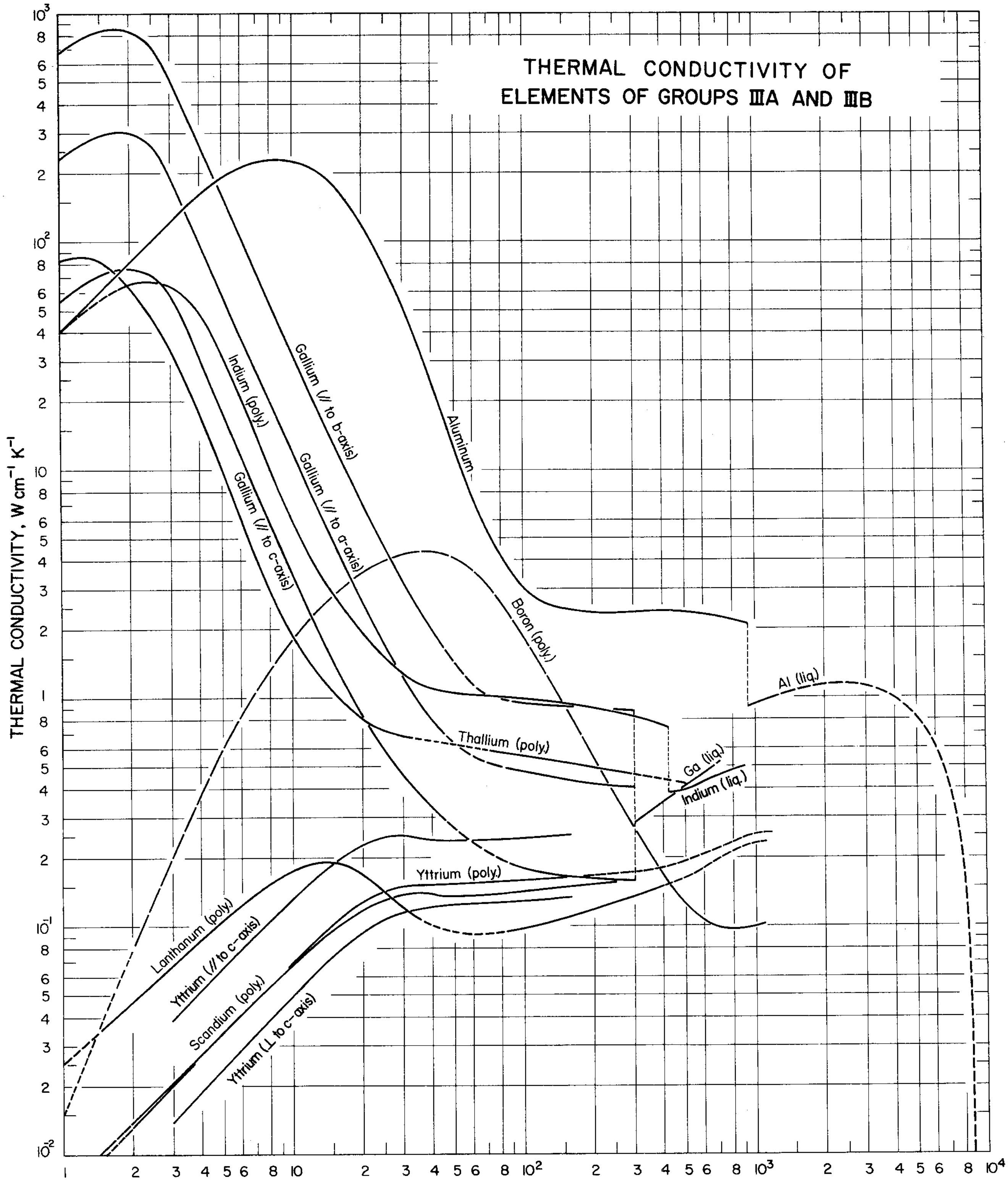
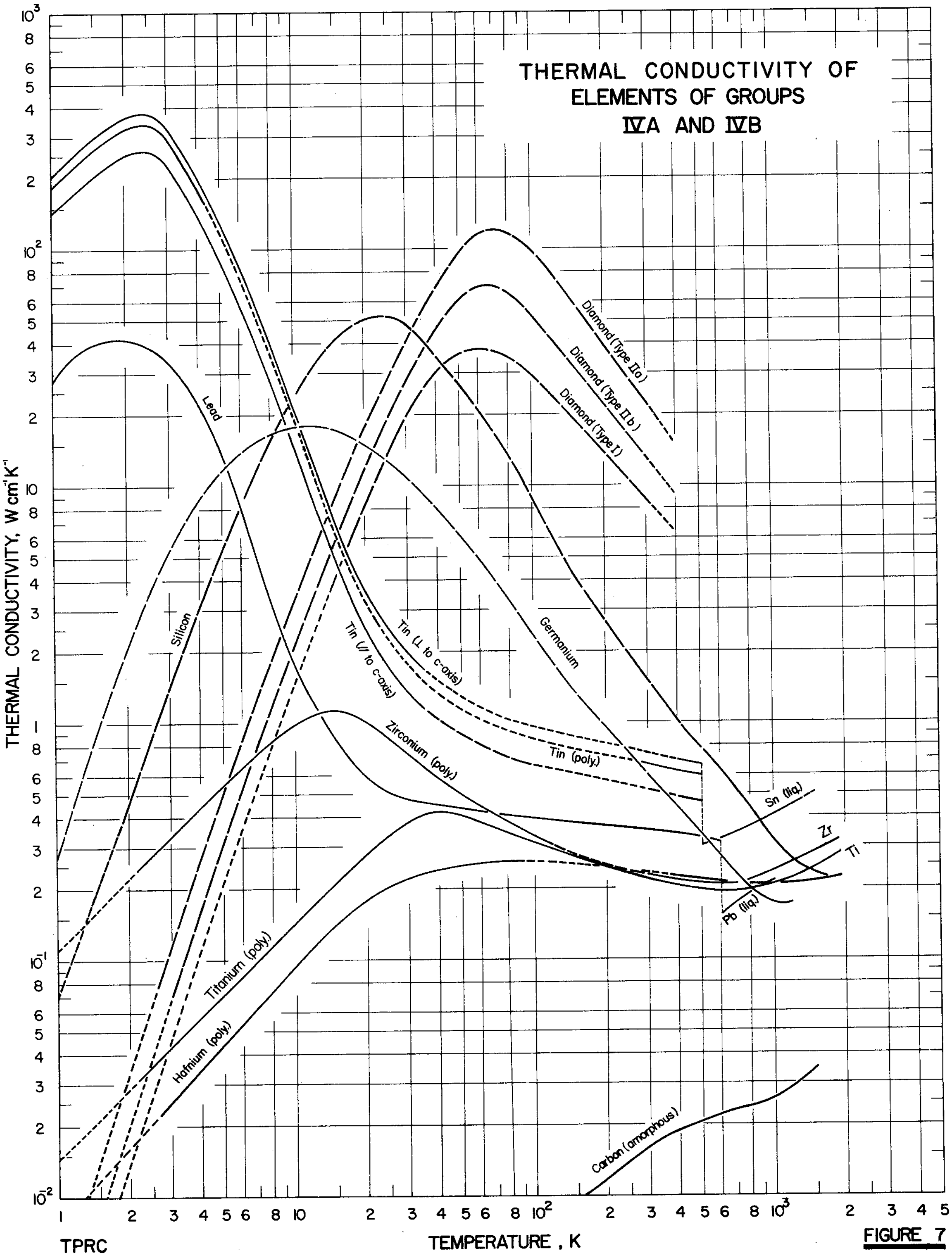
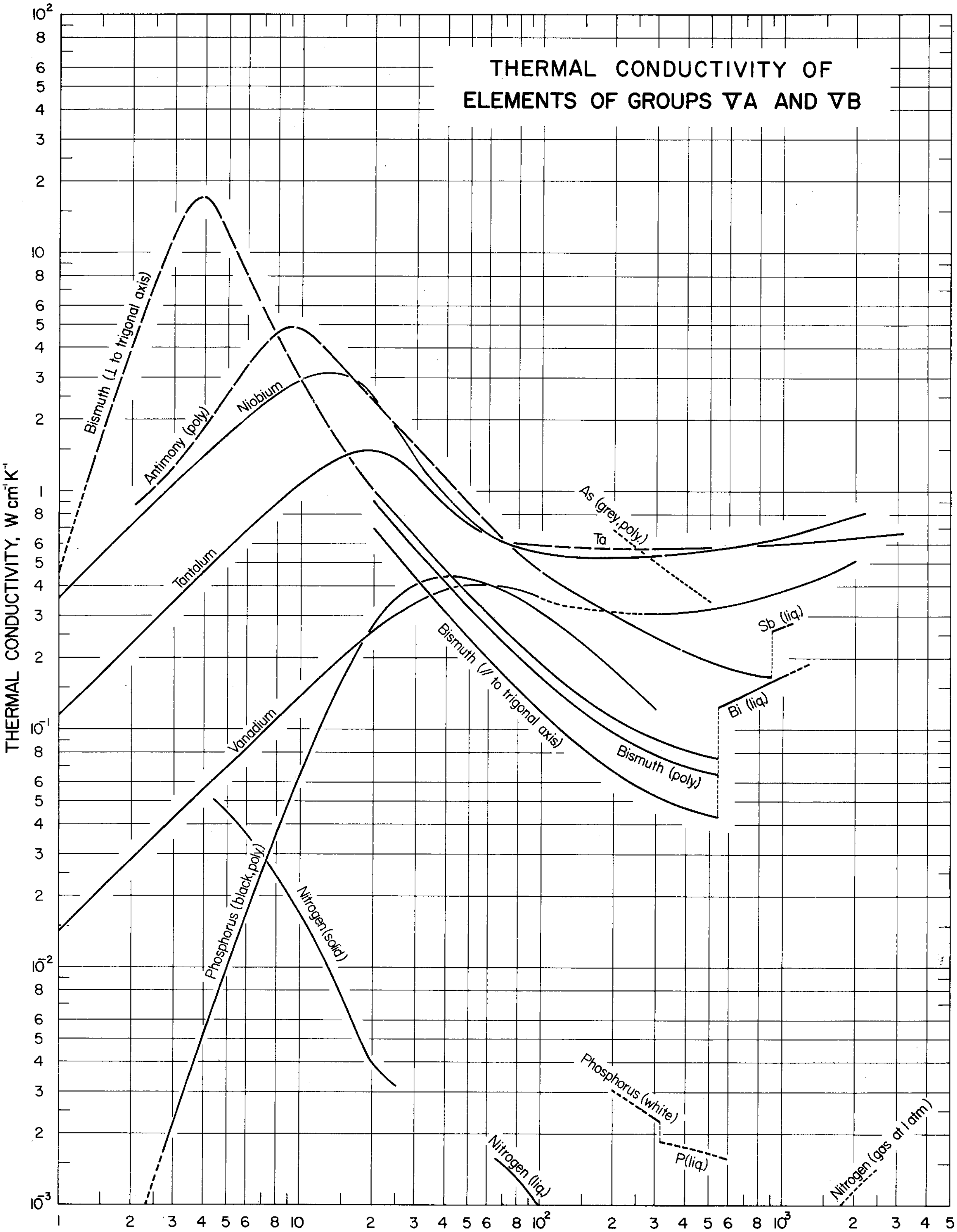

THERMAL CONDUCTIVITY OF
ELEMENTS OF GROUPS IIIA AND IIIB
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Aluminum
Gallium (// to b-axis)
Gallium (// to a-axis)
Gallium (// to c-axis)
Indium (poly.)
Boron (poly.)
Thallium (poly.)
Al (liq.)
Ga (liq.)
Indium (liq.)
Yttrium (poly.)
Lanthanum (poly.)
Yttrium (// to c-axis)
Scandium (poly.)
Yttrium (⊥ to c-axis)
TPRC

FIGURE 6



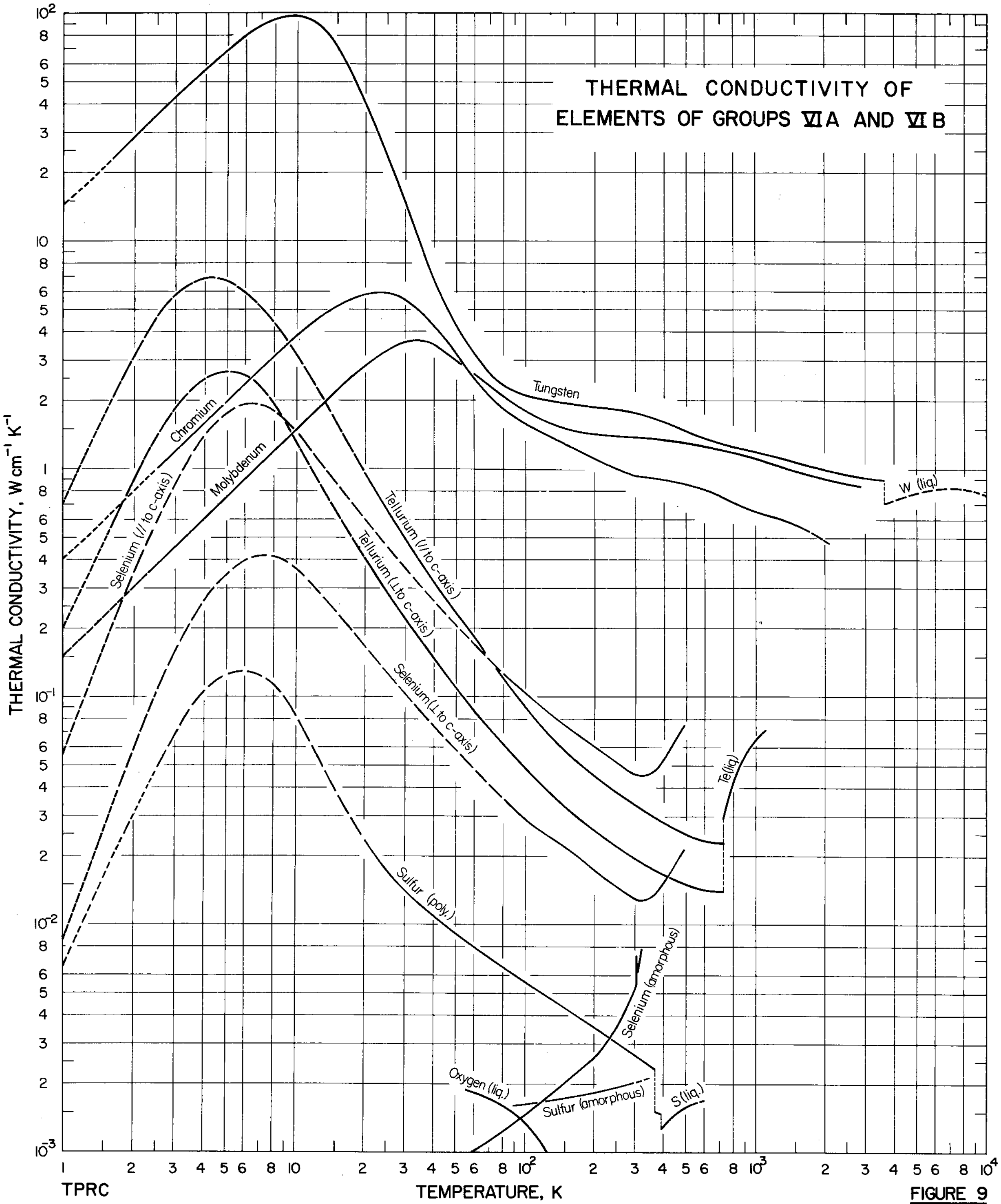
TPRC

FIGURE 7



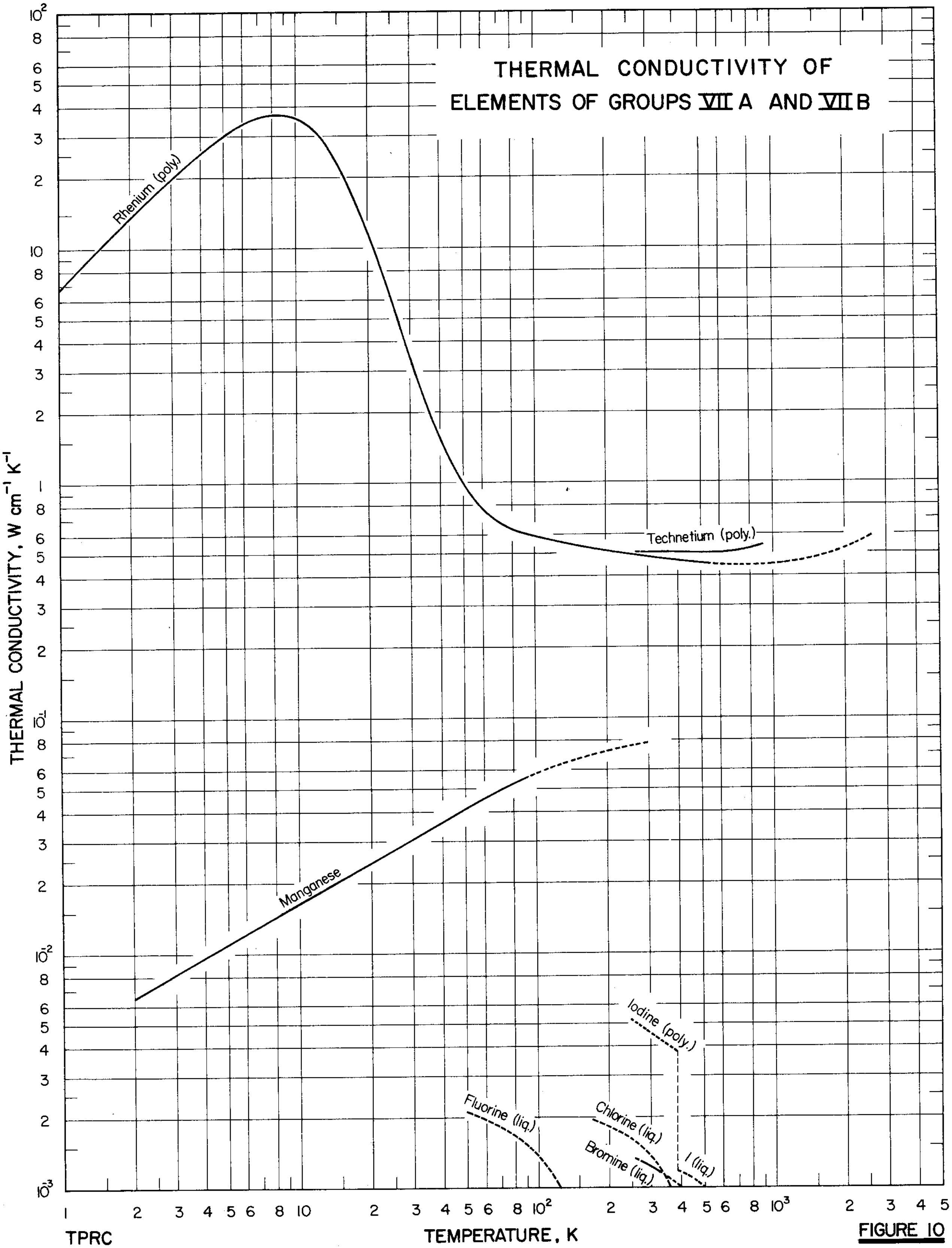
THERMAL CONDUCTIVITY OF ELEMENTS OF GROUPS ⅤA AND ⅤB
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE , K
Bismuth (⊥ to trigonal axis)
Antimony (poly.)
Niobium
Tantalum
Vanadium
As (grey,poly.)
Ta
Sb (liq.)
Bi (liq.)
Bismuth (// to trigonal axis)
Bismuth (poly.)
Phosphorus (black,poly.)
Nitrogen (solid)
Phosphorus (white)
P(liq.)
Nitrogen (liq.)
Nitrogen (gas at 1 atm)
TPRC

FIGURE 8



TPRC

FIGURE 9


THERMAL CONDUCTIVITY OF
ELEMENTS OF GROUPS VII A AND VII B
Rhenium (poly.)
Technetium (poly.)
Manganese
Iodine (poly.)
Fluorine (liq.)
Chlorine (liq.)
Bromine (liq.)
I (liq.)
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC
FIGURE 10

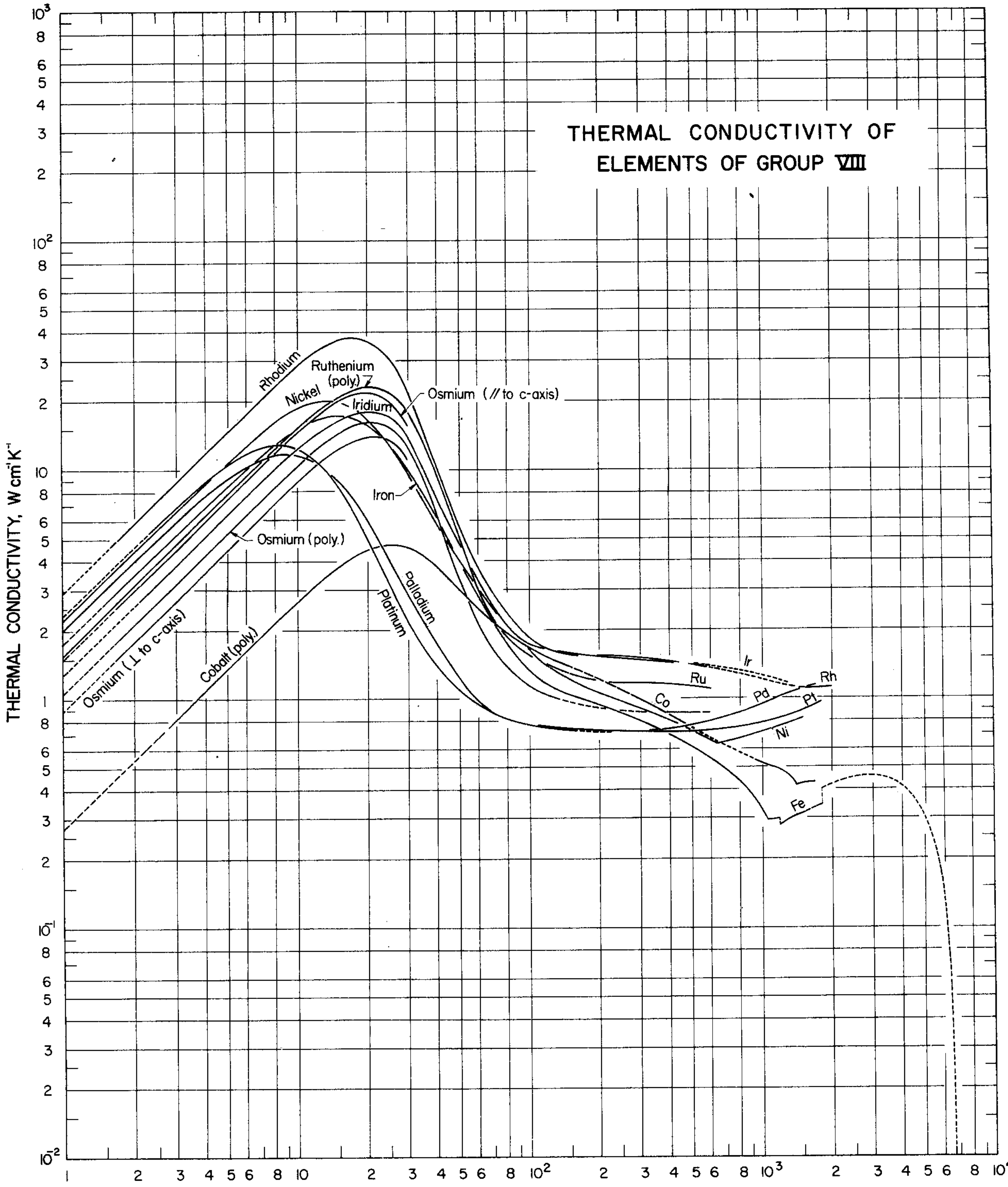
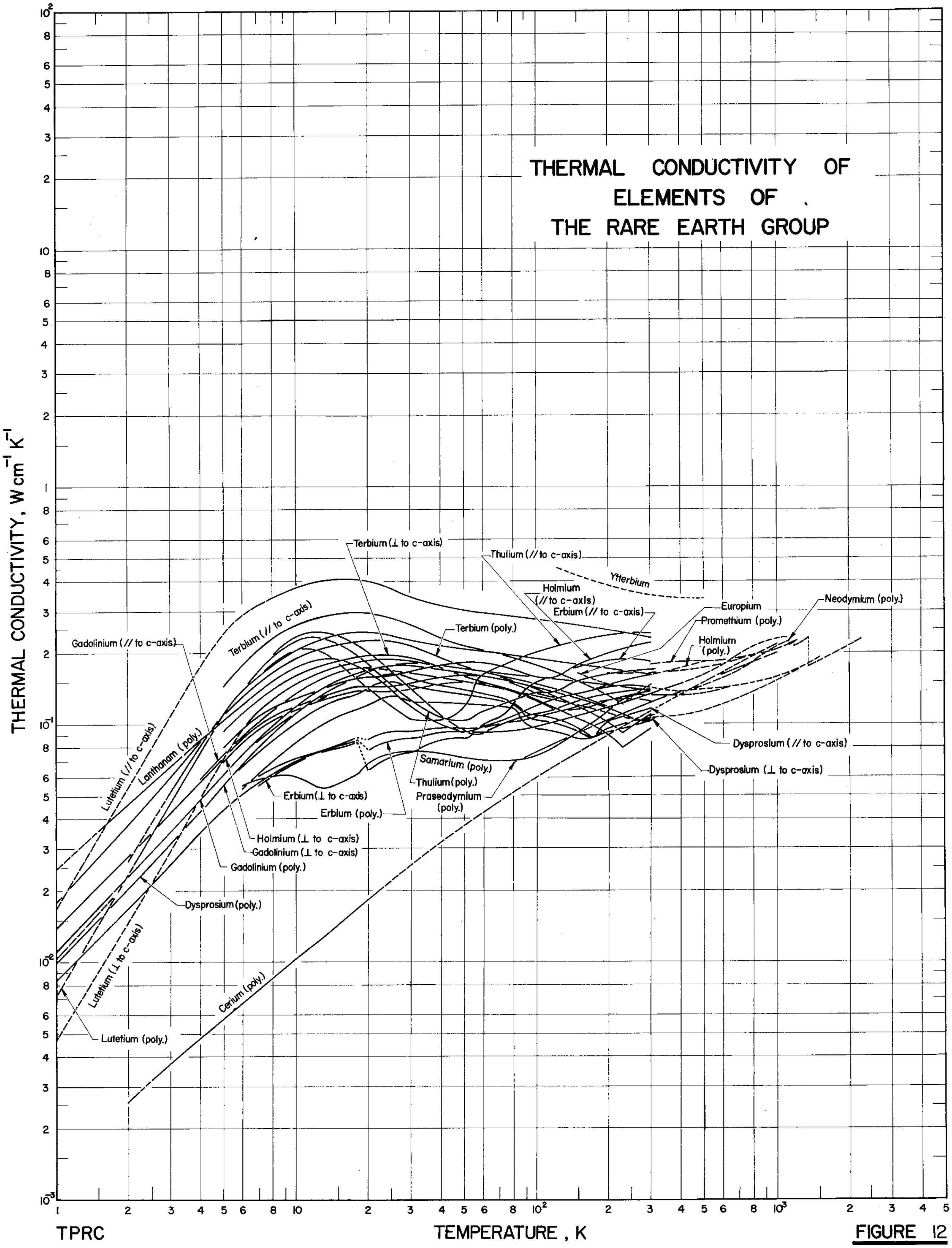
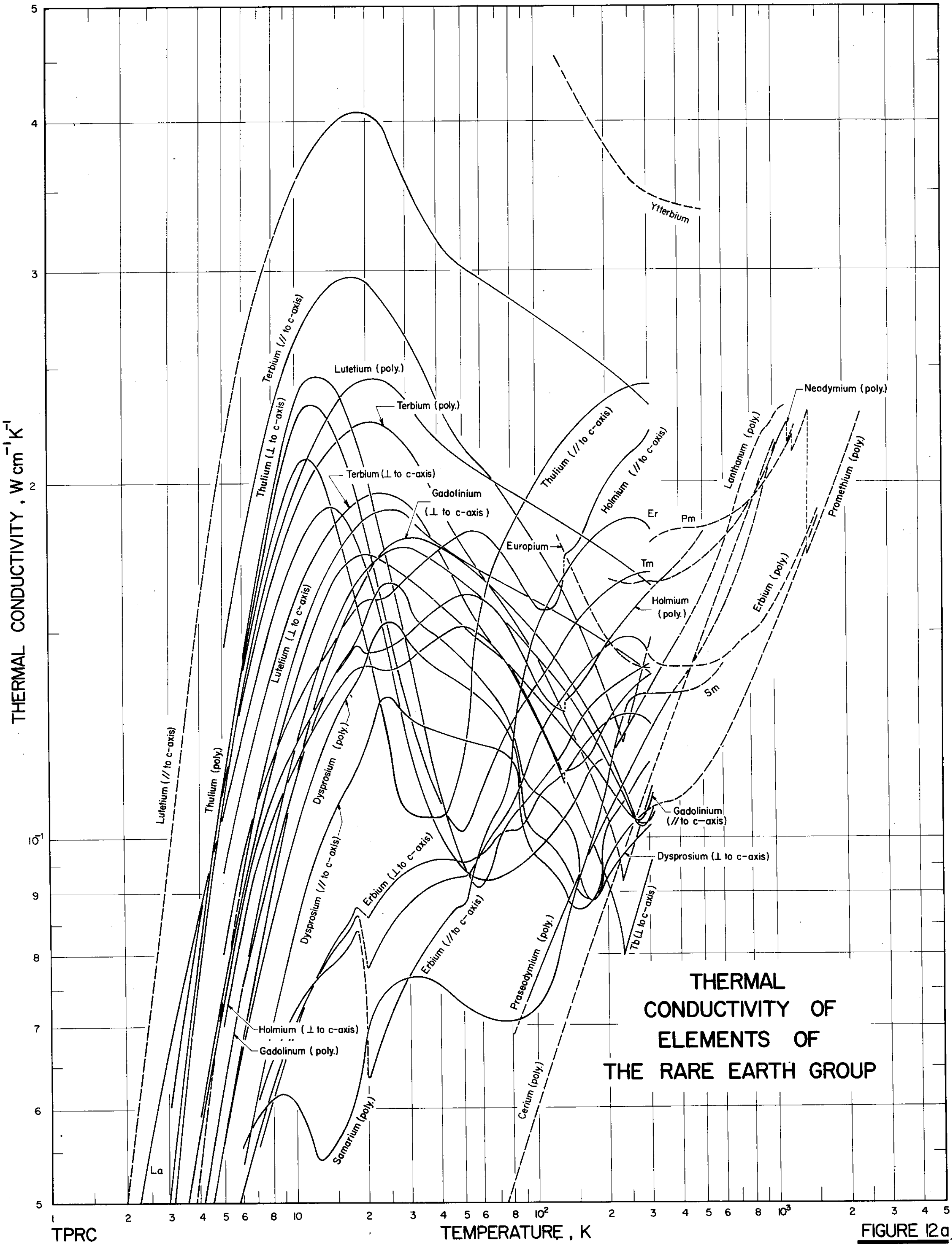

THERMAL CONDUCTIVITY OF
ELEMENTS OF GROUP VIII
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Rhodium
Ruthenium (poly.)
Nickel
Iridium
Osmium (// to c-axis)
Iron
Osmium (poly.)
Osmium (⊥ to c-axis)
Cobalt (poly.)
Palladium
Platinum
Ir
Ru
Rh
Co
Pd
Pt
Ni
Fe
TPRC

FIGURE 11



THERMAL CONDUCTIVITY OF ELEMENTS OF THE RARE EARTH GROUP
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Terbium (⊥ to c-axis)
Thulium (// to c-axis)
Ytterbium
Holmium (// to c-axis)
Erbium (// to c-axis)
Europium
Neodymium (poly.)
Promethium (poly.)
Terbium (poly.)
Holmium (poly.)
Terbium (// to c-axis)
Gadolinium (// to c-axis)
Dysprosium (// to c-axis)
Dysprosium (⊥ to c-axis)
Samarium (poly.)
Thulium (poly.)
Praseodymium (poly.)
Erbium (⊥ to c-axis)
Erbium (poly.)
Lutetium (// to c-axis)
Lanthanum (poly.)
Holmium (⊥ to c-axis)
Gadolinium (⊥ to c-axis)
Gadolinium (poly.)
Dysprosium (poly.)
Lutetium (⊥ to c-axis)
Cerium (poly.)
Lutetium (poly.)
TPRC

FIGURE 12



THERMAL CONDUCTIVITY OF ELEMENTS OF THE RARE EARTH GROUP

FIGURE 12a

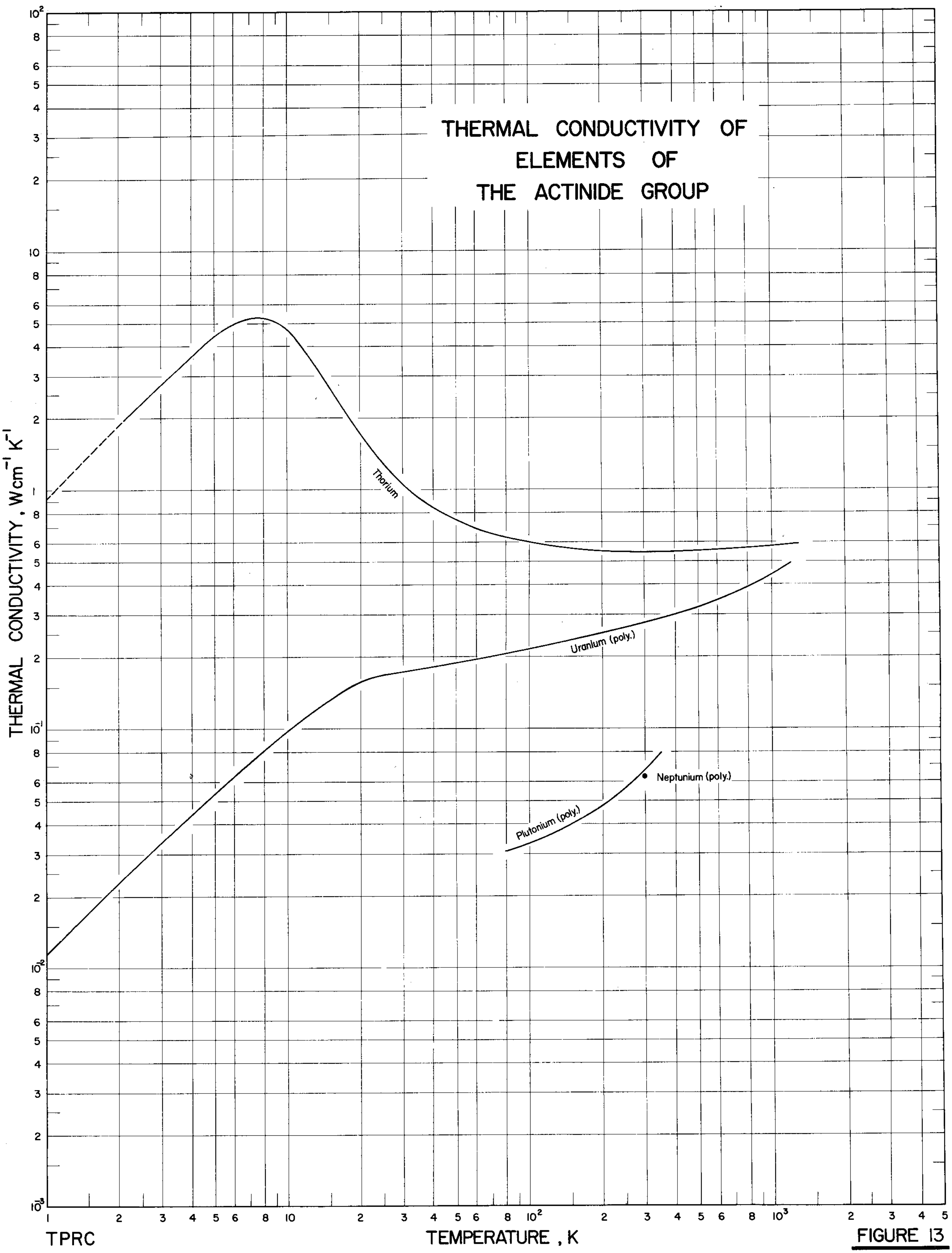

THERMAL CONDUCTIVITY OF
ELEMENTS OF
THE ACTINIDE GROUP
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Thorium
Uranium (poly.)
Neptunium (poly.)
Plutonium (poly.)
TPRC

FIGURE 13

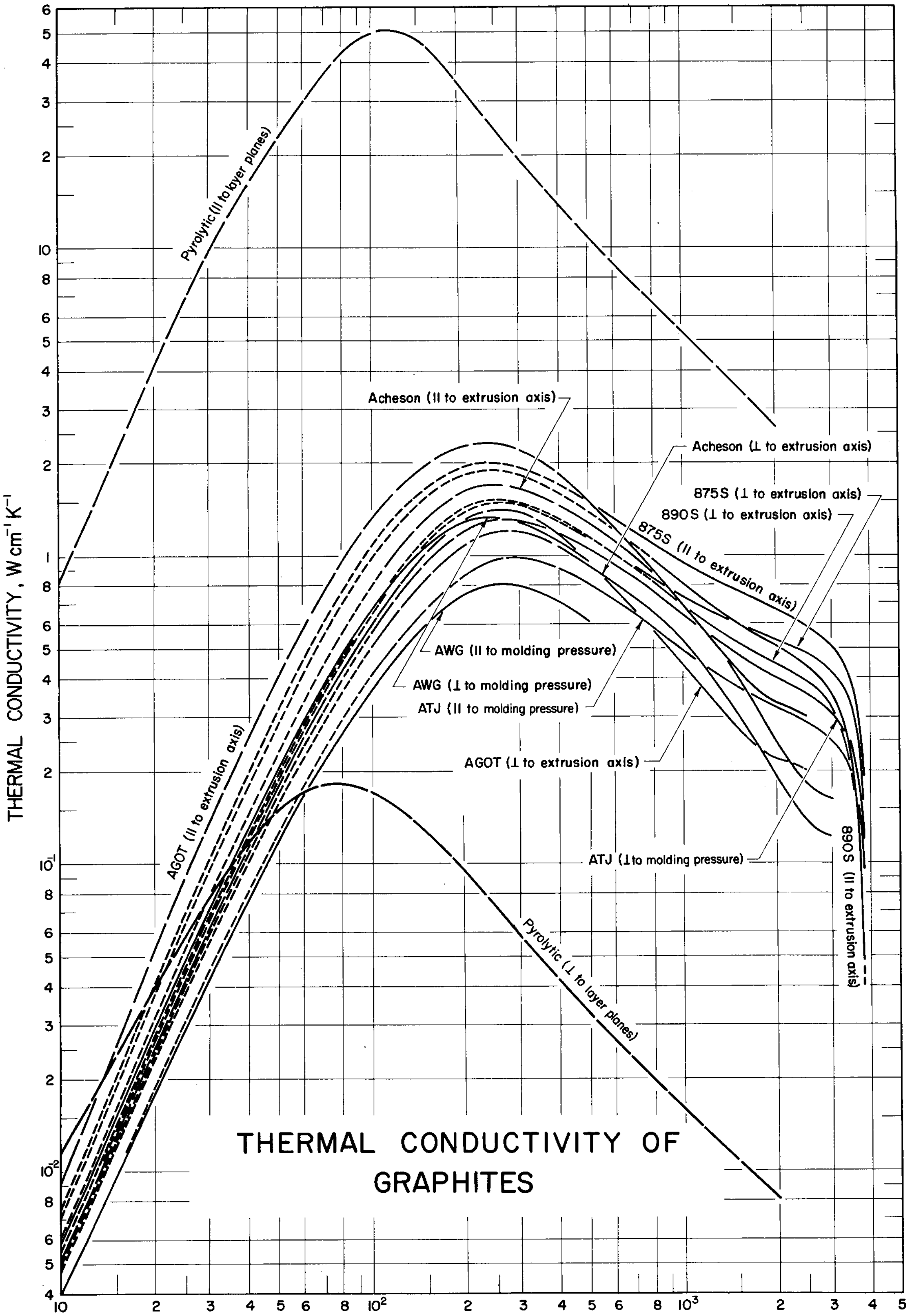

THERMAL CONDUCTIVITY OF GRAPHITES
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Pyrolytic (II to layer planes)
Pyrolytic (⊥ to layer planes)
Acheson (II to extrusion axis)
Acheson (⊥ to extrusion axis)
875S (⊥ to extrusion axis)
890S (⊥ to extrusion axis)
875S (II to extrusion axis)
890S (II to extrusion axis)
AWG (II to molding pressure)
AWG (⊥ to molding pressure)
ATJ (II to molding pressure)
ATJ (⊥ to molding pressure)
AGOT (⊥ to extrusion axis)
AGOT (II to extrusion axis)
TPRC

FIGURE 14

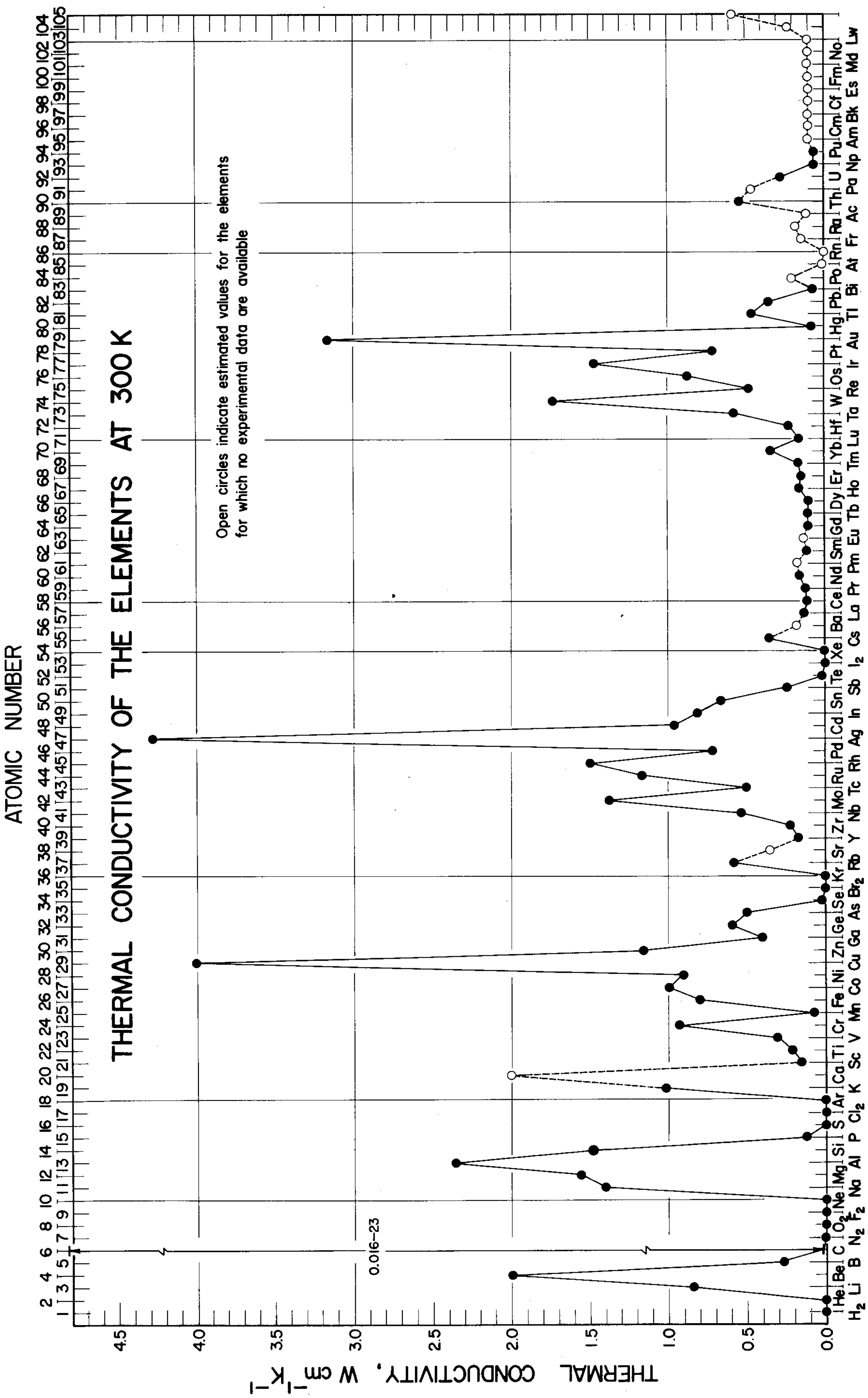
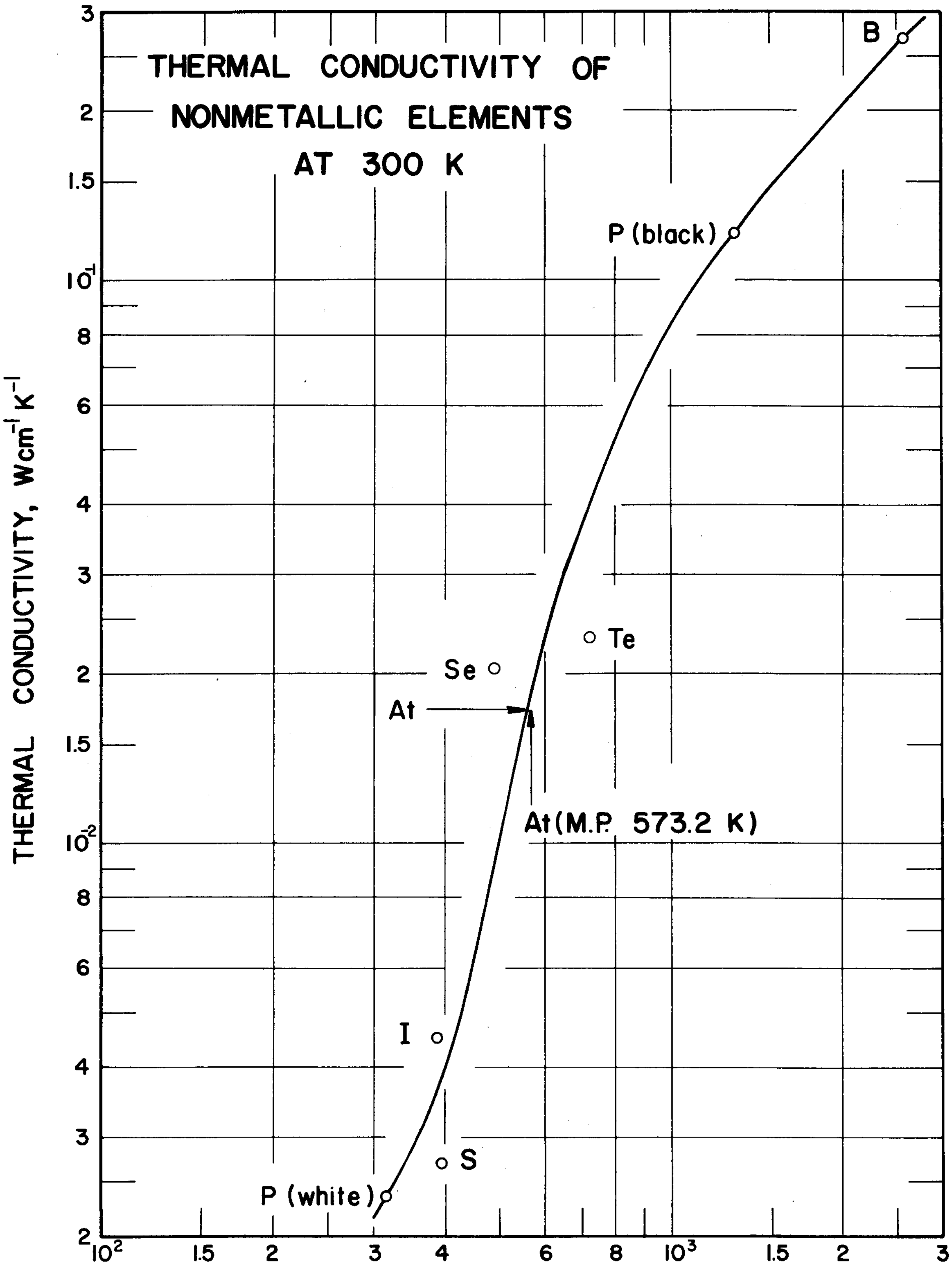

THERMAL CONDUCTIVITY OF THE ELEMENTS AT 300 K
Open circles indicate estimated values for the elements for which no experimental data are available
ATOMIC NUMBER
ELEMENT
THERMAL CONDUCTIVITY, W cm^{-1}K^{-1}
0.016–23
TPRC

FIGURE 15



TPRC FIGURE 15a

temperature ranges where no experimental data are available. In some instances, notably for nonmetals and semimetals at low temperatures where the specimen cannot be uniquely characterized to correspond exactly with the thermal conductivity values, values considered as typical are represented by heavy long-dashed curves.

For all the elements, logarithmic plotting of thermal conductivity against temperature is adopted in order that details are clearly shown for the lower temperature region. In the cases of elements which become superconductors at low temperatures these figures contain the available data for both the normal and superconducting states, but so far all recommendations have been limited to the normal state. Corresponding linear plots are also given for those solid elements which have received considerable attention at temperatures above normal. In addition, for each of the liquid and gaseous elements one or more departure plots are included which show the deviations of the available data from the recommended values.

In the figures, the melting point (M.P.), phase transition point (T.P.), superconducting transition point [T.P.(s.c.)], critical temperature (C.T.), Curie temperature, Néel temperature, etc., of the elements have been indicated. Some of these transition points are also mentioned in the text. The inclusion of these transition points is intended to caution the reader against the existence of such transitions so that one must be extremely cautious in attempting to extrapolate the thermal conductivity values across any such transition temperature, since at such temperature the thermal conductivity generally exhibits sharp discontinuities. No attempt has been made to critically evaluate these transition temperatures, and they should not be considered as recommended values. Some of the given values, however, are the defining fixed points or secondary reference points of the International Practical Temperature Scale of 1968 (IPTS–68) such as the indicated melting points of gold, silver, tin, zinc, aluminum, antimony, bismuth, cadmium, cobalt, copper, indium, iridium, lead, mercury, nickel, palladium, platinum, rhodium, and tungsten, and the boiling point of mercury.

In the departure plots for the nonmetallic elements which are liquid or gaseous at N.T.P.,

$$\text{Percent departure} = \frac{\text{Experimental value} - \text{Recommended value}}{\text{Recommended value}} \times 10^2. \quad (16)$$

By the above definition, departures are positive if the experimental data are greater than the recommended values and vice versa.

The tables on specimen characterization and measurement information give for each set of data the following information: the publication reference number, author's name (or names), year of publication, experimental method used for the measurement, temperature range covered by the data, substance name and specimen designation, as well as detailed description and characterization of the specimen and information on measurement conditions that are contained in the original paper. Whenever available, information on the electrical resistivity has also been included. In these tables the code designations used for the experimental methods for thermal conductivity determinations are as follows:

C	Comparative method
E	Direct electrical heating method
F	Forbes' bar method
L	Longitudinal heat flow method
P	Periodic or transient heat flow method
R	Radial heat flow method
T	Thermoelectrical method

For a comprehensive yet concise review of all these methods, the reader is referred to the text in [1421].

In the tables of recommended, provisional, or typical thermal conductivities, the values are presented with uniform but step-increasing increments in temperature as the temperature increases. For those elements which are solid at N.T.P. and for mercury, the values are presented such that temperatures with uniform increments in both kelvin and Celsius are accommodated. In other words, those values given for temperatures 123.2 K, 173.2 K, 223.2 K, 273.2 K, 323.2 K, . . . are for —150° C, —100° C, —50° C, 0° C, 50° C, ... The ".2" has been dropped for temperatures above 3000 K.

In the tables the third and occasionally the fourth significant figure are given for the thermal conductivity values, but this is only for internal comparison and for tabular smoothness and should not be considered indicative of the degree of accuracy. The accuracy of the recommended or provisional values for each element in different temperature ranges is given in the discussion. The asterisked values in the tables are interpolated, extrapolated, or estimated, but more factually they are in the temperature ranges where no experimental data are available. The thermal conductivity is zero at absolute zero temperature, i.e., at the point ($T = 0$, $k = 0$). This is a theoretical consequence based upon the premise that the specific heat is zero at absolute zero temperature according to the third law of thermodynamics.

The compiled 5200 sets of experimental thermal conductivity data were published over a period of 110 years from 1861 to 1970. It is realized that many different temperature scales were used for these data. However, in thermal conductivity measurements, the thermal conductivity values are determined by the measured differences in temperature and not by the absolute magnitude of temperature. Furthermore the thermal conductivity is only a weak function of temperature. Therefore, the effect of using different temperature scales on the reported thermal conductivity values is practically negligible. Consequently, no attempt has been made to convert the original data to a common scale. For the recommended values, the temperatures are based on the IPTS–68.

In the Thirteenth General Conference of Weights and Measures held in October 1967 in Paris, the unit "watt per metre-kelvin" (symbol: W m^{-1} K^{-1}) was adopted as the SI unit for thermal conductivity. In this work, the unit "$W\ cm^{-1}\ K^{-1}$" is used which is a slight modification of the SI unit. Table 1a gives conversion factors which may be used to convert the thermal conductivity values in $W\ cm^{-1}\ K^{-1}$ presented in this work to values in the SI unit or in any of the several other units listed.

For a solid element at moderate and high temperatures the true thermal conductivity values for different well-annealed high-purity (99.99+%) samples at each temperature should be close, and therefore a set of recommended thermal conductivity values can be given for a well-annealed high-purity element. At low temperatures, however, the thermal conductivity values for different samples with small differences in impurity and/or imperfection differ greatly, and a set of recommended or provisional values applies only to a sample with a particular amount of impurity and imperfection. Thus, the low-temperature thermal conductivity of a solid element may be represented by a family (or families, for a non-cubic crystal) of curves, each of which is recommended for a sample of a particular amount of impurity and imperfection, and hence having a particular residual electrical resistivity for a metal, as shown in figure 1. In this work, such a family of recommended curves for specimens with different hypothetical impurities and imperfections has not been generated. Instead, a single, well-defined curve is drawn to link with the recommended curve for moderate and high temperatures so as to complete the functions for the full range of temperature. The recommended low-temperature values in the table, which are for the purest form of each element for which a measurement has been made, are of course only applicable to that particular characterized sample whose residual electrical resistivity has clearly been specified. Consequently, this recommended curve should not be interpreted as a unique function for the low temperature region, but it is only applicable to a sample of specified conditions. For samples with different amounts of impurities and imperfections, i.e., having different residual electrical resistivities for a metallic element, one may similarly derive low-temperature thermal conductivity curves following the same guidelines and procedures as used in this work or may exercise proper selectivity and discretion based on the extensive information reported for each data set in the accompanying table for specimen characterization and measurement information.

As mentioned before, the residual electrical resistivity ρ_0 is used for the characterization of a metallic sample to correspond with the recommended low-temperature thermal conductivity values. At temperatures around 4 K or below, $\rho_0 >> \rho_i$, and hence ρ_0 may be written as

$$\rho_0 = \frac{L_0 T}{k_e}. \tag{17}$$

It is ρ_0 which is determined experimentally as the residual electrical resistivity resulting from electron-defect scattering. If however ρ_0 is calculated from an equation similar to (17) but using a measured value of the thermal conductivity, this value is k and not k_e. Denoting the value so calculated by ρ_0', then

$$\rho_0' = \frac{L_0 T}{k} = \frac{L_0 T}{k_e + k_g} = \frac{\rho_0}{1 + k_g/k_e}. \tag{18}$$

It can be seen from equation (18) that if $k_g \geqq 0$ then $\rho_0' \leqq \rho_0$. This is usually true, and the experimental ρ_0 is then the value given to correspond with the recommended k values.

It happens occasionally, however, that the calculated $\rho_0' > \rho_0$, implying that $k_g < 0$. As negative values for k_g are impossible, the measured ρ_0 is concluded to be in error, and in this case the calculated value ρ_0' has been given as corresponding with the recommended k values.

Regarding those elements which are liquid or gaseous at N.T.P., the provision of recommended values of the thermal conductivity at the critical point takes no account of anomalies in the immediate vicinity of this point. While evidence seems to be accumulating that a rapid increase in thermal conductivity to very large, if not infinite, values does occur in the immediate vicinity of the critical point, the temperature span of any such departure is very short, and in the preparation of the present tables this factor has been disregarded. The values recommended here for the critical point are thus obtained through arbitrary extrapolations of the saturated liquid and vapor curves with no considerations being given to such anomalies. This approach was considered justified by the very meager and indefinite investigations which have been concerned with such an effect. The present approach has been taken so that interpolation of the recommended critical-point values with those tabulated for lower temperatures will enable intermediate temperature values to be obtained which will be accurate except for the small temperature region where anomalies may occur. Furthermore, the values at the critical point are needed for data correlation using the principle of the corresponding states. Likewise, the error estimates refer to possible errors in estimating such values. Should recent studies on anomalies prove to be confirmed, the present values might be regarded as "pseudo-critical" values of thermal conductivities. While the merit of our present approach could be questioned by some, it might be added that the above defined "critical" thermal conductivities have been found to give consistent values when comparing "critical" thermal conductivities of families of substances. At the present time, similar treatments of "true" critical values present serious difficulties.

The recommended values for the various gases, which cover very wide ranges of temperature, are only for a pressure of one atmosphere. The pressure dependence of thermal conductivity is not yet included in this work.

TABLE 1a. Conversion factors for units of thermal conductivity

MULTIPLY ↓ by appropriate factor to OBTAIN→	$Btu_{IT}\ h^{-1}\ ft^{-1}\ F^{-1}$	Btu_{IT} in. $h^{-1}\ ft^{-2}\ F^{-1}$	$Btu_{th}\ h^{-1}\ ft^{-1}\ F^{-1}$	Btu_{th} in. $h^{-1}\ ft^{-2}\ F^{-1}$	$cal_{IT}\ s^{-1}\ cm^{-1}\ C^{-1}$	$cal_{th}\ s^{-1}\ cm^{-1}\ C^{-1}$	$kcal_{th}\ h^{-1}\ m^{-1}\ C^{-1}$	$J\ s^{-1}\ cm^{-1}\ K^{-1}$	$W\ cm^{-1}\ K^{-1}$	$W\ m^{-1}\ K^{-1}$	$mW\ cm^{-1}\ K^{-1}$
$Btu_{IT}\ h^{-1}\ ft^{-1}\ F^{-1}$	1	12	1.00067	12.0080	4.13379×10^{-3}	4.13656×10^{-3}	1.48916	1.73073×10^{-2}	1.73073×10^{-2}	1.73073	17.3073
Btu_{IT} in. $h^{-1}\ ft^{-2}\ F^{-1}$	8.33333×10^{-2}	1	8.33891×10^{-2}	1.00067	3.44482×10^{-4}	3.44713×10^{-4}	0.124097	1.44228×10^{-3}	1.44228×10^{-3}	0.144228	1.44228
$Btu_{th}\ h^{-1}\ ft^{-1}\ F^{-1}$	0.999331	11.9920	1	12	4.13102×10^{-3}	4.13379×10^{-3}	1.48816	1.72958×10^{-2}	1.72958×10^{-2}	1.72958	17.2958
Btu_{th} in. $h^{-1}\ ft^{-2}\ F^{-1}$	8.32776×10^{-2}	0.999331	8.33333×10^{-2}	1	3.44252×10^{-4}	3.44482×10^{-4}	0.124014	1.44131×10^{-3}	1.44131×10^{-3}	0.144131	1.44131
$cal_{IT}\ s^{-1}\ cm^{-1}\ C^{-1}$	2.41909×10^{2}	2.90291×10^{3}	2.42071×10^{2}	2.90485×10^{3}	1	1.00067	3.60241×10^{2}	4.1868	4.1868	4.1868×10^{2}	4.1868×10^{-3}
$cal_{th}\ s^{-1}\ cm^{-1}\ C^{-1}$	2.41747×10^{2}	2.90096×10^{3}	2.41909×10^{2}	2.90291×10^{3}	0.999331	1	3.6×10^{2}	4.184	4.184	4.184×10^{2}	4.184×10^{-3}
$kcal_{th}\ h^{-1}\ m^{-1}\ C^{-1}$	0.671520	8.05824	0.671969	8.06363	2.77592×10^{-3}	2.77778×10^{-3}	1	1.16222×10^{-2}	1.16222×10^{-2}	1.16222	11.6222
$J\ s^{-1}\ cm^{-1}\ K^{-1}$	57.7789	6.93347×10^{2}	57.8176	6.93811×10^{2}	0.238846	0.239006	86.0421	1	1	1×10^{2}	1×10^{3}
$W\ cm^{-1}\ K^{-1}$	57.7789	6.93347×10^{2}	57.8176	6.93811×10^{2}	0.238846	0.239006	86.0421	1	1	1×10^{2}	1×10^{3}
$W\ m^{-1}\ K^{-1}$	0.577789	6.93347	0.578176	6.93811	2.38846×10^{-3}	2.39006×10^{-3}	0.860421	1×10^{-2}	1×10^{-2}	1	10
$mW\ cm^{-1}\ K^{-1}$	5.77789×10^{-2}	0.693347	5.78176×10^{-2}	0.693811	2.38846×10^{-4}	2.39006×10^{-4}	8.60421×10^{-2}	1×10^{-3}	1×10^{-3}	0.1	1

4. Thermal Conductivity of the Elements

Actinium

No information is available for the thermal or electrical conductivity of actinium. However, very rough estimation of its room-temperature thermal conductivity may be made on the basis of similarities between actinium and the other elements of the same group. The thermal conductivity values at 300 K of the other three members scandium, yttrium, and lanthanum of Group III B are 0.158, 0.172, and 0.135 W cm^{-1} K^{-1}, respectively. The extrapolation to atomic number 89 of a curve fitted to these points plotted in a large working graph of thermal conductivity versus atomic number similar to figure 15 gives a value of 0.115 W cm^{-1} K^{-1} for actinium at 300 K. This derived value is probably good to ± 50 percent.

Aluminum

There are 111 sets of data available for the thermal conductivity of aluminum as listed in table 3 and shown partly in figures 16, 17, and 17a.

At low temperatures, most of the thermal conductivity maxima conform well to a straight line (in a log-log graph) for which the slope is —2.62, and most of the experimental data at temperatures below 1.5 T_m can be fitted by equation (7) using constants $m = 2.62$, $n = 2.00$, $a'' = 4.79 \times 10^{-6}$ as given in table 1 and using appropriate values for the parameter β.

The heavy curve shown in figure 16 for which the calculated ρ_0 equals 0.000594 $\mu\Omega$ cm and $\beta = 0.0243$ fits the data of Fenton, Rogers, and Woods [425] (curve 64), whose experimental ρ_0 of 0.000568 $\mu\Omega$ cm gives an experimental L of 2.337×10^{-8} V^2 K^{-2} which is 4.3 percent below the theoretical value. Therefore $\rho_0 = 0.000594$ $\mu\Omega$ cm (instead of 0.000568 $\mu\Omega$ cm) is used to correspond to this recommended curve.

To derive recommended values at higher temperatures, the curve which fits the data of Fenton, et al. [425] (curve 64) to their upper limit of 25 K continues to decrease smoothly towards the data of Powers, Schwartz, and Johnston [1154] (curve 1) at a little above 100 K. It continues in an intermediate position between their data and the lower curve of Flynn [446] (curve 110) and, after a minimum at about 240 K, rises to a gentle maximum around 360 K. Through weight given to the recent determinations by Duggin [372] (curves 106 and 107) the recommended curve to the melting point has been lowered by about 1 percent at 800 K from TPRC's earlier recommendation [1126], and now lies above the data of Duggin [372] and Flynn [446] and below those of Powell, Tye, and Woodman [1143] (curves 48 and 49).

It is interesting to note that it was not until the publication of the data of Powell, Tye, and Woodman [1143] (curve 50), which show a pronounced minimum of thermal conductivity in the subnormal-temperature region, that the existence of such a minimum was fully recognized. Although theoretical investigations of the electronic thermal conductivity of metals by Bloch [169a], Wilson [1568, 1569], Makinson [875], Kroll [789a], Umeda and Yamamoto [1448a], and Sondheimer [1342a–1342c] all indicate a minimum in the theoretical curve of thermal conductivity, which occurs at a temperature around $\theta/4$, where θ is the Debye temperature, it has often been stated that such a minimum has never been observed experimentally [see, e.g., 719a, 1612b, 287a]. On the premise of nonexistence of such a minimum of thermal conductivity, several subsequent theoretical investigations have been devoted to the elimination of this minimum from the theoretical curve. Thus, by modifying Bloch theory in his recalculations, Ziman [1612a] has greatly reduced the dip in the theoretical conductivity curve to about 9 percent from Bloch's original 40 percent of the high-temperature limiting value, and furthermore the minimum is shifted to a higher temperature of between 0.4 θ and 0.5 θ. He was disappointed with the remaining "discrepancy" that the conductivity minimum was not entirely eliminated, though, he said, he was working in the right direction to remove it. Collins and Ziman [287a] have pursued this idea further and their results show that with sufficient increase in the proportion of electron-phonon Umklapp scattering to normal scattering in their model used, the minimum eventually disappears. Klemens [770a] has modified Sondheimer's method by solving the Bloch equation numerically. He obtained a shallower minimum, around which his result for thermal conductivity exceeds Sondheimer's by 11 percent. A further modification of Sondheimer's method was made by Kasuya [719a]. His result is, in turn, about 20 percent greater than that of Klemens, and shows that the conductivity minimum is completely removed.

In spite of the efforts which successfully remove the minimum from the theoretical thermal conductivity curve, such a minimum exists in reality. In fact, long before the publication of the data of Powell, et al. [1143], Lees [830] has reported a thermal conductivity minimum for a sample of 99 percent aluminum (curve 108) more than half a century ago, and the thermal conductivity curve of Powers, Ziegler, and Johnston [1156] (curve 109) published in 1951 for an aluminum alloy with 98.17 percent Al (by difference) has also a minimum; both appear to have been overlooked. Subsequent to the publication by Powell, et al., the thermal conductivity minimum for aluminum has been reported by Flynn [446] (curve 110) and by Moore, McElroy, and Barisoni [987] (curve 81). All the conductivity minima occur at different temperatures, ranging from about 0.35 θ to 0.6 θ, and indicate a general trend that the lower the conductivity minimum, the lower is the corresponding temperature. The present recommended curve shows a minimum at about 240 K, which is about 0.62 θ ($\theta = 390$ K for aluminum at room temperature).

It should be pointed out that most of the theories mentioned above have been developed for monovalent metals, to which aluminum does, of course, not belong. However, a minimum does exist also in the thermal conductivity of sodium, a monovalent metal whose earlier experimental thermal conductivity has often been compared with theory and has ironically been the basis for the assumption of nonexistence of the conductivity minimum.

The few experimental values for the thermal conductivity of molten aluminum differ considerably. Only Powell, Tye, and Metcalf [1140] (curve 51) included measurements of the electrical conductivity, and it is interesting to note that their values of the Lorenz function are close to the theoretical value, being respectively only about 0.5 percent and 1.5 percent lower at 973 and 1223 K. Mention of this is made because Grosse [546] has assumed the theoretical value of the Lorenz function to hold from the melting point to the critical point when deriving values for the thermal conductivity of aluminum over the entire liquid range (curve 111).

The electrical conductivity values assumed by Grosse [546] for liquid aluminum near the melting point were those of Roll and Motz [1217]. These values were some 6 percent higher than those of Powell, et al. [1140] which accounts for much of the difference between the two almost parallel thermal conductivity curves. The present recommended curve is the heavy and partly short-dashed line shown between them in figure 17a, but biased toward the experimentally determined thermal conductivity values. At about 950 K this line passes close to the values of Konno [778] (curve 13) which are the first such measurements made on liquid aluminum.

These recommended values indicate that on passing from the solid to the liquid state the thermal conductivity of aluminum decreases by a factor of about 2.3.

An observation regarding the effect of heat treatment on the electrical conductivity of molten aluminum was reported by Kononenko, Yatsenko, Rubinshtein, and Privalov [779], who found that preheating to 1300 K for one hour in vacuum led to lower resistivity values. They believed that oxides became partially dissociated and rose to the surface of the melt. Following this treatment their electrical resistivity values at 973 and 1273 K were respectively 7 and 7.6 percent less than those of Powell, et al. [1140], whose electrical resistivity determinations have been made in air, whereas their thermal conductivity values were determined under vacuum conditions, but without any preheating.

The findings of Kononenko, et al. [779] suggest that further measurements on molten aluminum are required for both thermal and electrical conductivities.

The recommended values for the solid are thought to be accurate to within $\pm$ 5 percent below room temperature and ± 2 to ± 3 percent above. The values below 150 K are applicable only to aluminum having residual electrical resistivity of 0.000594 $\mu\Omega$ cm. For liquid aluminum near the melting point the values are probably good to within ± 8 percent. Above 1273 K the values are provisional.

TABLE 2. Recommended thermal conductivity of aluminum†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	k	T	k	T	k	T	k
0	0	60	8.50	933.52	0.907*	2673.2	1.15*
1	41.1	70	5.85	973.2	0.921	2800	1.14*
2	81.8	80	4.32	1000	0.930	2873.2	1.13*
3	121	90	3.42	1073.2	0.955	3000	1.13*
4	157	100	3.02	1100	0.964	3073	1.12*
5	188	123.2	2.62	1173.2	0.986	3200	1.11*
6	213	150	2.48	1200	0.994	3273	1.10*
7	229	173.2	2.41	1273.2	1.01	3400	1.09*
8	237	200	2.37	1300	1.02*	3473	1.07*
9	239	223.2	2.35	1373.2	1.04*	3600	1.05*
10	235	250	2.35	1400	1.05*	3673	1.05*
11	226	273.2	2.36	1473.2	1.07*	3800	1.03*
12	214	298.2	2.37	1500	1.07*	3873	1.02*
13	201	300	2.37	1573.2	1.08*	4000	0.997*
14	189	323.2	2.39	1600	1.09*	4073	0.986*
15	176	350	2.40	1673.2	1.10*	4273	0.952*
16	163	373.2	2.40	1700	1.11*	4500	0.912*
18	138	400	2.40	1773.2	1.11*	4773	0.861*
20	117	473.2	2.37	1800	1.12*	5000	0.818*
25	75.2	500	2.36	1873.2	1.13*	5273	0.764*
30	49.5	573.2	2.33	1900	1.13*	5500	0.719*
35	33.8	600	2.31	1973.2	1.14*	5773	0.662*
40	24.0	673.2	2.26	2000	1.14*	6000	0.614*
45	17.7	700	2.25	2073.2	1.14*	6273	0.555*
50	13.5	773.2	2.19	2173.2	1.15*	6500	0.505*
		800	2.18	2200	1.15*	6773	0.444*
		873.2	2.12	2273.2	1.15*	7000	0.392*
		900	2.10	2400	1.15*	7273	0.329*
		933.52	2.08	2473.2	1.15*	7500	0.275*
				2600	1.15*	7773	0.210*
						8000	0.156*
						8273	0.0915*
						8500	0.0365*

†The recommended values are for well-annealed high-purity aluminum, and those below 150 K are applicable only to a specimen having residual electrical resistivity of 0.000594 $\mu\Omega$ cm. Above 1273 K the values are provisional.

*Estimated or extrapolated.

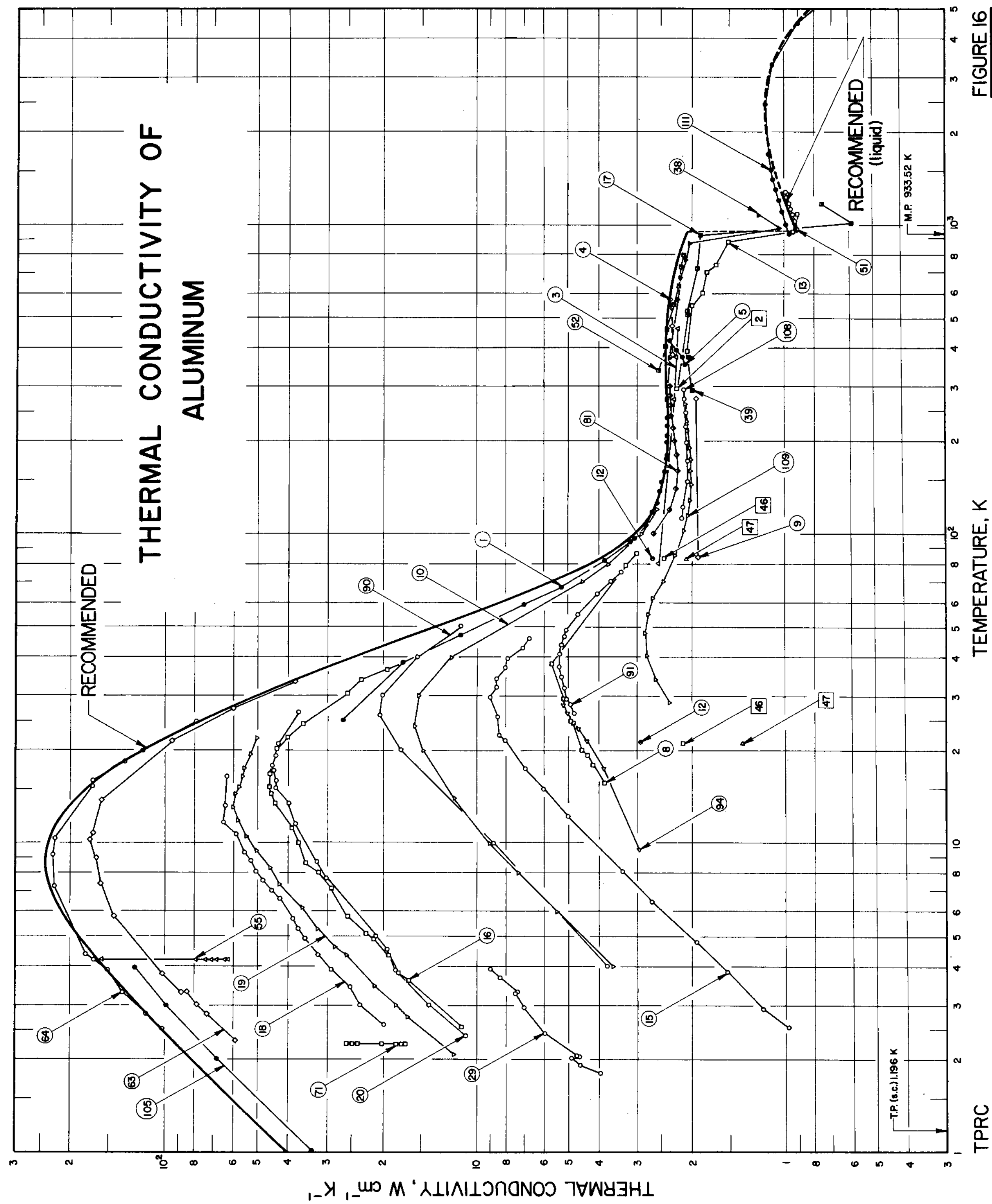

THERMAL CONDUCTIVITY OF ALUMINUM
RECOMMENDED
RECOMMENDED (liquid)
M.P. 933.52 K
T.P. (s.c.) 1.196 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 16

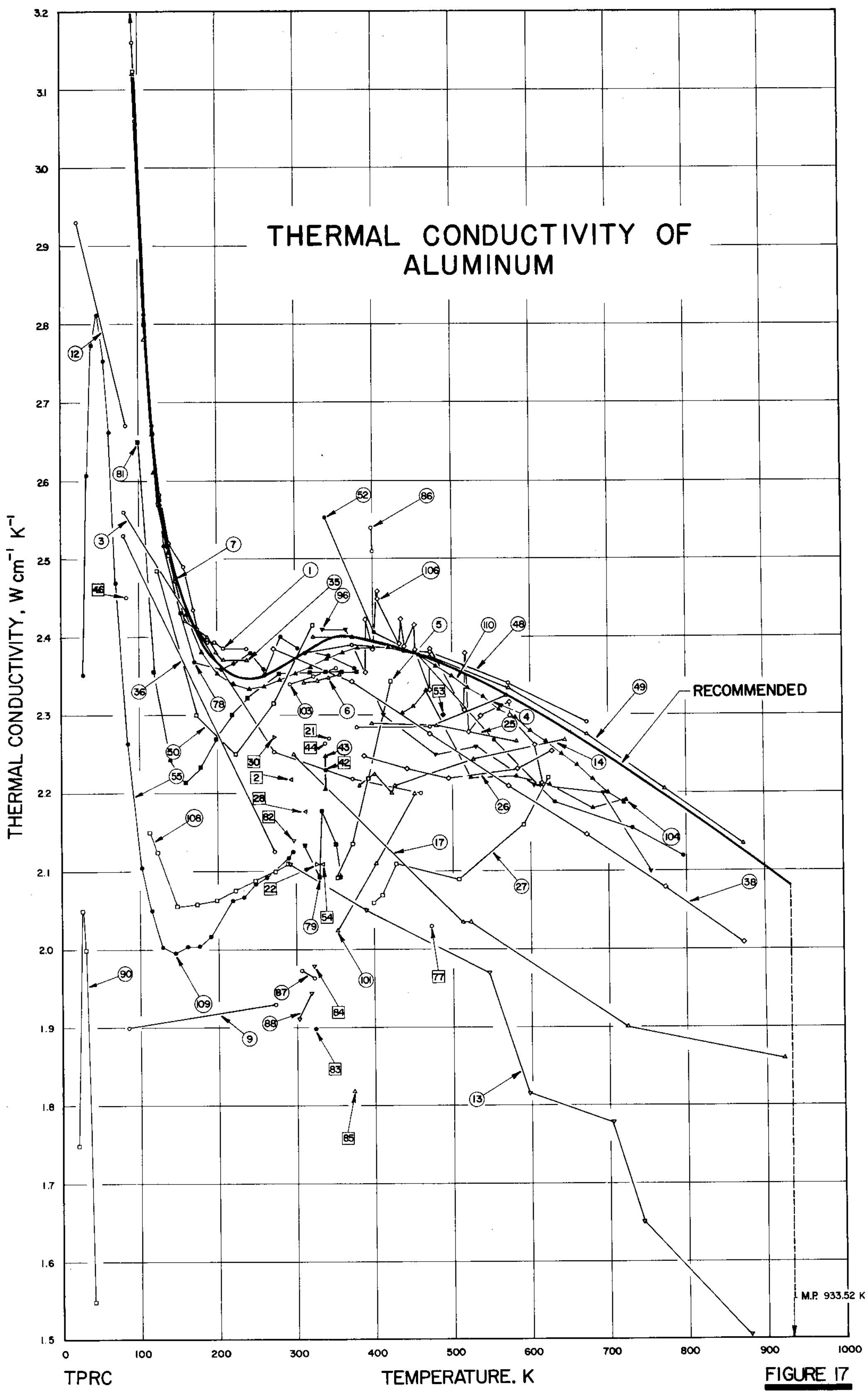

THERMAL CONDUCTIVITY OF ALUMINUM
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
RECOMMENDED
M.P. 933.52 K
TPRC

FIGURE 17

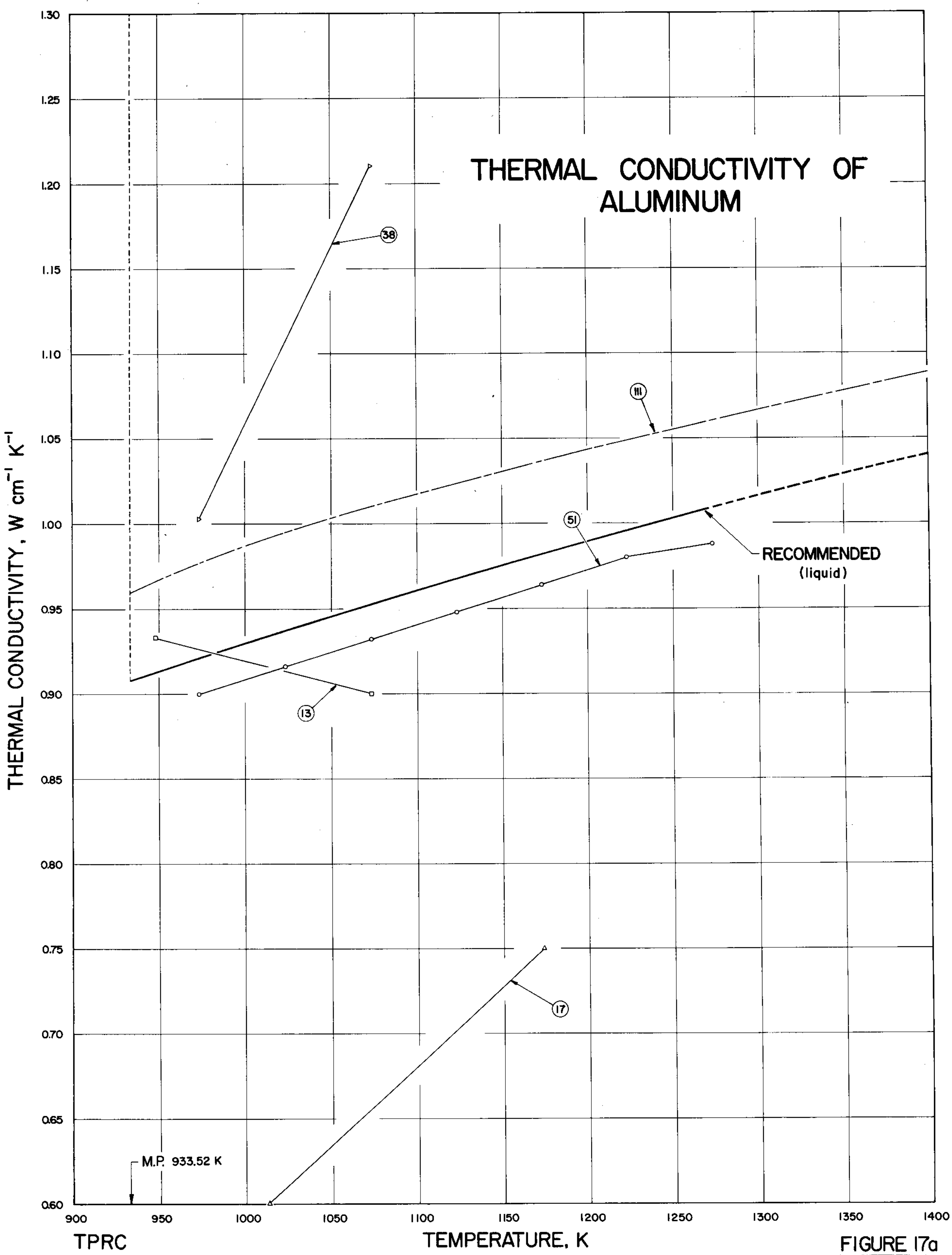

THERMAL CONDUCTIVITY OF ALUMINUM
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
TEMPERATURE, K
M.P. 933.52 K
RECOMMENDED
(liquid)
38
111
51
13
17
TPRC

FIGURE 17a

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1154	Powers, R.W., Schwartz, D., and Johnston, H.L.	1950	L	25-238		99.99⁺ pure; 0.5 in. dia x 20 in. long; supplied by Aluminum Co. of America; cold-drawn with 55% reduction in dia; measured in a vacuum of $<10^{-6}$ mm Hg.
2	1067	Parker, W.J., Jenkins, R.J., Butler, C.P. and Abbott, G.L.	1961	P	295.2		Pure; 1.9 x 1.9 x 0.352 cm; thermal conductivity value calculated from measured data of thermal diffusivity and heat capacity and the density value taken from Smithsonian Physical Tables (9th ed., 1954).
3	1358, 880	Staebler, J. Mannchen, W.	1929	L	80-460		Pure; electrical resistivity reported as 0.725, 2.700, 3.922, and 5.160 μohm cm at 89, 273, 374, and 476 K, respectively.
4	222	Bungardt, W. and Kallenbach, R.	1951	L	379-570		99.92 Al, 0.04 Si, 0.03 Fe, 0.006 Cu, and 0.005 Ti; annealed at 450 C.
5	524	Grand, C. and Villey, J.	1927	E	353-423		High purity.
6	176	Bode, K.H. and Fritz, W.	1958	L	311-357		99.986 Al, 0.0062 Si, 0.0045 Fe, 0.003 Cu and 0.0001 Mg; 50 mm dia x 70 mm high; manufactured by Metallgesellschaft AG; density 2.691 g cm^{-3} at 20 C.
7	687	Johnston, H.L.	1948	C	94-147		99.99⁺ pure; supplied by Aluminum Co. of America; aluminum used as comparative material.
8	345	deNobel, J.	1951	L	16-87		High purity; as rolled; measured in a vacuum of $<5 \times 10^{-6}$ mm Hg.
9	1268	Schott, R.	1916	L	85, 273		Commercial aluminum; 0.5 cm dia x 5 cm long; measured in vacuum.
10	1100, 582	Hall, W.J., Powell, R.L., and Roder, H.M.	1957	L	4.0-120	JM 340	99.995 pure; single crystal; specimen axis inclined 6°, 40°, and 50° to [001], [011], and [111] direction, respectively; a rod of dia 3.68 mm made by Horizons Inc.; ground down to 3.66 mm in dia, then annealed in vacuum at ~400 C for two hrs; electrical resistivity from graph 0.025, 0.026, 0.028, 0.065, 0.45, and 2.7 μohm cm at 4, 10, 20, 40, 100, and 300 K, respectively.
11*	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Al-1	Pure; 7 cm long bar specimen obtained from Aluminum Co. of America; annealed in vacuo at 300 C for 2.5 hrs; electrical resistivity reported as 0.0188, 0.3065, and 2.50 μohm cm at -252, -190, and 0 C, respectively.
12	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Al-100	Commercial aluminum; annealed in vacuo at 250 C; electrical resistivity reported as 0.1577, 0.458, and 2.65 μohm cm at -252, -190, and 0 C, respectively.
13	778	Konno, S.	1919	L	389-1073		Pure.
14	1267	Schofield, F.H.	1925	L	382-645		99.7 pure; supplied by British Aluminium Co., Ltd; billets 6.75 in. in dia cast from a maximum temp of 700 C, annealed at 500 C for 2.5 hrs, extruded at 420 C to 0.75 in. dia, then annealed at 450 C for 2.5 hrs; density 2.70 g cm^{-3} at 21 C; electrical resistivity reported as 2.83, 2.79, 2.81, 3.45, 3.53, 3.53, 4.47, 4.48, 6.15, 6.23, 6.24, 7.39, 8.77, 8.79, and 9.31 μohm cm at 16.2, 16.8, 16.8, 73.0, 77.0, 79.0, 160.0, 161.0, 302.7, 304.4, 306.2, 399.0, 500.0, 502.4, and 540.7 C, respectively.
15	937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.5-46	JM-4899	99.994 pure; polycrystalline; 1~2 mm dia x 5 cm long; supplied by Johnson-Matthey and Co., Ltd; annealed; $\rho(293K)/\rho(20K) = 279$.
16	1220	Rosenberg, H.M.	1955	L	2.6-42	JM-4899	99.994 pure; polycrystalline; 0.394 mm dia x 2.97 cm long; supplied by Johnson-Matthey Co.; annealed in vacuum at 600 C for several hrs, electrical resistivity ratio $\rho(293K)/\rho(20K) = 279$.
17	160	Bidwell, C.C. and Hogan, C.L.	1947	F	298-1173	Al-1	99.95 pure; 2.5 cm dia x 25 cm long.

* Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	70	Andrews, F.A., Webber, R.T., and Spohr, D.A.	1951	L	2.6-17	Al-1	99.996⁺ Al, 0.001 Mg, 0.001 Si, 0.0006 Fe, 0.0004 Cu, and 0.0004 Na; single crystal; 0.15 in. dia x 4 in. long supplied by Aluminum Co. of America; residual electrical resistivity ρ_r = 0.00304 µohm cm; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 840.
19	70	Andrews, F.A. et al.	1951	L	2.1-22	Al-2	Similar to the above specimen except ρ_r = 0.00385 µohm cm and $\rho(273K)/\rho(4.2K)$ = 676.
20	70	Andrews, F.A. et al.	1951	L	2.4-27	Al-3	99.995⁺ Al, 0.002 Mg, 0.001 Si, traces of Fe, Cu, and Na; polycrystal; same dimensions and supplier as the above specimen; ρ_r = 0.00551 µohm cm; $\rho(273K)/\rho(4.2K)$ = 467.
21	1524, 1525	Weeks, J.L. and Seifert, R.L.	1952	C	343.2	2S-Al	Rod specimen 1.75 in. long; density 2.7 g cm^{-3}; Armco iron used as comparative material.
22	1327	Smith, A.W.	1925	L	326		99.97⁺ pure; 1.9 cm dia x 10 cm long; electrical conductivity 33.8 x 10^4 ohm^{-1} cm^{-1} at 23 C.
23*	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.36-0.81	Al-2	Polycrystalline; in superconducting state.
24*	69	Andrews, F.A., Webber, R.T., and Spohr, D.A.	1950	L	2.6-16		99.996⁺ pure; single crystal; supplied by Aluminum Co. of America; machined and then etched; crystal slightly damaged by machining.
25	591	Hase, R., Heierberg, R., and Walkenhorst, W.	1940	E	398-583		99.992 Al, 0.0030 Fe, 0.0027 Si, and 0.0024 Cu; cast at 700 C in a mold and cooled to 200 C, rolled to 15 mm dia, drawn to 12.5 mm dia, then reduced to 6.5 mm dia.
26	591	Hase, R., et al.	1940	E	388-628		99.93 Al, 0.038 Fe, 0.03 Si, and 0.0022 Cu; same fabrication method as above.
27	591	Hase, R., et al.	1940	E	399-623		99.5 Al, impurities unknown; same fabrication method as above.
28	1463	Van Dusen, M.S.	1922	C	313.2		99.7 pure; cylindrical specimen of 3 cm long; zinc used as comparative material.
29	640	Howling, D.H., Mendoza, E., and Zimmerman, J.E.	1955	L	1.8-3.9		99.998 pure; 2.00 mm dia x 9.88 cm long; annealed in vacuo for 5 hrs at 500 C.
30	407	Eucken, A. and Warrentrup, H.	1935	R	273.2	Al-1	99.7 pure; electrical conductivity 37.10 x 10^4 ohm^{-1} cm^{-1} at 0 C.
31*	1599	Zavaritskii, N.V.	1958	L	0.13-1.3	Al-1	0.01 impurity; with large crystals; annealed in vacuum for 4 hrs at about 600 C; measured in a magnetic field of 0.2 oersted; in superconducting state.
32*	1599	Zavaritskii, N.V.	1958	L	0.44-1.2	Al-1	The above specimen in normal state; measured in a longitudinal magnetic field of 115 oersted.
33*	1599	Zavaritskii, N.V.	1958	L	0.16-1.2	Al-2	Same specifications as the above specimen Al-1; in superconducting state.
34*	1599	Zavaritskii, N.V.	1958	L	0.21-1.2	Al-2	The above specimen in normal state.
35	1153	Powers, R.W. and Schwartz, D.	1949	L	38-238		99.99⁺ pure; 0.5 in. rod specimen; supplied by Aluminum Co. of America; cold drawn.
36	77	Aoyama, S. and Ito, T.	1940	C	80, 273		Pure; 4.00 mm dia x 60.0 mm long.
37*	688	Johnston, H.L.	1949	L	25-82		99.99⁺ pure; supplied by Aluminum Co. of America; cold drawn.
38	615	Hogan, C.L.	1950	F	273-1073		99.996 pure; tube specimen 12 in. long with a bore of 0.25 in.; manufactured from Norton's RA 98 material.

* Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
39	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373		99 Al, 0.48 Fe, and 0.36 Cu; 1.2068 cm dia x 26.9 cm long; density 2.71 g cm^{-3} at 18 C; electrical conductivity 31.6 and 24.3 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
40*	939	Mendelssohn, K., Sharma, J.K., and Yoshida, K.	1965	L	0.45-0.97		Pure aluminum wire; in normal state.
41*	939	Mendelssohn, K., et al.	1965	L	0.43-0.96		The above specimen measured in superconducting state.
42	695	Jones, T.I., Street, K.N., Scoberg, J.A., and Baird, J.	1963	C	338.2		0.15 U; 0.500 in. dia x 3 in. long; prepared by dissolution of reactor grade uranium (99.5$^+$ pure) in aluminum (99.99 pure) at ~100 C above the alloy liquidus temperatures, cast in a graphite mold at 100 C, machined to required dimensions; measured in a vacuum of <5 x 10^{-4} mm Hg; copper used as comparative material.
43	695	Jones, T.I., et al.	1963	C	338.2		Similar to above except specimen heat treated at 620 C for 5 days.
44	695	Jones, T.I., et al.	1963	C	338.2		99.99 pure; extruded.
45*	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Al-3	From the same cast piece as Al-1 (curve 11); drawn and annealed, 2.5% stretched, recrystallized by annealing; grain size 5 to 15 mm long; electrical resistivity reported as 0.0351, 0.319, and 2.52 μohm cm at -252, -190, and 0 C, respectively.
46	559	Grüeisen, E. and Goens, E.	1927	L	21,83	Al-101	Same material as Al-100 (curve 12); tempered then 3% stretched, recrystallized by annealing; thermal conductivity measuring length = 2 crystal grains; electrical resistivity reported as 0.219, 0.525, and 2.72 μohm cm at -252, -190, and 0 C, respectively.
47	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Al-21	Moderately pure; single crystal; grown by recrystallization; electrical resistivity reported as 0.340, 0.663, and 2.84 μohm cm at -252, -190, and 0 C, respectively.
48	1143	Powell, R.W., Tye, R.P., and Woodman, M.J.	1965	C	313-673	S.P.	S.P. (super pure) aluminum rod from British Aluminium Co.; specimen 2.53 cm in dia and 20.4 cm long; electrical resistivity reported as 2.86 and 7.12 ohm cm at 40 and 400 C, respectively; Armco iron used as comparative material.
49	1143	Powell, R.W., et al.	1965	L	323-873	S.P.	S.P. (super pure) aluminum; 99.993 pure; from British Aluminium Co.; specimen 2.81 cm in dia and 28.0 cm long; electrical resistivity reported as 2.98 and 9.92 μohm cm at 50 and 600 C, respectively.
50	1143	Powell, R.W., et al.	1965	L	123-323	S.P.	S.P. (super pure) aluminum from British Aluminium Co.; specimen 8.0 x 0.44 x 0.44 cm; electrical resistivity reported as 0.74 and 3.02 μohm cm at -150 and 50 C, respectively.
51	1140	Powell, R.W., Tye, R.P., and Metcalf, S.C.	1965	C	973-1273	S.P.	S.P. (super pure) aluminum from British Aluminium Co.; in molten state; electrical resistivity reported as 26.3 and 30.9 μohm cm at 700 and 1000 C, respectively; Morgan Crucible Co. grade EY9 graphite used as comparative material.
52	964, 966	Mikryukov, V.E.	1957	E	333-797		99.99 pure; polycrystal; electrical resistivity reported as 3.15, 4.65, 6.82, and 9.41 μohm cm at 64.8, 184, 357.8, and 523.4 C, respectively; Lorenz function reported as 2.34, 2.40, 2.39, and 2.41 x 10^{-8} V^2 K^{-2} at 64.8, 184, 357.8, and 523.4 C, respectively.
53	850	Ling-Temco-Vought, Inc.	1964	C	490.1		Aluminum chips obtained from ALCOA; 26.65 cm^2 x 0.62 cm thick; copper used as comparative material.

*Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54	120	Batalov, V.S. and Peletskii, V.E.	1968	P	331.7		Specimen 10 cm long; measured in a vacuum of ~10^{-3} torr; thermal conductivity value calculated from thermal diffusivity measurement.
55	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 1	80 x 5 x 0.066 mm; made from a zone-refined material, cold rolled and then annealed in air for 24 hrs at 480-500 C; electrical resistivity reported as 0.000538 μohm cm at 4.2 K; measured in magnetic fields of strength ranging from 0.94 to 12.8 kOe perpendicular to the specimen surface.
56*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 1	The above specimen measured in transverse co-planar magnetic fields of strength ranging from 0 to 13.0 kOe.
57*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 2	80 x 5 x 0.035 mm; same source and fabrication method as the above specimen; electrical resistivity reported as 0.00103 μohm cm at 4.2 K; measured in magnetic fields of strength ranging from 0 to 12.7 kOe perpendicular to the specimen surface.
58*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 2	The above specimen measured in transverse co-planar magnetic fields of strength ranging from 0 to 12.8 kOe.
59*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 3	80 x 5 x 0.129 mm; same source and fabricating method as the above specimen; electrical resistivity reported as 0.000402 μohm cm at 4.2 K; measured in magnetic fields of strength ranging from 0 to 10.7 kOe perpendicular to the specimen surface.
60*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 3	The above specimen measured in transverse co-planar magnetic fields of strength ranging from 0 to 5.98 kOe.
61*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 4	80 x 5 x 0.081 mm; same source and fabrication method as the above specimen; electrical resistivity reported as 0.000505 μohm cm at 4.2 K; measured in magnetic fields of strength ranging from 0 to 13.2 kOe perpendicular to the specimen surface.
62*	62	Amundsen, T. and Olsen, T.	1965	L	4.2	Sp 4	The above specimen measured in transverse co-planar magnetic fields of strength ranging from 0 to 10.3 kOe.
63	425	Fenton, E.W., Rogers, J.S., and Woods, S.B.	1963	L	2-33	Al_3	99.9999 pure; specimen made from zone-refined Al, 0.125 in. in dia and about 6 cm long; supplied by Consolidated Mining and Smelting Co. of Canada; drawn and etched; residual electrical resistivity ρ_0 0.000903 μohm cm.
64	425	Fenton, E.W., et al.	1963	L	3-25	Al_6	Similar to the above specimen except ρ_0 0.000568 μohm cm.
65*	1382	Swift, D.L.	1966	P	298.2		Grained ingot supplied by Alcoa Aluminum Co.; mesh size -30 +45; specimen contained in a 0.75 in. dia x 2 in. long stainless steel cylindrical cell; thermal conductivity measured by using the transient line source method; measured in argon under a pressure of ~100 psig.
66*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in nitrogen under a pressure of ~100 psig.
67*	1299	Sharma, J.K.N.	1967	L	0.44-0.96		99.999 pure; polycrystalline; specimen 1 mm in dia and 70 cm long; prepared by Mr. A.T. Thomas of Aluminium Laboratories Ltd, Banbury; form factor $(\ell/a) = 8.42 \times 10^3$ cm^{-1}; electrical resistivity 4.28×10^{-9} ohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 664$; measured in magnetic field of 200 G; in normal state; run No. 28.

* Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
68*	1299	Sharma, J. K. N.	1967	L	0.44-0.95		The above specimen measured in superconducting state; run No. 28.
69*	1299	Sharma, J. K. N.	1967	L	0.45-0.94		The above specimen measured in magnetic field of 200 G; in normal state; run No. 27.
70*	1299	Sharma, J. K. N.	1967	L	0.42-0.95		The above specimen measured in superconducting state; run No. 27.
71	61	Amundsen, T. and Olsen, T.	1963	L	2.3		Film specimen of 0.04 mm thick and 5 mm in width; measured in magnetic fields perpendicular to the plane of the film ranging from 0.29 to 12.90 kilogauss.
72*	61	Amundsen, T. and Olsen, T.	1963	L	3.5		The above specimen measured in perpendicular magnetic fields ranging from 0.04 to 13.26 kilogauss.
73*	61	Amundsen, T. and Olsen, T.	1963	L	4.7		The above specimen measured in perpendicular magnetic fields ranging from 0.03 to 13.13 kilogauss.
74*	61	Amundsen, T. and Olsen, T.	1963	L	2.3		The above specimen measured in magnetic fields parallel to the plane of the film ranging from 0.45 to 13.59 kilogauss.
75*	61	Amundsen, T. and Olsen, T.	1963	L	3.5		The above specimen measured in parallel magnetic fields ranging from 0.18 to 13.11 kilogauss.
76*	61	Amundsen, T. and Olsen, T.	1963	L	4.7		The above specimen measured in parallel magnetic fields ranging from 0.10 to 13.02 kilogauss.
77	972	Miller, V. S.	1960		473.2		No details reported.
78	1558, 1557	Wilkes, K. E. and Powell, R. W.	1967	L	88-379		99.99989 Al, 0.00005 Cu, 0.00005 Si, and 0.00001 Mg; 1.226 cm dia x 10.16 cm long; obtained from Aremco Products, Inc; as received; density 2.700 g cm^{-3} at 23 C; electrical resistivity reported as 0.2257, 1.554, 2.450, and 2.724 μohm cm at 77.78, 194.6, 273.2, and 298.5 K, respectively; Lorenz function reported as 1.841, 1.906, 2.182, and 2.204 x 10^{-8} V^2 K^{-2} at 183.6, 200, 300, and 297.5 K, respectively; measured in a vacuum of 5 x 10^{-6} torr.
79	110	Bakish, R., Fenster, S. K., and Kambouroglou, A.	1968	L	321-357		Anisotropic Al; specially fabricated to have a "fibrous" structure; heat flow in longitudinal direction.
80*	110	Bakish, R., et al.	1968	L	342-382		Anisotropic Al; specially fabricated to have a "fibrous" structure; heat flow in transverse direction.
81	987	Moore, J. P., McElroy, D. L., and Barisoni, M.	1966	L	100-380		99.999 pure; cylindrical specimen machined from a stock obtained from Reynolds Aluminum Co.; electrical resistivity 0.441, 0.668, 0.901, 1.133, 1.367, 1.599, 1.830, 2.062, 2.292, 2.522, 2.751, 2.982, 3.211, and 3.443 μohm cm at 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, and 360 K, respectively; $\rho(273K)/\rho(4.2K) \sim 520$. (Revised thermal conductivity data obtained from the authors in a private communication.)
82	1416	Todd, G. W.	1927	C	298.2		7.96 mm dia rod; copper used as comparative material; thermal conductivity obtained by comparing thermal expansion of the materials. (Measuring temperature assumed 25 C.)
83	1324	Smart, D.	1960	P	323.2		2.9 cm dia x 11.4 cm long; measured by a transient method.
84	1324	Smart, D.	1960	C	373.2		2.9 cm dia x 15.2 cm long; measured by a transient method.

* Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
85	321	Day, R. K.	1965	C	373.2		Commercial purity; 0.5 in. dia x 0.5 in. thick; copper used as comparative material.
86	299	Costas, L. P.	1960	L	399, 400		99.9$^+$ pure; 1 in. dia x 2 in. long.
87	464	Fritz, W. and Bode, K.-H.	1960	C	307-321		Commercially pure; specimen dia 20 mm length 18 mm; using yellow brass as standard.
88	464	Fritz, W. and Bode, K.-H.	1960	C	303-318		Commercially pure; specimen dia 20 mm length 18 mm; using aluminum as standard.
89*	1268	Schott, R.	1916	L	85-273		Commercially pure.
90	494	Gladun, C. and Holzhauser, W.	1964	P	4-50		99.99 pure; measured by a transient heat method; data taken from a smoothed curve.
91	366	Donth, E. and Gladun, C.	1962	P	26-78		99.5 pure; rod specimen; measured by a transient method with a heat supply $\dot{Q}$ = 0.22 watt; data taken from smoothed curve.
92*	366	Donth, E. and Gladun, C.	1962	P	64-90		The above specimen measured with $\dot{Q}$ = 0.88 watt; data taken from smoothed curve.
93*	366	Donth, E. and Gladun, C.	1962	P	22-47		The above specimen measured with $\dot{Q}$ = 0.12 watt; data taken from smoothed curve.
94	366	Donth, E. and Gladun, C.	1962	P	9.5-28		The above specimen measured with $\dot{Q}$ = 0.056 watt; data taken from smoothed curve.
95*	366	Donth, E. and Gladun, C.	1962	P	28-64		The above specimen measured with $\dot{Q}$ = 0.12 watt; data taken from smoothed curve.
96	968	Mikryukov, V. E. and Karagezyan, A. G.	1961	E	336-755		99.9 pure; 3 mm dia x 300 mm long.
97*	1244	Satterthwaite, C. B.	1962	L	0.3-1.2	Al 430	Nominally pure; supplied by ALCOA; prepared from a 0.625 in. dia x 7 in. long bar by machining the end sections to 0.5 in. in dia and 0.375 in. long, with the center portion 15 cm long milled to a ribbon 0.5 mm thick and 2 mm wide, folded several laps into multi-S shape, then annealed at 525 C for 2 hrs; transition temp Tc = 1.178 K; in superconducting state.
98*	1244	Satterthwaite, C. B.	1962	L	0.3-1.2	Al 430	The above specimen measured in normal state; reported values calculated from the given formula k = 4.00 T (W cm^{-1} K^{-1}) in the same temp range as above.
99*	1244	Satterthwaite, C. B.	1962	L	0.3-1.2	Al 3660	Zone-refined aluminum obtained from Aluminum Industrie A. G., Switzerland; same fabrication method as the above specimen; transition temp (S. C.) 1.187 K; in superconducting state.
100*	1244	Satterthwaite, C. B.	1962	L	0.3-1.2	Al 3660	The above specimen measured in normal state; reported values calculated from the given formula k = 34.08 T (W cm^{-1} K^{-1}) in the same temp range as above.
101	542	Griffiths, E. and Shakespear, G. A.	1921	L	353-453	V 625	Commerically pure; sand cast.
102*	804	Küster, W., Bode, K. H., and Fritz, W.	1968	L	309-357		99.990 Al, 0.004 Si, 0.003 Cu, <0.002 Mg, and <0.001 Fe; 50 mm dia x 70 mm long; density 2.699 g cm^{-3}; measured in a standard apparatus.
103	804	Küster, W., et al.	1968	L	294-353		99.986 pure; 50 mm dia x 70 mm long; measured in the same apparatus as the above specimen.
104	804	Küster, W., et al.	1968	L	438-723		99.996 pure; 50 mm dia x 90 mm long; measured in another apparatus.
105	1567	Willott, W. B.	1967	L	1.0-4.0	Al 9	Obtained from Cominco; specimen 1 mm in dia and ~1 m long, wound into a helix of convenient size; annealed in vacuum; electrical resistivity ratio $\rho(293K)/\rho(1.2K)$ = 3250; Lorenz function 2.498, 2.489, 2.466, 2.404, and 2.265 x 10^{-8} V^2 K^{-2} at 0, 1, 2, 3, and 4 K, respectively; smoothed values reported.

* Not shown in figure.

TABLE 3. THERMAL CONDUCTIVITY OF ALUMINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
106	372	Duggin, M. J.	1968		388-613		0.003 Cu, 0.003 Fe, 0.002-0.003 Si, 0.001-0.002 Mg, and 0.001 Zn.
107*	372	Duggin, M. J.	1968		392-609		Cut from the same sheet as the above specimen.
108	830	Lees, C. H.	1908	L	113-291		99 Al; turned from a rod supplied by Johnson, Matthey and Co.; density 2.70 g cm^{-3} at 20 C; electrical resistivity 2.72 μohm cm at 0 C.
109	1156	Powers, R. W., Ziegler, J. B., and Johnston, H. L.	1951	L	29-297	J 51	0.56 Fe, 0.56 Mg, 0.38 Si, 0.29 Cu, 0.02 Mn, 0.01 Cr, and 0.01 Ti.
110	446	Flynn, D. R.	1965		120-720		No details.
111	546	Grosse, A. V.	1965		933.4-8650		Calculated from electrical resistivity according to the Wiedemann-Franz-Lorenz law.

* Not shown in figure.

Americium

No information is available in the literature for the thermal conductivity of americium. Based upon the unpublished measurements of M. B. Brodsky on the electrical resistivity of americium at temperatures from 4 to 60 K, Meaden [914] has made an estimation of its thermal conductivity at low temperature. The electrical resistivity values of Brodsky [914] are 29, 30, 33, 39, and 45 $\mu\Omega$ cm at 4, 10, 20, 40, and 60 K. Using the theoretical Lorenz number, Meaden [914] obtained $k = 0.008$ W cm^{-1} K^{-1} at 10 K. However, he believed that this value was far too low and the actual thermal conductivity of americium at 10 K might well be two or three times greater. The reasoning is based on the fact that the above residual electrical resistivity contains an impurity-induced spin-disorder term and only the true impurity resistivity should be used if the electronic thermal conductivity is sought. At the same time magnon and phonon conductions are to be expected, leading to an increase in the Lorenz function which might far exceed 2.443×10^{-8} V^2 K^{-2}.

The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidence shows that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of americium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ± 50 percent.

Antimony

The available information on the thermal conductivity of antimony is all for the metallic crystalline form. Since antimony crystallizes in the rhombohedral form, a single crystal of the metal has three principal axes. Rausch [1184] has reported thermal and electrical conductivity values at 79.5 K and 91.2 K for flow directions parallel to each axis (curves 13–18). The extreme differences in thermal conductivity were only about 3 percent at 91.2 K and 6 percent at 79.5 K, yet the corresponding electrical conductivities differed by nearly 50 percent. This would suggest the presence of a considerable phonon component of thermal conductivity. For the trigonal axis direction Red'ko, Bresler, and Shalyt [1189] (curve 30) find the phonon and electron components of the thermal conductivity to be comparable in the region of 90 K. These workers also find both components to increase to maxima below 10 K, the total thermal conductivity having a maximum value of 7.62 W cm^{-1} K^{-1} at 7.42 K. Only magnetic fields of moderate strength were required to suppress the electronic component, and this enabled the two components to be measured. Long, Grenier, and Reynolds [858] (curve 26) have previously used this method to determine the phonon component, k_g, for another single crystal in which the heat flow was perpendicular to the trigonal axis, the total thermal conductivity then being calculated from the relation $k = k_g + L_0 T/\rho$, where L_0 is the theoretical Lorenz function and ρ is the measured electrical resistivity. This yielded a maximum of 9.74 W cm^{-1} K^{-1} at 3.04 K. Subsequently, further measurements to lower temperatures have been made on this sample. The inclusion of proposed values for the principal crystal directions should however await more extensive experimental information.

Antimony is a metal for which the low-temperature thermal conductivity is predominantly due to phonon contribution and therefore the values do not follow the correlation adopted by Cezairliyan and Touloukian [248–250]. Hence for polycrystalline antimony a smooth curve has been drawn for the range 2 to 90 K through the data of White and Woods [1151] (curve 6) for their sample of highest thermal conductivity and having $\rho_0 = 0.054$ $\mu\Omega$ cm. This curve has been extended to high temperatures as a curve of gradually decreasing slope to the 850 K value of Dutchak and Panasyuk [383] (curve 23). The course followed is a little above, but in fair agreement with the data of Rausch [1184] (curve 13–18), Gehlhoff and Neumeier [481] (curve 2), Eucken and Neumann [406] (curve 11), and Smith [1327] (curve 12), but is entirely at variance with the data of Konno [778] (curve 3). These last constitute the only set of measurements in the range 380 to 850 K, but have been considered doubtful.

There is clearly a strong need for further determinations of the thermal conductivity of pure antimony from room temperature upwards.

The thermal conductivity of molten antimony has been measured by Konno [778] (curve 3) and by Dutchak and Panasyuk [383, 384] (curves 23 and 24), whilst Mardykin and Filippov [884] (curve 31) have derived values for the range 1170 to 1430 K from thermal diffusivity observations for a sample of very low purity, 96.8 percent antimony. The proposed curve has tentatively been drawn to fit the later of the two determinations by Dutchak and

Panasyuk [383] (curve 23) as these had indicated the thermal conductivity to increase by 55 percent on passing from the solid to the liquid phase, a change in fair agreement with that of the electrical conductivity. The curve is also expected to lie above that of Mardykin and Filippov owing to the low purity of their sample.

The tabulated values are for well-annealed high-purity metallic antimony. Those above 100 K are provisional values and are considered accurate to within ±15 percent of the true values at moderate temperatures and ±25 percent near the melting point and above. Values below 100 K are merely typical values for the low-temperature thermal conductivity of high-purity polycrystalline antimony.

TABLE 4. Provisional thermal conductivity of antimony†

(Temperature, T, K; Thermal Conductivity, k, W $cm^{-1}K^{-1}$)

Solid Polycrystalline				Liquid	
T	k	T	k	T	k
2	0.87	173.2	0.326	903.89	0.259
3	1.27	200	0.302	973.2	0.267
4	1.86	223.2	0.283	1000	0.270
5	2.58	250	0.267	1073.2	0.277*
6	3.34	273.2	0.255	1100	0.280*
7	4.06	298.2	0.244		
8	4.63	300	0.243		
9	4.89	323.2	0.235		
10	4.80	350	0.226		
11	4.50	373.2	0.219		
12	4.07	400	0.213		
13	3.79	473.2	0.199		
14	3.51	500	0.195		
15	3.25	573.2	0.186		
16	3.04	600	0.183		
18	2.67	673.2	0.176		
20	2.38	700	0.174		
25	1.87	773.2	0.170		
30	1.54	800	0.168		
35	1.30	850	0.167		
40	1.13	873.2	0.167		
45	0.994	900	0.167		
50	0.883	903.89	0.167		
60	0.725				
70	0.620				
80	0.550				
90	0.500				
100	0.464				
123.2	0.405				
150	0.356				

†The values are for well-annealed high-purity antimony, and those below 100 K are merely typical values.

*Extrapolated.

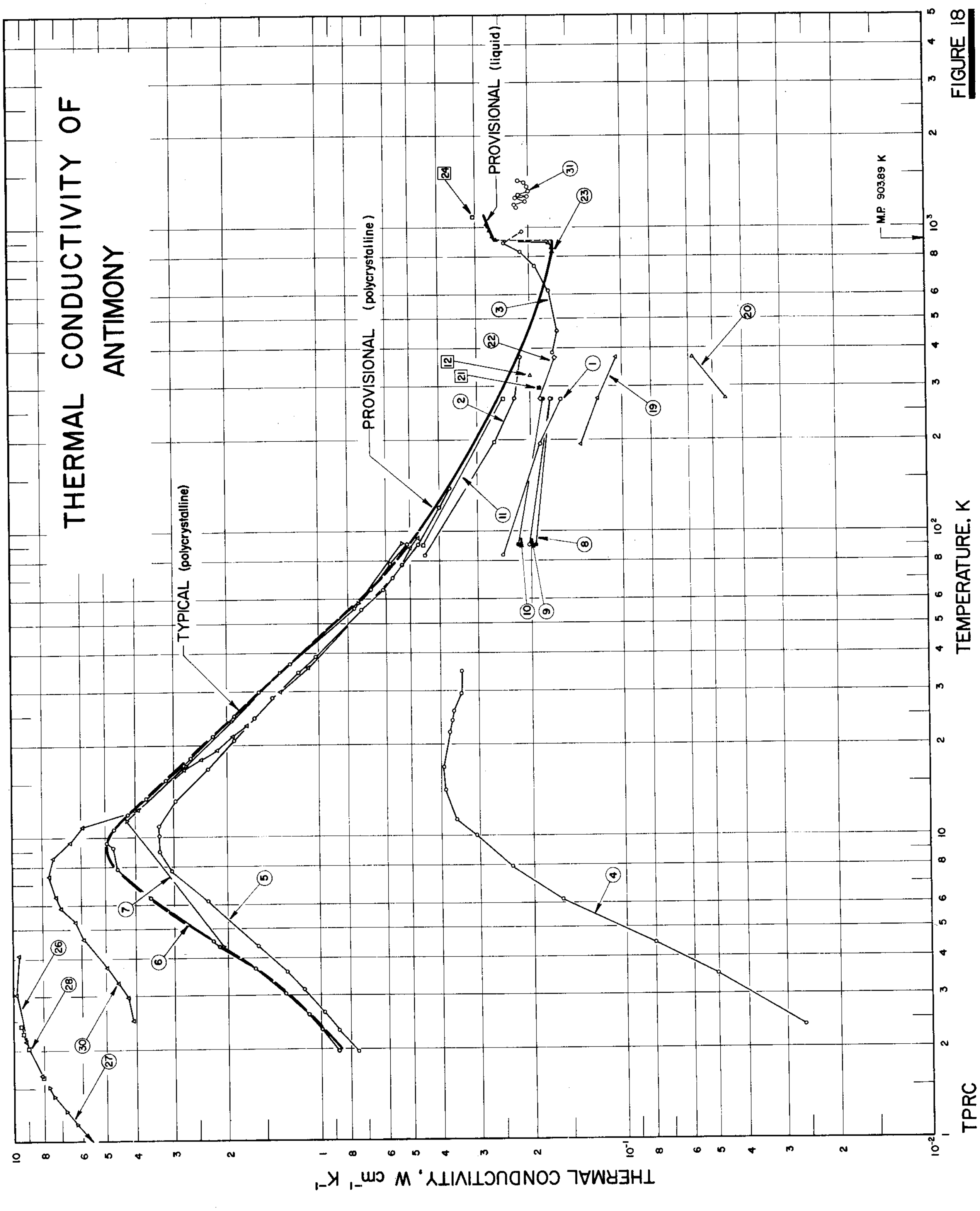

THERMAL CONDUCTIVITY OF ANTIMONY
PROVISIONAL (liquid)
PROVISIONAL (polycrystalline)
TYPICAL (polycrystalline)
M.P. 903.89 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 18

TABLE 5. THERMAL CONDUCTIVITY OF ANTIMONY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	405	Eucken, A. and Gehlhoff, G.	1912	L	83-273		Pure; cold-drawn.
2	481	Gehlhoff, G. and Neumeier, F.	1913	L	83-373		Pure.
3	778	Konno, S.	1919	L	386-965		No details reported
4	1220	Rosenberg, H. M.	1955	L	2.4-35	Sb 1	Polycrystalline; extruded wire; 1.625 cm long, 0.163 cm dia; made from Johnson Matthey Spectrographically Standardized Metals; annealed at 500 C in vacuo for 2 hrs; electrical resistivity ratio $\rho(293K)/\rho(20K) = 6.37$.
5	1551	White, G. K. and Woods, S. B.	1958	L	2.0-138	Sb 1	High purity polycrystalline specimen; 0.43 x 0.25 x 6 cm; sawn from a lump of extra high purity grade antimony supplied by Bradley Mining Co.; electrical resistivity 47.7 μohm cm at 295 K; residual electrical resistivity 0.057 μohm cm.
6	1551	White, G. K. and Woods, S. B.	1958	L	2.0-91	Sb 2	High purity polycrystalline specimen; 5 mm dia, 6 cm long; crystal width 2 to 5 mm; supplied by Bradley Mining Co.; prepared by zone-refining high purity grade antimony; annealed at 600 C for one wk; electrical resistivity 41.3 μohm cm at 295 K; residual electrical resistivity 0.054 μohm cm.
7	1551	White, G. K. and Woods, S. B.	1958	L	4.4-91	Sb 2a	Second run of the above specimen.
8	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystalline specimen with fine grains; cast at 200 C; electrical conductivity at 90 and 273 K being 8.34 and 2.43 x 10^4 ohm^{-1} cm^{-1} respectively.
9	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystalline specimen with fine grains; electrical conductivity at 90 and 273 K being 8.13 and 2.38 x 10^4 ohm^{-1} cm^{-1} respectively.
10	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystalline specimen with medium size grains; electrical conductivity at 90 and 273 K being 8.08 and 2.35 x 10^4 ohm^{-1} cm^{-1} respectively.
11	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystalline specimen with coarse grains; electrical conductivity at 90 and 273 K being 7.89 and 2.32 x 10^4 ohm^{-1} cm^{-1} respectively.
12	1327	Smith, A. W.	1925	L	327.2		Total impurity less than 0.03%; made from Baker's Analyzed Metal.
13*	1184	Rausch, V. K.	1947	L	91.2	P_I	Single crystal cylindrical specimen; longitudinal axis of the specimen parallel to the z-axis of the crystal; supplied by Kahlbaum; electrical resistivity 26.26 μohm cm at 0 C; measured at 91.2 K in magnetic fields ranging from 0 to 11.6 kilooersteds.
14*	1184	Rausch, V. K.	1947	L	79.5	P_I	The above specimen similarly measured at a temp of 79.5 K.
15*	1184	Rausch, V. K.	1947	L	91.2	S 14	Similar to the above specimen except longitudinal axis of the specimen perpendicular to z- and x-axis of the crystal; electrical resistivity 37.11 μohm cm at 0 C; measured at 91.2 K.
16*	1184	Rausch, V. K.	1947	L	79.5	S 14	The above specimen similarly measured at 79.5 K.
17*	1184	Rausch, V. K.	1947	L	91.2	S 10	Similar to the above specimen except longitudinal axis perpendicular to z-axis and parallel to x-axis of the crystal; measured at 91.2 K in magnetic fields of 0 to 11.6 kilooersteds.
18*	1184	Rausch, V. K.	1947	L	81.2	S 10	The above specimen similarly measured at a temp of 81.2 K.

* Not shown in figure.

TABLE 5. THERMAL CONDUCTIVITY OF ANTIMONY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
19	482	Gehlhoff, G. and Neumeier, F.	1913	L	193-373		Specimen pressed from powder at 5000 Kg cm^{-2} for 1 hr; antimony supplied by C.A.F. Kahlbaum.
20	482	Gehlhoff, G. and Neumeier, F.	1913	L	273,373		Similar to the above specimen except pressed at 2500 Kg cm^{-2} for 1 hr.
21	869	Lussana, S.	1918	L	297		Specimen 0.45 cm dia; supplied by Erba; measured under 1.0 atm pressure.
22	859	Lorenz, L.	1881	L	273,373		Electrical conductivity at 273 and 373 K being 2.199 and 1.522 x 10^4 ohm^{-1} cm^{-1} respectively (the paper gives electrical conductivity values as 2.199 and 1.522 x 10^5 ohm^{-1} cm^{-1}, obviously a typographical error).
23	383	Dutchak, Ya.I. and Panasyuk, P.V.	1967	C	825-1023		Molten metal placed in a hole 21 mm in dia drilled in an asbestos cement cylinder 30 mm in height; steel 1Kh18N9T used as comparative material.
24	384	Dutchak, Ya.I. and Panasyuk, P.V.	1966	P	1073.2		Molten specimen contained in a thin-walled stainless steel cylindrical crucible of dimensions 24 mm dia x 100 mm long; electrical resistivity reported as 82.9, 90.2, and 100 μohm cm at 620, 700, and 800 C, respectively; thermal conductivity values calculated from measured thermal diffusivity and the specific heat data using the density data taken from Bienias, A. and Sauerwald, F. (Z. Anorg. Chem., <u>41</u>, 51, 1927).
25*	1051	Ohyama, M.	1967	C	298		Pure; slowly cooled specimen; n-type Bi_2Te_3 used as comparative material; thermal conductivity value calculated from the mean of 2 measurements.
26	858	Long, J.R., Grenier, C.G., and Reynolds, J.M.	1965	L	1.6-4.0		99.9999 pure; single crystal; cut from a Cominco grade 69 zone-refined bar; 20 x 4.6 x 2 mm with the trigonal axis along the 2 mm thickness and a binary axis along the 4.6 mm width; electrical resistivity 0.00479, 0.00550, 0.00645, 0.00765, 0.00911, 0.0109, and 0.0129 μohm cm at 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, and 4.5 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 3600 and $\rho(300K)/\rho(1.2K)$ = 9500; residual electrical resistivity 0.004 μohm cm; measured perpendicular to the trigonal axis with magnetic field parallel to this axis; Kg is the observed quantity and K is derived from $K = Kg + L_0T/\rho$.
27	169,168	Blewer, R.S. and Zebouni, N.H.	1966	L	0.54-1.5		The same specimen and method as used by Long, J.R., et al. (see curve No. 26).
28	169,168	Blewer, R.S. and Zebouni, N.H.	1966	L	1.6-2.4		Another run of the above specimen.
29*	169,168	Blewer, R.S. and Zebouni, N.H.	1966	L	0.44-1.5		Another run of the above specimen.
30	1189	Red'ko, N.A., Bresler, M.S., and Shalyt, S.S.	1969	L	2.5-95		Single crystal; specimen 2 x 2.5 x 26 mm; electrical resistivity ratio $\rho(293K)/\rho(4.2K)$ = 2300; electrical conductivity from graph 831.8, 783.4, 641.2, 537.0, 49.4, 42.8, 33.1, 29.0, 2.75, 1.93, and 1.46 x 10^5 ohm^{-1} cm^{-1} at 1.80, 2.55, 3.28, 4.41, 17.4, 18.1, 19.9, 20.8, 64.0, 76.0, and 91.6 K, respectively; Lorenz function from graph 2.18, 2.10, 1.98, 1.97, 2.00, 2.12, 1.90, 1.79, 1.60, 1.47, 1.43, 1.45, 1.48, 1.58, 1.66, and 1.81 x 10^8 V^2 deg^{-2} at 2.37, 2.72, 3.65, 4.30, 5.05, 8.45, 11.3, 13.4, 20.0, 28.7, 43.0, 49.4, 55.2, 68.9, 77.1, and 89.9 K, respectively; measured along the c_3-axis.
31	884	Mardykin, I.P. and Filippov, L.P.	1968	P	1173-1430		96.8 pure; in liquid state; thermal conductivity values calculated from measured thermal diffusivity and specific heat capacity.

* Not shown in figure.

Argon

The thermal conductivity of argon in each physical state is discussed separately below.

Solid

Available data on the thermal conductivity of solid argon includes the work of Dobbs and Jones [365], White and Woods [1552], Bernè, Boato, et. al. [148, 170], and Krupskii et al. [792, 791] while some calculations and correlations have appeared [696, 751, 133, 131, 752]. Most of the above results have only been presented in graphical form.

Comparison of the available data reveals reasonable agreement at temperatures above about 10 K and severe disagreement at temperatures lower than 10 K. In the region from 5 to 8 K an order of magnitude difference exists between the [1552] and [148] data. Such differences are probably produced by structure variations caused by different impurity content, although further high precision experimentation is needed to confirm this supposition. The disagreement at the higher temperatures has also been ascribed by Krupskii as being due to this factor.

The provisional values were obtained from a large scale plot of the available information and were not generated for temperatures below 8 K due to the experimental uncertainty. From 8 to 20 K the uncertainty may be as much as fifty percent, the uncertainty gradually decreasing with increasing temperature to ten percent at the highest temperatures tabulated. Due to the almost complete absence of tabulated experimental data, apart from the Krupskii results, no departure plot is presented. Further experimental studies are required to resolve the large discrepancies between the results of Krupskii and others. While the general trend of the Krupskii results appears to be reasonable, the adoption of those results as reference values would not enable any estimates of thermal conductivity maximum or values for temperatures below the maximum in thermal conductivity to be made using the White and Woods values. It was felt that, at this time, the retention of the former choice [1420, 608, 844] of the White and Woods values as the basis, along with other results where appropriate, would provide a means of tabulation of values over a larger temperature range than would otherwise be possible, even at possibly reduced accuracy. Further experimental studies seem urgently needed to resolve this difference.

Liquid

Five experimental works were located on the thermal conductivity of liquid argon. Keyes [748] made measurements in a coaxial-cylinder apparatus near saturation conditions at three temperatures from 87 K to 112 K. The measurements of Uhlir [1447] were made in a coaxial-cylinder apparatus covering temperatures from 86 to 150 K and pressures up to 96 atm. with an uncertainty reported to be from 0.5 to 2.5 percent. Other measurements for the liquid and gaseous phases were carried out in a coaxial-cylinder apparatus with an accuracy of two percent, by Ziebland-Burton [229, 1612], from 93 to 151 K for the liquid phase with pressures to 120 atm. Bailey and Kellner [105] also used a concentric cylinder apparatus from 90 to 300 K and pressures to 500 kg/cm^2, while Ikenberry and Rice [654] made measurements from 91 to 150 K for the compressed liquid.

In the initial analysis, values for saturated vapor pressures were obtained from graphical extrapolation of the data of both Uhlir and Ziebland-Burton, no correction being made to the values of Keyes. The three sets of data for the saturated liquid were given equal weight and were fitted to a quadratic equation represented by

$$k\ (\mathrm{W\ m^{-1}\ K^{-1}}) = 0.216149 - 9.714328 \cdot 10^{-4}\,T - 1.070133 \cdot 10^{-6}\,T^2.$$

In arriving at this formula, values at the critical point were excluded. This equation, considered valid in the temperature range from 80 to 140 K, fitted the above data with a mean deviation of 0.6 percent and a maximum of 1.9 percent. Recommended values below 140 K were generated from the above formula.

Subsequent to the initial analysis, the Ikenberry and Rice and Bailey and Kellner data were examined. Values for saturated vapor pressure were obtained, where required, by graphical extrapolation. No significant discord with the above formula was noted except for the 29 and 49 kg cm^{-2} isobars of Bailey. These isobars were also omitted from Bailey's own evaluation in his figure 8. Vasserman and Rabinovich [1481] tabulated thermal conductivities for integral temperatures and pressures from a consideration of the [229, 748, 1447, 1611, 654] data. Approximate values for the saturated state can be obtained from their tables and agree with those recommended here to within ± 2.5 percent for temperatures from 85 to 140 K. Their correlation favors the Ziebland-Burton data.

The values recommended below 140 K are considered to be correct within 2 percent. Values above 140 K were obtained from a large-scale graph. The experimental difficulties increase considerably in this temperature region and the recommended values at 145, 150 K and the critical point are probably uncertain by as much as five, ten and twenty-five percent, respectively. As shown by Liley [845], values of the thermal conductivity of argon in the saturated states near the critical point can be correlated with the enthalpy of vaporization. However, possible critical anomalies have not been considered. Both the Bailey paper cited above and a further paper [104] show that any anomaly must occur above about 150 K. The reliability of existing data is not felt, at this time, sufficient to enable a detailed study of this region.

Saturated Vapor

No experimental data were found for the thermal conductivity of saturated argon vapor. The only information located was estimations of Owens and Thodos [1058], Uhlir [1447], and Ziebland, et al. [1612, 1610.] Below about 140 K the estimates are in fair agreement, the Uhlir values being intermediate. Above 140 K a wide variation in estimates exists. The more recent Vasserman and Rabinovich [1481] tables present correlated values for integral temperatures and pressures and not for the saturated states.

The values were plotted on a large scale graph in which the Owens and Thodos values were adjusted to agree with the atmospheric pressure value at 88 K. The increase necessary at 88 K was linearly reduced for higher temperatures to zero at the critical temperature. Values obtained in this way were in excellent agreement with the Uhlir values up to 125 K. Above 125 K they were lower than the other estimates.

The provisional values were deduced from the plot of the Owens and Thodos estimates. Based upon the agreement of these with other estimates and upon the uncertainty in the saturated liquid values, they should be accurate to about 2.5 percent below 125 K, fifteen percent at 135 K and twenty-five percent at and above 145 K. These error estimates agree roughly with the deviations of the few values obtainable for saturated conditions from [1481]. However, their values are invariably higher than those presented here. Bailey and Kellner [105] measured thermal conductivity-temperature isobars for 19.5 and 39.5 kg cm^{-2}. From plotting their tabulated data, it was possible to draw a curve for the saturated vapor through

TABLE 6. Recommended thermal conductivity of argon†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		84	1.270*		
		85	1.258	85	0.055*
8	60	90	1.201	90	0.059*
9	46	95	1.142	95	0.064*
10	37	100	1.082	100	0.068*
12	27	105	1.021	105	0.072*
14	22	110	0.963	110	0.077*
16	18	115	0.903	115	0.082*
18	16	120	0.842	120	0.088*
20	13.6	125	0.780	125	0.095*
25	9.9	130	0.718	130	0.103*
30	7.8	135	0.655	135	0.109*
35	6.5	140	0.592	140	0.120*
40	5.6	145	0.518	145	0.140*
45	5.1	150	0.404	150	0.19*
50	4.6	151	0.25*‡	151	0.25*‡
60	3.8				
70	3.3				
80	3.0				

†Values for the solid and saturated vapor are provisional.
*Estimated or extrapolated. ‡Pseudo-critical value.

TABLE 6. Recommended thermal conductivity of argon—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (At 1 atm)

T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		400	0.2233	750	0.353	1500	0.561*
		410	0.2276	760	0.356	1550	0.575*
		420	0.2318	770	0.359	1600	0.588*
88	0.0574*	430	0.2359	780	0.362	1650	0.602*
90	0.0587	440	0.2400	790	0.366	1700	0.615*
100	0.0652	450	0.2441	800	0.369	1750	0.628*
110	0.0716	460	0.2481	810	0.372	1800	0.641*
120	0.0779	470	0.2520	820	0.375	1850	0.654*
130	0.0839	480	0.2559	830	0.378	1900	0.667*
140	0.0898	490	0.2599	840	0.381	1950	0.680*
150	0.0957	500	0.2638	850	0.384	2000	0.692*
160	0.1016	510	0.268	860	0.387	2100	0.717*
170	0.1074	520	0.272	870	0.390	2200	0.741*
180	0.1131	530	0.276	880	0.393	2300	0.766*
190	0.1188	540	0.280	890	0.396	2400	0.790*
200	0.1244	550	0.283	900	0.398	2500	0.815*
210	0.1300	560	0.287	910	0.401		
220	0.1355	570	0.290	920	0.404		
230	0.1409	580	0.294	930	0.407		
240	0.1462	590	0.297	940	0.410		
250	0.1515	600	0.301	950	0.413		
260	0.1567	610	0.305	960	0.416		
270	0.1619	620	0.308	970	0.418		
280	0.1671	630	0.311	980	0.421		
290	0.1722	640	0.315	990	0.424		
300	0.1772	650	0.319	1000	0.427		
310	0.1822	660	0.322	1050	0.441		
320	0.1871	670	0.326	1100	0.454		
330	0.1919	680	0.329	1150	0.468		
340	0.1966	690	0.333	1200	0.481		
350	0.2013	700	0.336	1250	0.495		
360	0.2059	710	0.339	1300	0.508		
370	0.2103	720	0.343	1350	0.521		
380	0.2147	730	0.346	1400	0.535*		
390	0.2190	740	0.349	1450	0.548*		

*Estimated or extrapolated.

the isobaric values at saturation temperatures. The values so obtained are higher than those of [1481] or suggested here.

Gas

Experimental measurements have been reported for the thermal conductivity of gaseous argon for temperatures between about 90 and 1173 K and many correlations and calculations have appeared, the more recent extending to temperatures well above 15 000 K. While our earlier tables recommended values to 10 000 K [843, 1420, 608, 844], the present work has limited the selection to an upper limit of 2500 K. This has been done since the accuracy of some of the higher temperature studies was dubious.

As shown by the departure plots, most experimental, correlated and calculated values are in reasonable accord and the accuracy of the recommended values, derived by drawing a smooth curve through these sources, can be assessed as about one percent for temperatures between 100 and 500 K, five percent for temperatures below 100 K and between 500 and 1500 K, and ten percent above 1500 K.

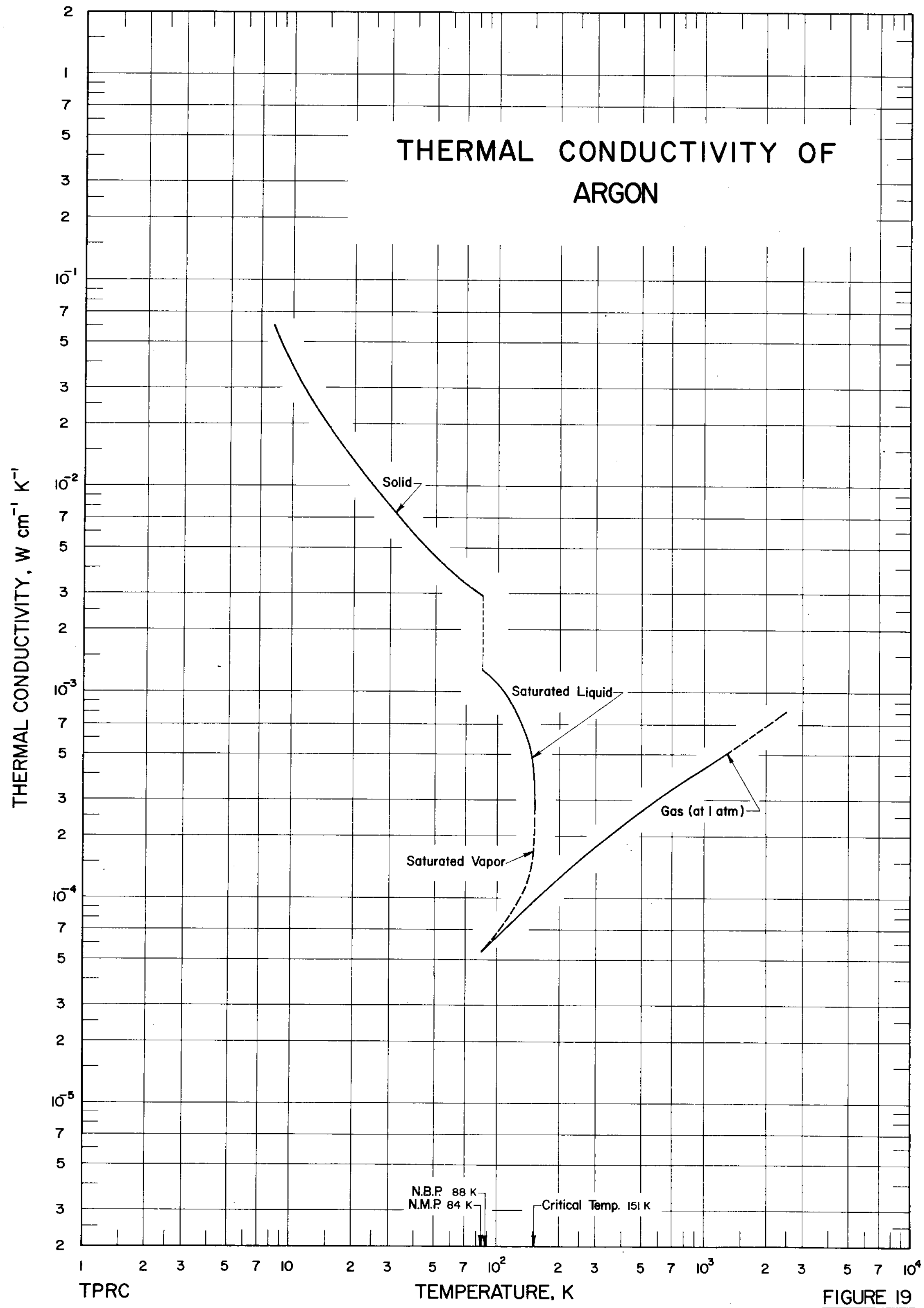

THERMAL CONDUCTIVITY OF ARGON
Solid
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.B.P. 88 K
N.M.P. 84 K
Critical Temp. 151 K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TEMPERATURE, K
TPRC

FIGURE 19

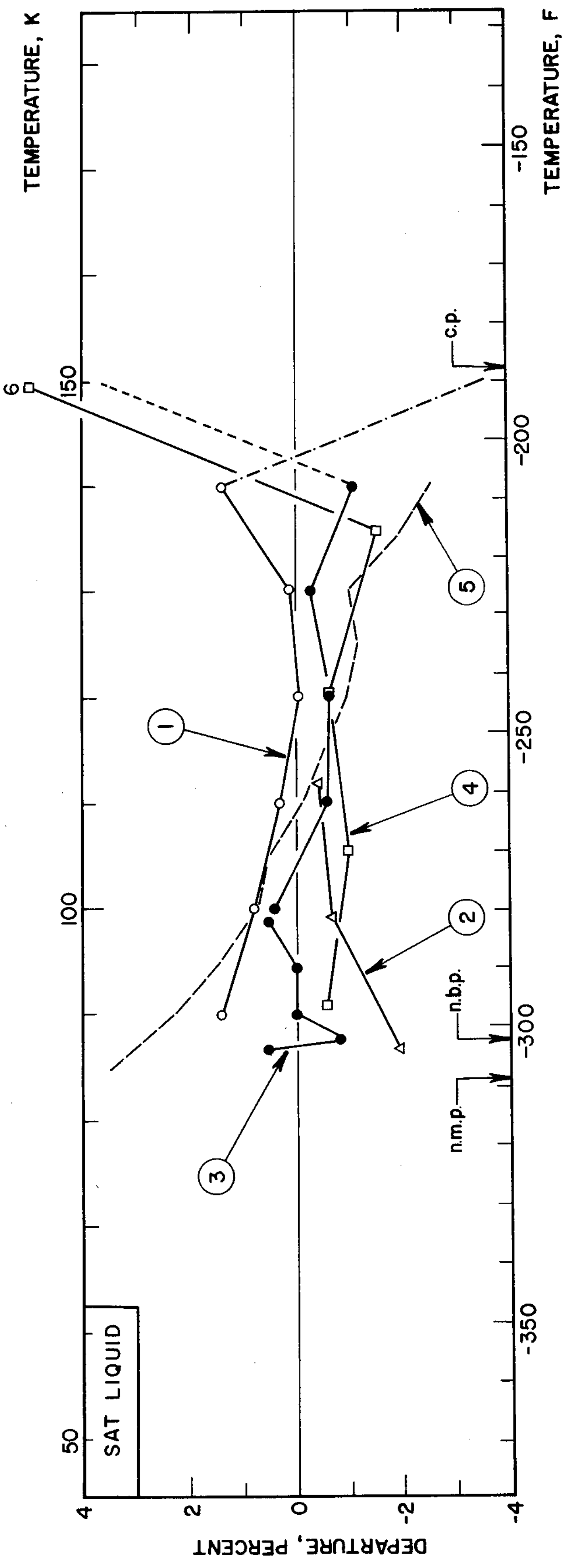
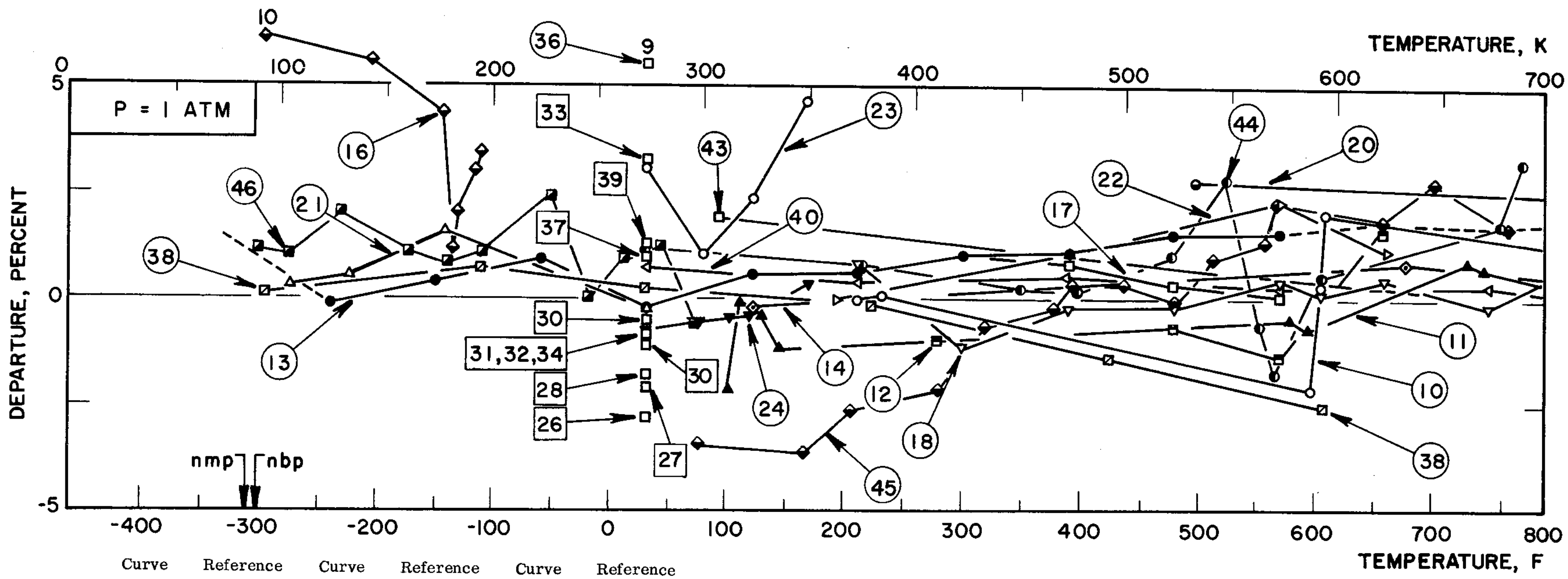


FIGURE 20. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID ARGON

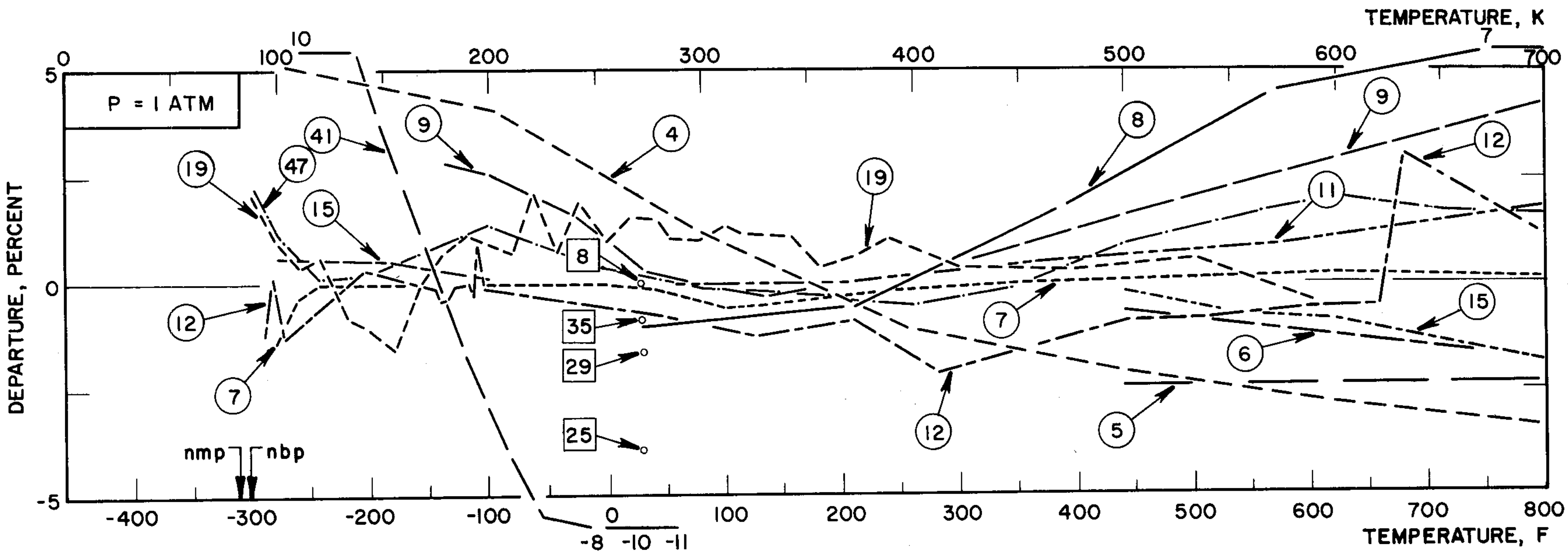
Curve	Reference
1	229, 1612
2	748
3	1447
4	654
5	1481

FIGURE 21. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON



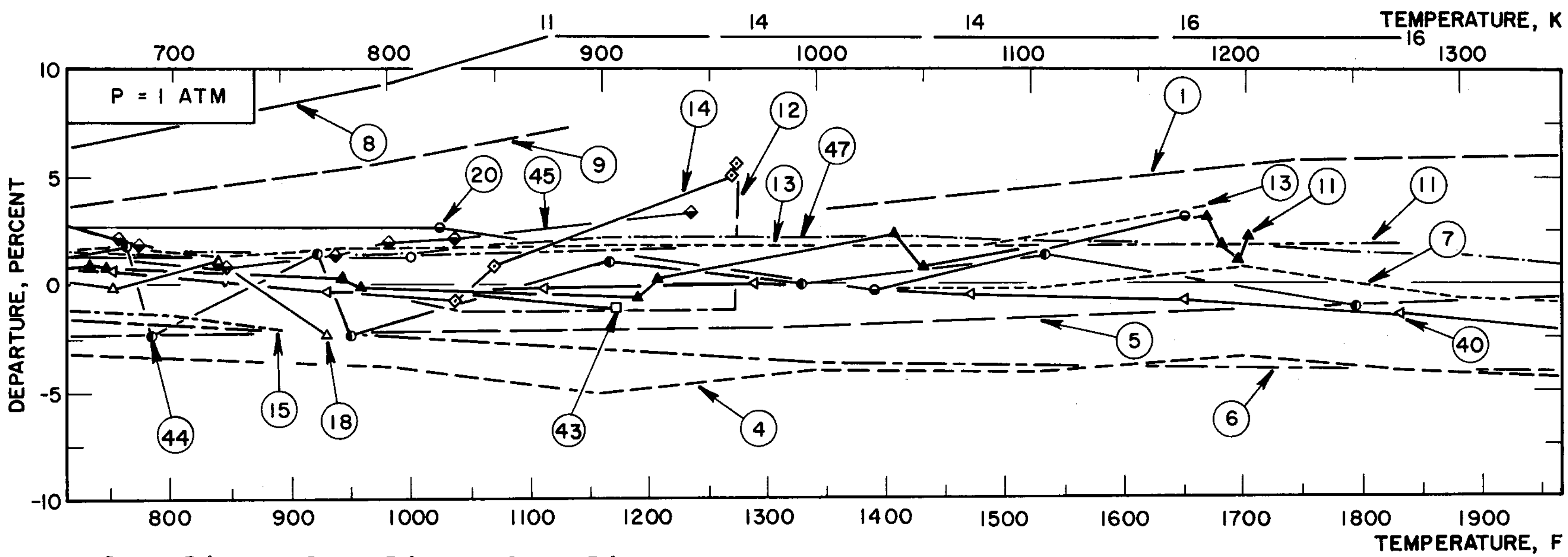
Curve	Reference	Curve	Reference	Curve	Reference
10	267, 268	22	747	33	305, 306
11	1478	23	957	34	1572
12	750	24	959	36	1355
13	746	26	710	37	706
14	1225, 1226	27	1515	38	705
16	1611	28	833	39	360
17	474	30	1447	40	1254, 1255
18	1269	31	651	43	1084
20	1486	32	402	44	297
21	748			45	838
				46	105

FIGURE 21. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



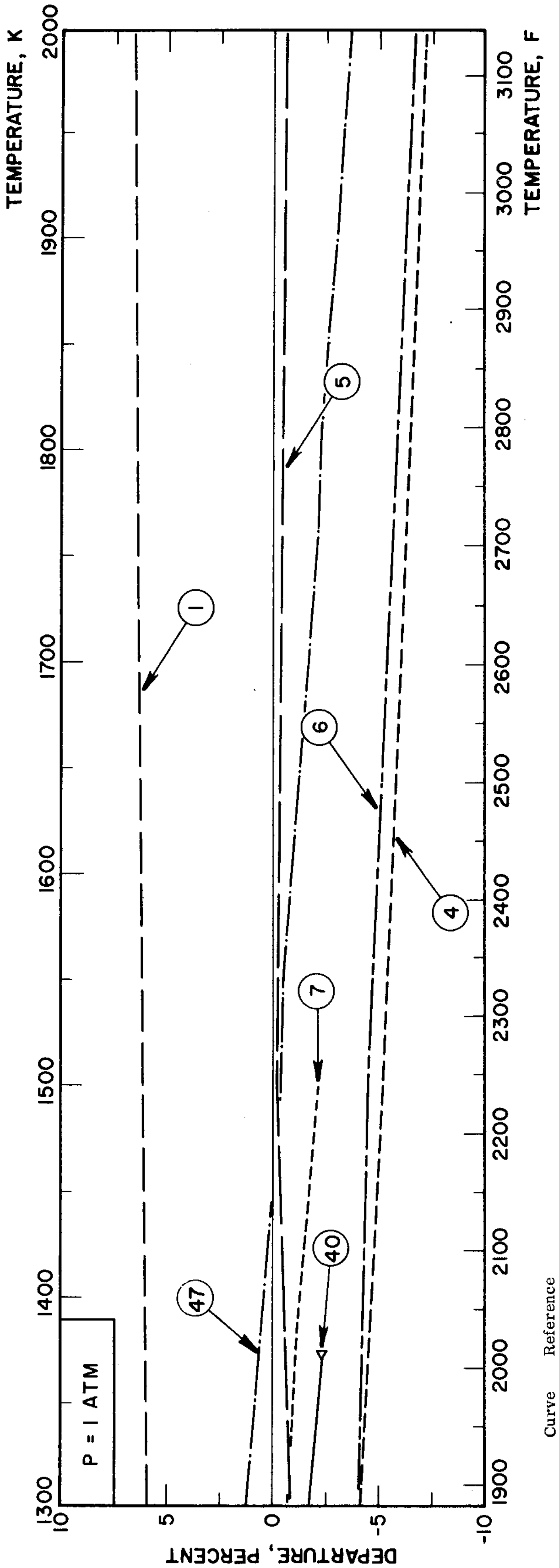
Curve	Reference	Curve	Reference
4	1381	15	454
5	89	19	839
6	1090	25	1016
7	604, 605	29	741
8	273	35	403
9	1429	41	54
11	1478	47	1474
12	750		

FIGURE 21. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



Curve	Reference	Curve	Reference	Curve	Reference
1	1303	10	267, 268	40	1254, 1255
4	1381	11	1478	43	1084
5	89	12	750	44	297
6	1090	13	746	45	838
7	604	14	1225, 1226	47	1474
8	273	18	1269		
9	1429	20	1486		

FIGURE 21. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



Curve	Reference
1	1303
4	1381
5	89
6	1090
7	604
40	1254, 1255
47	1474

Arsenic

Only two experimental determinations of the thermal conductivity of arsenic have been found. The first was by Little [852] (curve 1), who reported room temperature measurements of several thermo-magnetic effects for a polycrystalline sample of gray arsenic. Little's value for the thermal conductivity was 0.368 W cm^{-1} K^{-1}. The same sample had an electrical resistivity of 46 $\mu\Omega$ cm, and was considered of good purity since the temperature coefficient of electrical resistivity was 0.00435 Ω cm K^{-1}. From $k_e = 2.443 \times 10^{-8}\, T/\rho$ the electronic thermal conductivity component at 293 K is 0.156 W cm^{-1} K^{-1} and the lattice component k_g is 0.212 W cm^{-1} K^{-1}. On the assumption that the relation $k = 2.443 \times 10^{-8}\, T/\rho + 62/T$ holds for the temperature range 200 to 500 K, the lightly dashed curve has been derived.

The more recent determination by Ohyama [1051] (curve 2) provides one value lying about 26 percent below that curve.

The stated high purity of Little's specimen seems in doubt in view of some electrical resistivity determinations by Taylor, Bennett, and Heyding [1391], who from measurements made at 293 K on single crystals reported $\rho_{\parallel} = 35.6 \pm 1.8$ and $\rho_{\perp} = 25.5 \pm 0.5$ $\mu\Omega$ cm. Assuming very approximately that $\rho = 1/3\ (2\rho_{\perp} + \rho_{\parallel})$ gives the much lower value of 28.9 $\mu\Omega$ cm for the electrical resistivity of polycrystalline arsenic. On the further assumption that the lattice component is of the same order for this sample, the heavily dashed curve has been derived and this is very tentatively proposed as representing the thermal conductivity of pure polycrystalline gray arsenic. These provisional values should be good to within ±15 percent.

No information is available for molten arsenic.

Arsenic is clearly an element for which accurate thermal conductivity determinations are required for a wide range of temperature.

TABLE 7. Provisional thermal conductivity of arsenic†

(Temperature, T, K; Thermal Conductivity, k, W $cm^{-1}K^{-1}$)

Solid Gray, polycrystalline	
T	k
200	0.690*
223.2	0.633*
250	0.578*
273.2	0.539*
293.2	0.510
298.2	0.502*
300	0.500*
323.2	0.474*
350	0.446*
373.2	0.427*
400	0.406*
473.2	0.360*
500	0.348*

†The provisional values are for well-annealed high-purity polycrystalline gray arsenic.

*Extrapolated or estimated.

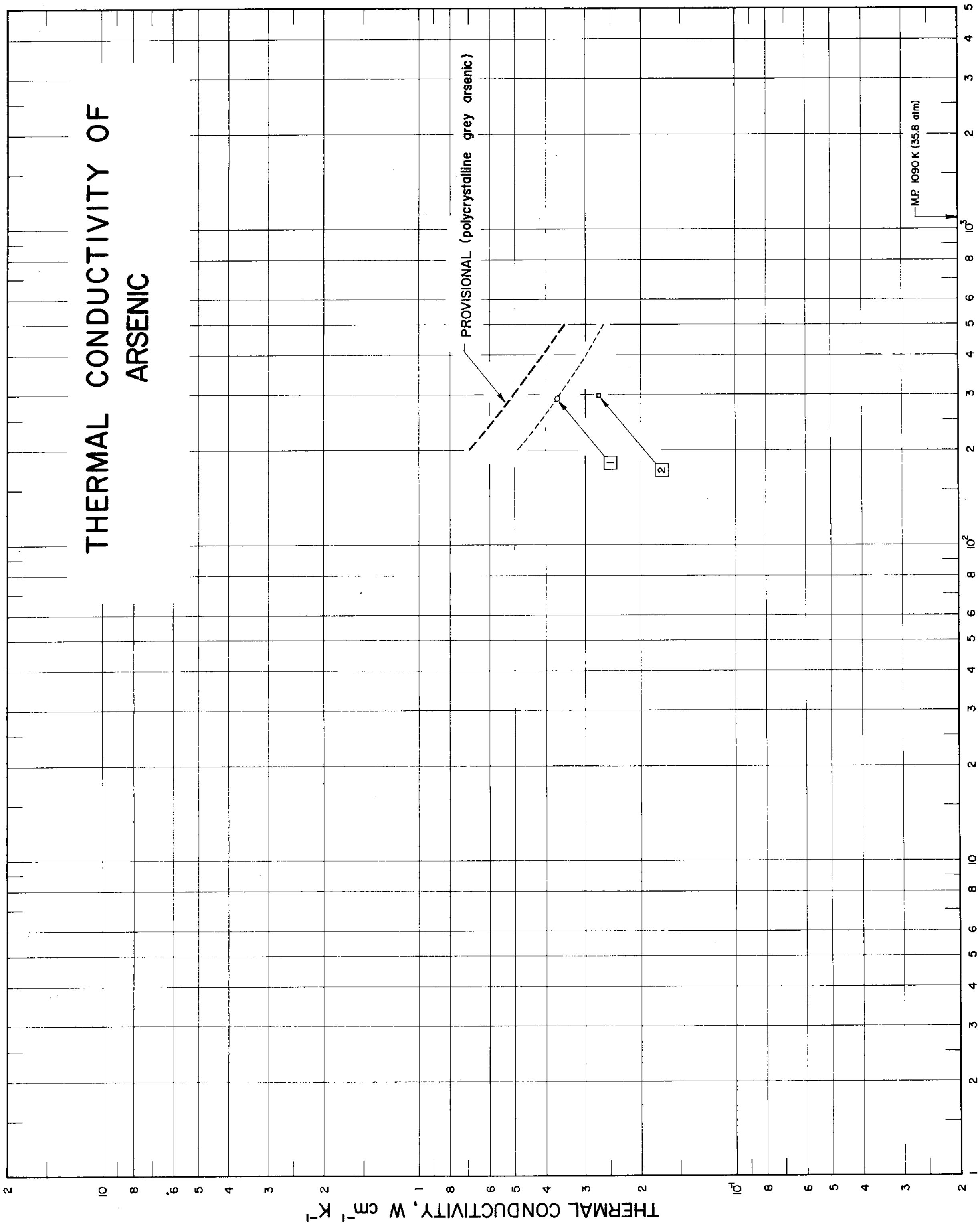

THERMAL CONDUCTIVITY OF ARSENIC
PROVISIONAL (polycrystalline grey arsenic)
M.P. 1090 K (35.8 atm)
1
2
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TPRC

FIGURE 22

TABLE 8. THERMAL CONDUCTIVITY OF ARSENIC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	852	Little, N.C.	1926	E	293.2		Polycrystalline; a curving plate 2.7 x 1.1 x 0.02 cm in size; obtained by distilling rough crystal in vacuum at about 400 C and permitting the gaseous element to condense on the walls of the containing glass tube, the deposits then ground and smoothed to size; electrical resistivity 46 μohm cm at 20 C; measuring in magnetic fields of 4000 and 8000 gauss found to have no effect on the thermal conductivity.
2	1051	Ohyama, M.	1967	C	298		Pure; slowly cooled; n-type Bi_2Te_3 used as comparative material; thermal conductivity value calculated from the mean of 2 measurements.

Astatine

No information on the thermal conductivity of astatine is available. However, very rough estimation of its room-temperature thermal conductivity may be made. In figure 15a, the thermal conductivities of a number of nonmetallic solid elements at 300 K are plotted against the melting temperatures of the elements, and a reasonable curve can be drawn to indicate roughly the thermal conductivity at 300 K as a function of the melting temperature. From the intercept of the curve with the melting temperature of 573.2 K, the thermal conductivity of 0.0197 W cm^{-1} K^{-1} is obtained for astatine at 300 K. This estimated value is probably good to ±50 percent.

Barium

No values appear to have been reported for the thermal conductivity of barium. Meaden [912] has listed values for the electrical resistivity, ρ, over the range 4 to 295 K, and, on the assumption that the theoretical Lorenz function, L_0, holds for barium at 4 K and above the Debye temperature, 110.5 K, the following values have been derived from the expression $k = L_0 T \rho^{-1}$. These derived values at 4, 150, 200, 250, and 295 K are 0.390, 0.205, 0.194, 0.186, and 0.184 W cm^{-1} K^{-1}, respectively. They should be good to ±20 percent. The value at 4 K is, however, applicable only to barium having a residual electrical resistivity of 0.25 $\mu\Omega$ cm.

TABLE 9. Provisional thermal conductivity of barium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid	
T	k
0	0
4	0.390*
150	0.205*
173.2	0.199*
200	0.194*
223.2	0.190*
250	0.186*
273.2	0.185*
295	0.184*

†The values are for well-annealed high-purity barium, and the value at 4 K is applicable only to barium having a residual electrical resistivity of 0.25 $\mu\Omega$ cm.

*Estimated.

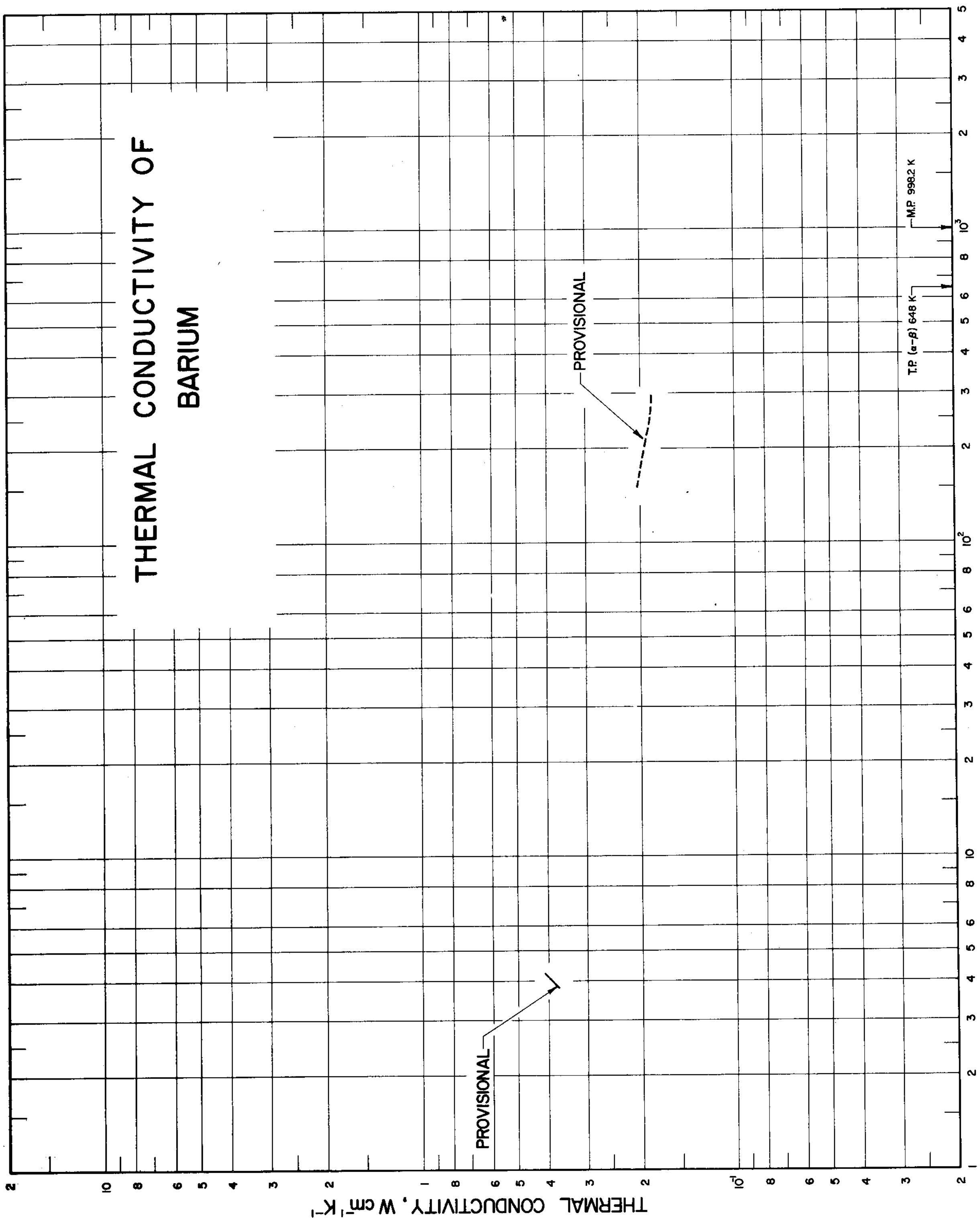

THERMAL CONDUCTIVITY OF
BARIUM
PROVISIONAL
PROVISIONAL
T.P. (α–β) 648 K
M.P. 998.2 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 23

Berkelium

No information is available for the thermal or electrical conductivity of berkelium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidence shows that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of berkelium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Beryllium

Beryllium is an important technological metal, yet from the examination of the data available for its thermal conductivity a need clearly exists for further determinations to be made, particularly at low temperatures. In only one instance has the maximum been clearly defined by a set of determinations. This maximum was at 115 K as obtained by White and Woods [1543] (curve 96) for an impure sintered rod of beryllium containing about 2 percent magnesium and a trace of iron. For high-purity beryllium the maximum should occur at a much lower temperature, but owing to the dearth of information the nature of the dependence of the maximum on purity and temperature cannot at present be determined.

The highest thermal conductivity values obtained for beryllium are those of Grüneisen and Erfling [556] (curve 6). These relate to a single crystal with the heat flow normal to the hexagonal axis, but were only measured for two temperatures, 23 and 91 K, and the maximum would appear to be between them. A rather tentative curve, which fits these two points and has a maximum at about 36 K, has been generated by using equation (7) with $n = 2.80$, $\alpha' = 2.56 \times 10^{-7}$, and $\beta = 0.553$.

At lower temperatures the curve shows closely the same slope as obtained for less pure polycrystalline beryllium samples. At higher temperatures the curve decreases through the temperature interval 91 to 295 K, which is devoid of any acceptable determination for pure beryllium, to link near room temperature with the band of values that range up to about 1400 K. Within this range a smooth continuation of the curve has been chosen. Many of the test samples contain beryllium oxide and it might be anticipated that below about 700 K the presence of beryllia would tend to give values for pure beryllium that are too high and above this temperature values that are too low. Thus, whilst at 500 K the recommended curve lies some 14 percent below the highest observed value, above 1200 K it tends to lie above the mean of the observed values, and nearly 10 percent below the highest-temperature values of Tye [1438] (curves 80–91). Using Tye's mean electrical resistivity of 45.4 $\mu\Omega$ cm for a temperature of 1264 K, and a thermal conductivity value taken from this curve yields a Lorenz function of 2.72×10^{-8} V^2 K^{-2}. Further measurements on pure single crystals over the full temperature range are required. No information is available for molten beryllium.

The tabulated values are for well-annealed high-purity polycrystalline beryllium. Owing to the low purity of the samples studied, the uncertainty of the recommended values (those above room temperature) is thought to be of the order of ±10 percent. The values below room temperature are provisional, and furthermore they are only applicable to beryllium having a residual electrical resistivity of 0.0135 $\mu\Omega$ cm. These values are probably good to within ±20 percent.

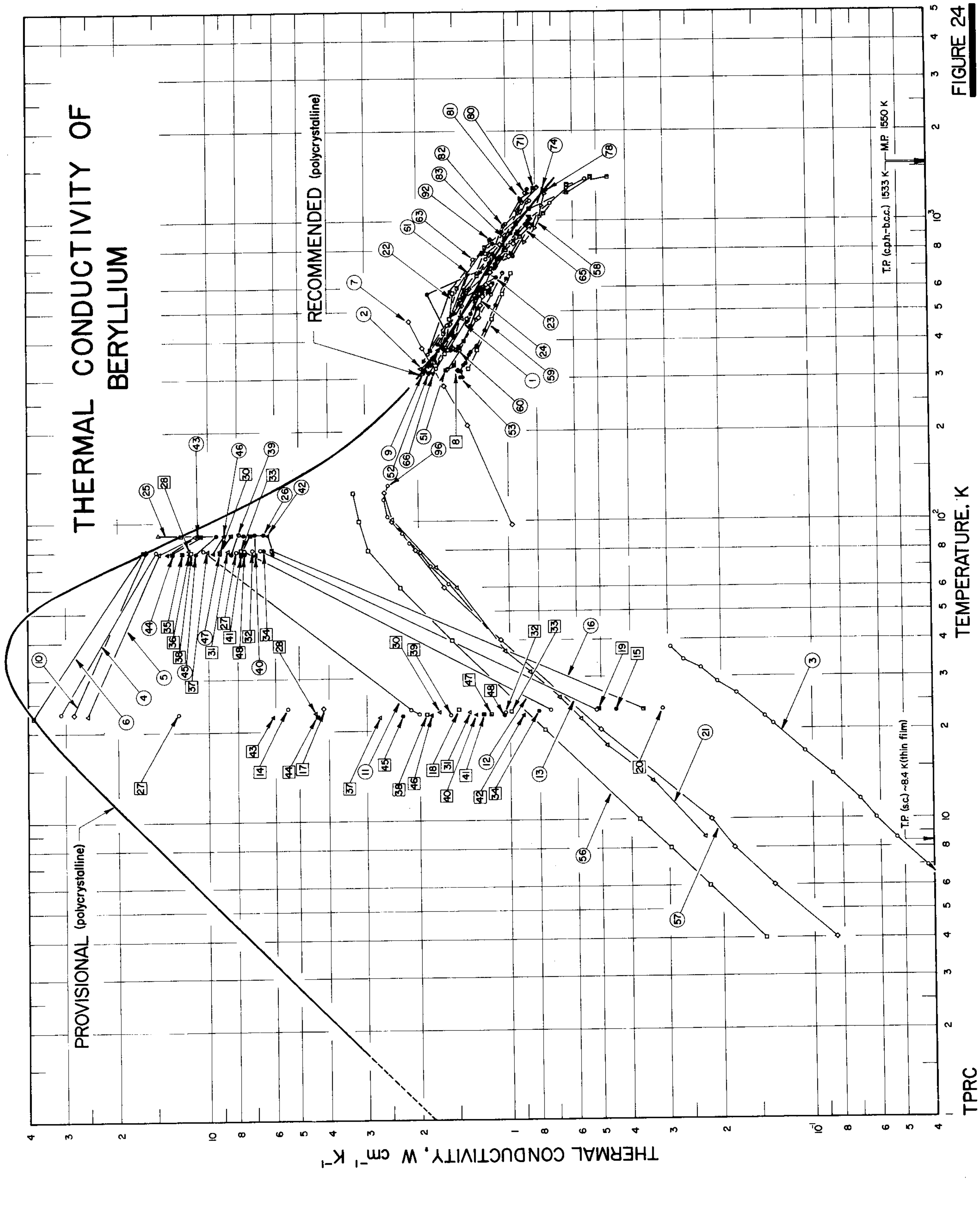
TABLE 10. Recommended thermal conductivity of beryllium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	250	2.36
1	1.81*	273.2	2.18
2	3.62	298.2	2.01
3	5.42	300	2.00
4	7.23	323.2	1.88
5	9.04	350	1.78
6	10.8	373.2	1.68
7	12.6	400	1.61
8	14.4	473.2	1.44
9	16.2	500	1.39
10	18.0	573.2	1.29
11	19.8	600	1.26
12	21.6	673.2	1.18
13	23.3	700	1.15
14	25.1	773.2	1.09
15	26.8	800	1.06
16	28.4	873.2	1.00
18	31.7	900	0.982
20	34.8	973.2	0.927
25	41.2	1000	0.908
30	45.6	1073.2	0.858
35	47.2	1100	0.842
40	46.2	1173.2	0.802
45	44.2	1200	0.787
50	40.0	1273.2	0.751
60	29.8	1300	0.738
70	21.7	1373.2	0.705
80	16.2	1400	0.694
90	12.5		
100	9.90		
123.2	6.54		
150	4.51		
173.2	3.64		
200	3.01		
223.2	2.66		

†The values are for well-annealed high-purity beryllium, and those below room temperature are provisional and are only applicable to a specimen having residual electrical resistivity of 0.0135 $\mu\Omega$ cm.

*Extrapolated.


THERMAL CONDUCTIVITY OF BERYLLIUM
RECOMMENDED (polycrystalline)
PROVISIONAL (polycrystalline)
T.P. (c.p.h.-b.c.c.) 1533 K
M.P. 1550 K
T.P. (s.c.) ~8.4 K (thin film)
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 24

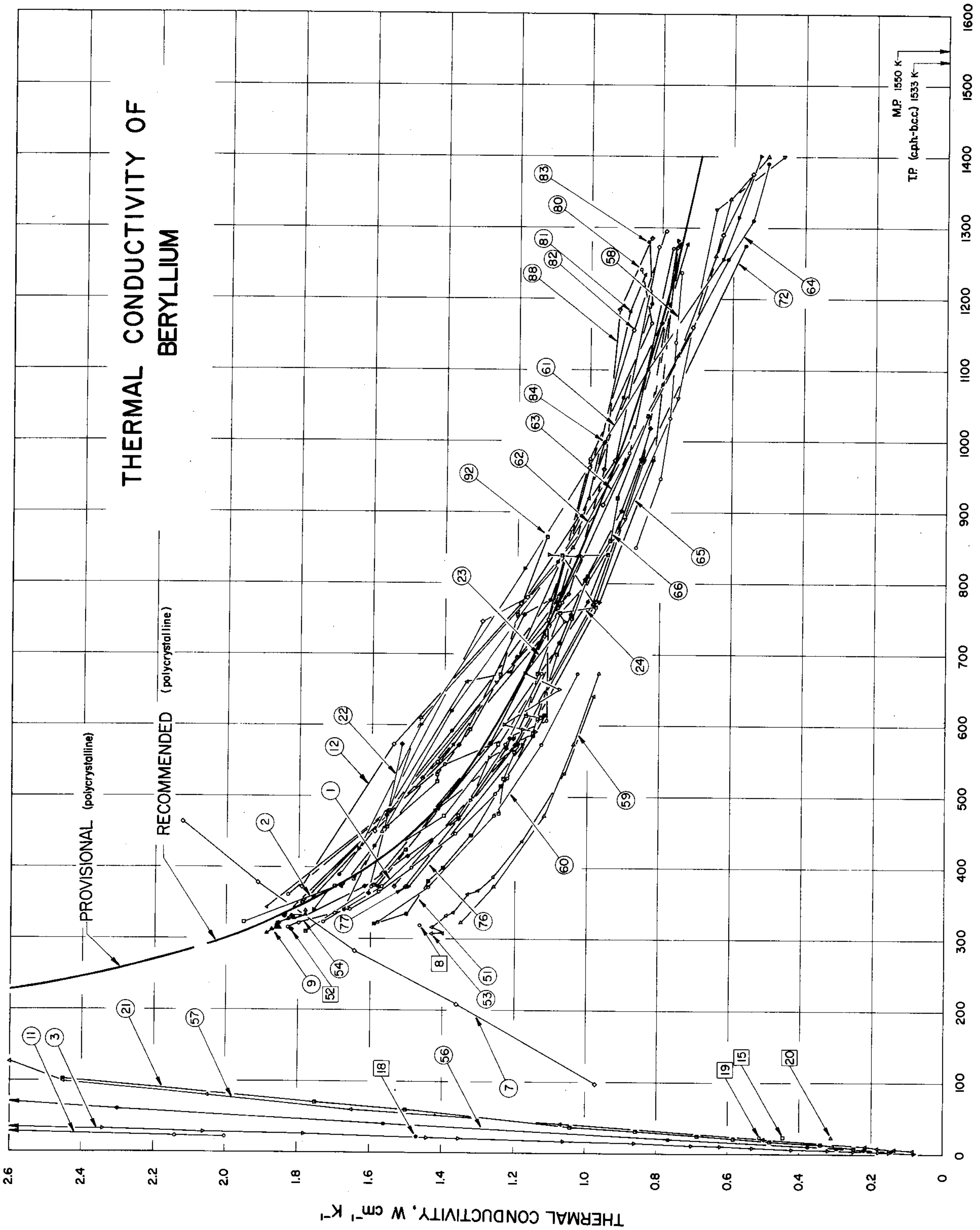

THERMAL CONDUCTIVITY OF BERYLLIUM
PROVISIONAL (polycrystalline)
RECOMMENDED (polycrystalline)
M.P. 1550 K
T.P. (c.p.h.-b.c.c.) 1533 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TPRC

FIGURE 25

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1114	Powell, R. W.	1953	C	312-714	Vi-A. R.	Specimen 1 x 1 x 6.6 cm; spectral analysis showed Al, Ba, Ca, Cu, Fe, Mg, Mn, Si, and Ti as impurities; prepared from a block of beryllium by American G. E. C.; sintered; density 1.83 g cm^{-3}; electrical resistivity reported as 5.2, 6.2, 7.7, 10.9, 14.5, 18.2, 22.2, 26.4, and 30.8 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 3.32, 3.24, 3.13, 3.12, and 3.05 x 10^{-8} V^2 K^{-2} at 50, 100, 200, 300, and 400 C, respectively.
2	1114	Powell, R. W.	1953	C	326-676	Vi-H. T.	The above specimen heat-treated at 700 C; electrical resistivity reported as 4.1, 5.0, 6.6, 9.9, 13.5, 17.1, 20.9, 25.2, and 29.9 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 3.02, 3.01, 2.93, 2.93, and 2.87 x 10^{-8} V^2 K^{-2} at 50, 100, 200, 300, and 400 C, respectively.
3	1220	Rosenberg, H. M.	1955	L	1.8-38	Be-1	Pure specimen; 2.01 cm long, 0.231 cm in dia; made from beryllium powder supplied by Atomic Energy Research Establishment; compressed and sintered at 1100 C in vacuo for several hrs; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 352.
4	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-81	Be 3	Single crystal; electrical resistivity reported as 0.0078, 0.0452, and 0.0755 μohm cm at 20.36, 78.00, and 90.17 K, respectively; heat flow perpendicular to hexagonal axis.
5	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 4	Single crystal; electrical resistivity reported as 0.0124, 0.0537, and 0.0868 μohm cm at 20.37, 77.83, and 90.29 K, respectively; heat flow perpendicular to hexagonal axis.
6	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	Single crystal; electrical resistivity reported as 0.0076, 0.0473, and 0.0770 μohm cm at 20.34, 77.95, and 89.86 K, respectively; heat flow perpendicular to hexagonal axis.
7	841	Lewis, E. J.	1929	F	97-464		Commercially pure specimen; traces of Al, Mg, Cr, Fe, Si, and Mg; ~0.5 total impurities; 21 cm long, 1 cm in dia; supplied by Beryllium Co. of America; electrical resistivity reported as 1.50, 6.45, 14.64, 22.45, 32.45, and 39.00 μohm cm at 84, 294, 496, 674, 880, and 973 K, respectively.
8	1584	Yans, F. M. and Gardner, N. R.	1959		319.2		Vacuum cast.
9	1167	Raeth, C. H.	1944	L	307-338		Pure; 2.553 cm long, 5.047 cm^2 cross-sectional area.
10	555	Grüneisen, E. and Adenstedt, H.	1938	L	23, 80	Be 2	Single crystal; hexagonal parallelepiped; supplied by Degussa Co.; length 1.6 cm, hexagonal cross section 0.00648 cm^2; electrical resistivity reported as 0.00458, 0.0454 and 3.58 μohm cm at 20.33, 79.02, and 273.15 K, respectively; density 1.84 g cm^{-3}; heat flow parallel to the hexagonal axis.
11	555	Grüneisen, E. and Adenstedt, H.	1938	L	23-81	Be 2	The above specimen measured at H (the transverse magnetic field strength) = 4490 oersteds and at θ (angle of rotation of the magnetic field in a plane perpendicular to the specimen axis) = -6°; H perpendicular to one of the binary lateral axes.
12	555	Grüneisen, E. and Adenstedt, H.	1938	L	23, 81	Be 2	The above specimen measured at H = 8750 oersteds and at θ = -6°.
13	555	Grüneisen, E. and Adenstedt, H.	1938	L	23, 81	Be 2	The above specimen measured at H = 10880 oersteds and at θ = -6°.
14	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.70	Be 2	The above specimen measured at H = 2280 oersteds and at θ = -6°.
15	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.50	Be 2	The above specimen measured at H = 12200 oersteds and at θ = -6°.
16	555	Grüneisen, E. and Adenstedt, H.	1938	L	23, 81	Be 2	The above specimen measured at H = 10880 oersteds and at θ = +24° at which H parallel to one of the binary lateral axes.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.70	Be 2	The above specimen measured at H = 2280 oersteds and at $\theta = +24°$.
18	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.45	Be 2	The above specimen measured at H = 4490 oersteds and at $\theta = +24°$.
19	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.40	Be 2	The above specimen measured at H = 8750 oersteds and at $\theta = +24°$.
20	555	Grüneisen, E. and Adenstedt, H.	1938	L	23.50	Be 2	The above specimen measured at H = 12200 oersteds and at $\theta = +24°$.
21	355	White, G.K. and Woods, S.B.	1955	L	9-102	Be 2	High purity, <0.1 Mg and trace of Fe; specimen 4 mm in dia; machined from a sintered rod of high purity beryllium; residual resistivity (extrapolated to 0 K) 1.20 μohm cm; electrical resistivity 1.14, 1.21, 1.20, 1.22, 1.22, 1.20, 1.20, 1.21, 1.21, 1.23, 1.21, 1.24, 1.24, 1.29, and 4.95 μohm cm at 0.7, 1.6, 2.3, 3.2, 4.3, 6.2, 9.7, 13.2, 31.3, 34.3, 59.0, 68.5, 77.9, 90.0, and 295 K, respectively (these results do not confirm the sample as of high purity).
22	1584	Yans, F.M. and Gardner, N.R. (compilers)	1959		363-573		Powder; sintered.
23	1584	Yans, F.M. and Gardner, N.R. (compilers)	1959		499-840		Vacuum cast; extruded.
24	1584	Yans, F.M. and Gardner, N.R. (compilers)	1959		476-840		Flake; extruded.
25	398	Erfling, H.D. and Grüneisen, E.	1942	L	92.1	Be 2	Single crystal; hexagonal parallelepiped; supplied by Degussa Co.; length 1.6 cm, hexagonal cross-section 0.00648 cm^2; electrical resistivity reported as 0.00458, 0.0450, 0.0763, and 3.58 μohm cm at 20.4, 79.0, 90.2, and 273.2 K, respectively; density 1.84 g cm^{-3}; measured in magnetic field of strength 0 to 11.7 kOe at θ (angle of rotation of magnetic field in a plane perpendicular to the specimen axis) = $-53°$ with the magnetic field perpendicular to one of the binary lateral axes.
26	398	Erfling, H.D. and Grüneisen, E.	1942	L	92.1	Be 2	The above specimen measured at $\theta = -23°$ and with the magnetic field parallel to one of the binary lateral axes.
27	556	Grüneisen, E. and Erfling, H.D.	1940	L	23, 81	Be 3	Single crystal; electrical resistivity reported as 0.0835, 0.0789, and 0.1002 μohm cm at 20.36, 78.00 and 90.17 K, respectively; heat flow perpendicular to the hexagonal axis z; measured in a magnetic field of strength 3.4 kOe perpendicular to z.
28	556	Grüneisen, E. and Erfling, H.D.	1940	L	23, 81	Be 3	The above specimen measured with the magnetic field of strength 3.4 kOe parallel to z; electrical resistivity reported as 0.1349, 0.0946, and 0.1114 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
29*	556	Grüneisen, E. and Erfling, H.D.	1940	L	80.6	Be 3	The above specimen measured in a magnetic field of strength 6.8 kOe perpendicular to z; electrical resistivity reported as 0.2037, 0.1465, and 0.1444 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
30	556	Grüneisen, E. and Erfling, H.D.	1940	L	23, 81	Be 3	The above specimen measured with the magnetic field of strength 6.8 kOe parallel to z; electrical resistivity reported as 0.3367, 0.1740, and 0.1756 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
31	556	Grüneisen, E. and Erfling, H.D.	1940	L	23, 81	Be 3	The above specimen measured in a magnetic field of strength 10.1 kOe perpendicular to z; electrical resistivity reported as 0.4829, 0.2422, and 0.2074 μohm cm at 20.36, 78.00, and 90.17 K, respectively.

* Not shown in figure.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
32	556	Grüneisen, E. and Erfling, H. D.	1940	L	23, 81	Be 3	The above specimen measured with the magnetic field of strength 10.1 kOe parallel to z; electrical resistivity reported as 0.6137, 0.2707, and 0.2533 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
33	556	Grüneisen, E. and Erfling, H. D.	1940	L	23, 81	Be 3	The above specimen measured in a magnetic field of strength 11.7 kOe perpendicular to z; electrical resistivity reported as 0.6271, 0.2992, and 0.2435 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
34	556	Grüneisen, E. and Erfling, H. D.	1940	L	23, 81	Be 3	The above specimen measured with the magnetic field of strength 11.7 kOe parallel to z; electrical resistivity reported as 0.7755, 0.3210, and 0.2968 μohm cm at 20.36, 78.00, and 90.17 K, respectively.
35	556	Grüneisen, E. and Erfling, H. D.	1940	L	79.0	Be 4	Single crystal; electrical resistivity reported as 0.0746, 0.0865, and 0.1114 μohm cm at 20.37, 77.83, and 90.29 K, respectively; heat flow perpendicular to z; measured in a magnetic field of strength 3.4 kOe perpendicular to z.
36	556	Grüneisen, E. and Erfling, H. D.	1940	L	79.0	Be 4	The above specimen measured with the magnetic field of strength 3.4 kOe parallel to z; electrical resistivity reported as 0.1226, 0.1038, and 0.1240 μohm cm at 20.37, 77.83, and 90.29 K, respectively.
37	556	Grüneisen, E. and Erfling, H. D.	1940	L	23, 79	Be 4	The above specimen measured in a magnetic field of strength 6.8 kOe perpendicular to z; electrical resistivity reported as 0.1989 and 0.1508 μohm cm at 20.37 and 77.83 K, respectively.
38	556	Grüneisen, E. and Erfling, H. D.	1940	L	23, 79	Be 4	The above specimen measured with the magnetic field of strength 6.8 kOe parallel to z; electrical resistivity reported as 0.2847 and 0.1886 μohm cm at 20.37 and 77.83 K, respectively.
39	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 4	The above specimen measured in a magnetic field of strength 10.1 kOe perpendicular to z; electrical resistivity reported as 0.3754, 0.2437, and 0.2184 μohm cm at 20.37, 77.83, and 90.29 K, respectively.
40	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 4	The above specimen measured in a magnetic field of strength 10.1 kOe parallel to z; electrical resistivity reported as 0.4939, 0.2934, and 0.2763 μohm cm at 20.37, 77.83, and 90.29 K, respectively.
41	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 4	The above specimen measured in a magnetic field of strength 11.7 kOe perpendicular to z; electrical resistivity reported as 0.480, 0.2972, and 0.2548 μohm cm at 20.37, 77.83, and 90.29 K, respectively.
42	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 4	The above specimen measured with the magnetic field of strength 11.7 kOe parallel to z; electrical resistivity reported as 0.612, 0.345, and 0.3228 μohm cm at 20.37, 77.83, and 90.29 K, respectively.
43	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	Single crystal; electrical resistivity reported as 0.0838 and 0.1028 μohm cm at 78.1 and 89.86 K, respectively; heat flow perpendicular to z; measured in a magnetic field of strength 3.4 kOe perpendicular to z.
44	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured with the magnetic field of strength 3.4 kOe parallel to z; electrical resistivity reported as 0.0962 and 0.1119 μohm cm at 78.1 and 89.86 K, respectively.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT OF INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
45	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured in a magnetic field of strength 6.8 kOe perpendicular to z; electrical resistivity reported as 0.1566 and 0.1507 μohm cm at 78.1 and 89.86 K, respectively.
46	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured with the magnetic field of strength 6.8 kOe parallel to z; electrical resistivity reported as 0.1790 and 0.1767 μohm cm at 78.1 and 89.86 K, respectively.
47	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured in a magnetic field of strength 10.1 kOe perpendicular to z; electrical resistivity reported as 0.2596 and 0.2187 μohm cm at 78.1 and 89.86 K, respectively.
48	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured in a magnetic field of strength 10.1 kOe parallel to z; electrical resistivity reported as 0.2781 and 0.2572 μohm cm at 78.1 and 89.86 K, respectively.
49*	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured in a magnetic field of strength 11.7 kOe perpendicular to z; electrical resistivity reported as 0.3180 and 0.2582 μohm cm at 78.1 and 89.86 K, respectively.
50*	556	Grüneisen, E. and Erfling, H. D.	1940	L	23-91	Be 8	The above specimen measured with the magnetic field of strength 11.7 kOe parallel to z; electrical resistivity reported as 0.3312 and 0.3002 μohm cm at 78.1 and 89.86 K, respectively.
51	1114	Powell, R.W.	1953	C	320-616	v A.R.	2.287 cm dia x 15.72 cm long; prepared from the Brush Beryllium Co's. crude reactor product, chill-cast and machined; as received; density 1.84 g cm^{-3}; electrical resistivity reported as 5.8, 6.7, 8.2, 11.3, 14.6, 18.1, 21.8, 25.6, and 29.2 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function reported as 3.24, 3.17, 3.05, and 2.95 x 10^{-8} V^2 K^{-2} at 50, 100, 200, and 300 C, respectively.
52	1114	Powell, R.W.	1953	C	313-1018	v H.T.	The above specimen heat-treated at ~700 C; electrical resistivity reported as 4.2, 5.0, 6.6, 9.9, 13.3, 16.9, 20.7, 24.4, and 29.2 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function reported as 2.78, 2.85, 2.82, 2.82, 2.79, 2.76, 2.64, and 2.59 V^2 K^{-2} at 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively.
53	1114	Powell, R.W.	1953	C		ii A.R.	2.25 cm dia x 7.7 cm long; prepared from the Brush Beryllium Co's. crude reactor product; chill cast; density 1.842 g cm^{-3}; electrical resistivity 7.1, 8.0, 9.6, 12.9, 16.3, 19.9, 23.8, 27.8, and 31.8 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 3.48, 3.34, 3.08, and 2.95 x 10^{-8} V^2 K^{-2} at 50, 100, 200, and 300 C, respectively.
54	1114	Powell, R.W.	1953	C		ii H.T.	The above specimen heat-treated at ~700 C; electrical resistivity 4.1, 5.1, 6.7, 10.2, 13.9, 17.8, 21.9, 26.3, and 30.9 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 2.78, 2.78, 2.84, and 2.84 x 10^{-8} V^2 K^{-2} at 50, 100, 200, and 300 C, respectively.
55*	321	Day, R.K.	1965	C	373.2		Commercial purity; 0.5 in. dia x 0.5 in. thick; copper used as comparative material.

* Not shown in figure.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
56	1101	Powell, R. L., Harden, J. L, and Gibson, E. F.	1960		4.0-125		99.132 Be, 0.768 O, 0.056 Al, 0.035 Si, 0.016 Ni, 0.010 Mn, trace B and Li; the oxygen contained in 1.2 BeO; specimen axis parallel to the pressing axis.
57	1101	Powell, R. L., Harden, J. L., and Gibson, E. F.	1960		4.0-125		99.125 Be, 0.755 O, 0.044 Al, 0.014 Ni, 0.009 Mn, trace B and Li; the oxygen contained in 1.18 BeO; specimen axis perpendicular to the pressing axis.
58	429	Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E.	1958	L	850-1238	YB-9052	99.428 Be and 0.572 O; the oxygen contained in 0.84 BeO.
59	1114	Powell, R. W.	1953	C	313-690	iv A. R.	98.5 Be, 0.18 Fe, 0.13 Al, 0.05 Cl, 0.03 Cu, the rest BeO (3% Al_2O_3); 6.6 x 1.0 x 1.0 cm; machined from a chill-cast bar prepared from German flake beryllium; density 1.823 g cm^{-3}; electrical resistivity 8.0, 8.9, 10.5, 13.8, 17.3, 21.1, 25.1, 29.4, and 33.9 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 3.71, 3.55, 3.27, 3.13, and 3.06 x 10^{-8} $V^2 K^{-2}$ at 50, 100, 200, 300, and 400 C, respectively.
60	1114	Powell, R. W.	1953	C	315-659	iv H. T.	The above specimen heat-treated at 700 C; electrical resistivity 5.6, 6.7, 8.4, 11.9, 15.5, 19.4, 23.6, 27.9, and 32.8 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, and 700 C, respectively; Lorenz function 3.27, 3.25, 3.16, 3.05, and 2.98 x 10^{-8} $V^2 K^{-2}$ at 50, 100, 200, 300, and 400 C, respectively.
61	609	Ho, J. and Wright, E. S.	1960		340-1400	Y 6825	98.555 Be, 0.947 O, 0.003 Mg, 0.015 Al, 0.01 Si, 0.001 Ca, 0.002 Ti, 0.008 Cr, 0.005 Mn, 0.15 Fe, and 0.004 Cu; the oxygen contained in 1.48 BeO.
62	609	Ho, J. and Wright, E. S.	1960		450-1400	Y 9384	99.196 Be, 0.541 O, 0.006 Mg, 0.05 Al, 0.008 Si, 0.002 Ca, 0.004 Ti, 0.01 Cr, 0.008 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; the oxygen contained in 0.845 BeO.
63	609	Ho, J. and Wright, E. S.	1960		450-1375	Y 6826	99.018 Be, 0.827 O, 0.01 Mg, 0.03 Al, 0.02 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.006 Mn, 0.15 Fe, 0.015 Ni, and 0.01 Cu; the oxygen contained in 1.292 BeO.
64	609	Ho, J. and Wright, E. S.	1960		340-1390	YB 1000	98.951 Be, 0.787 O, 0.015 Mg, 0.03 Al, 0.008 Si, 0.002 Ca, 0.002 Ti, 0.01 Cr, 0.01 Mn, 0.15 Fe, 0.02 Ni, and 0.015 Cu; the oxygen contained in 1.229 BeO.
65	609	Ho, J. and Wright, E. S.	1960		480-1400	LYB 1102	99.002 Be, 0.634 O, 0.02 Mg, 0.04 Al, 0.04 Si, 0.002 Ca, 0.004 Ti, 0.02 Cr, 0.008 Mn, 0.20 Fe, 0.02 Ni, and 0.01 Cu; the oxygen contained in 0.992 BeO.
66	609	Ho, J. and Wright, E. S.	1960		310-1035	BMI 5	99.303 Be, 0.390 O, 0.015 Mg, 0.03 Al, 0.01 Si, 0.001 Ca, 0.003 Ti, 0.015 Cr, 0.008 Mn, 0.20 Fe, 0.015 Ni, and 0.015 Cu; the oxygen contained in 0.609 BeO.
67*	1248	Sawyer, et al.			373-573		Sintered powder.
68*	534	Grenell, L. H., Linebrink, O. L., and Johnson, K. L.	1947		495-833		Vacuum-cast; extruded.
69*	534	Grenell, L. H., et al.	1947		481-839		Flake, extruded.
70*	854	Lockhart, R.	1948		322		Vacuum cast.
71	275	Chirkin, V. S.	1966	P	373-1273		1.264 impurities (mainly Mg and Al); 3.6 cm dia x 1.6 cm thick; hot-pressed; density 1.838, 1.832, 1.827, 1.821, and 1.813 g cm^{-3} at 100, 300, 500, 700, and 1000 C, respectively; thermal conductivity values calculated from measured thermal diffusivity and density with specific heat capacity values taken from Chirkin, V. S. ("Thermal Conductivity of Industrial Materials," ed. 2. M., Mashgiz, p. 146, 1962).

*Not shown in figure.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
72	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 1100 ± 50 C for 200 ± 4 hrs.
73*	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 900 ± 25 C for 200 ± 4 hrs.
74	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 1100 ± 50 C for 400 ± 8 hrs.
75*	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 900 ± 25 C for 400 ± 8 hrs.
76	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 1100 ± 50 C for 600 ± 12 hrs.
77	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 900 ± 25 C for 600 ± 12 hrs.
78	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 1100 ± 50 C for 800 ± 16 hrs; density 1.838, 1.832, 1.828, 1.822, and 1.814 g cm^{-3} at 100, 300, 500, 700, and 1000 C, respectively.
79*	275	Chirkin, V. S.	1966	P	373-1273		Similar to above but specimen heat-treated at 900 ± 25 C for 800 ± 16 hrs.
80	1438	Tye, R. P.	1968	L	362-1241	1	98.4 Be, 1.8 BeO, 0.15 C, 0.13 Fe, 0.09 Al, 0.03 Si, 0.01 Mg, 0.01 Mn, and 0.04 others; specimen in the form of a cylinder approx 100 mm long and 13 mm in dia with tapered ends; hot-pressed to >900 C; density 1.86 g cm^{-3}; electrical resistivity 4.28 μohm cm at 294 K.
81	1438	Tye, R. P.	1968	L	344-1234	2	Cut from the same stock in the same form as the above specimen; electrical resistivity 4.05, 6.99, 11.22, 14.88, 15.53, 21.3, 24.83, 30.22, 35.6, 40.66, 44.2, and 46.9 μohm cm at 22.1, 122.5, 253.3, 362.5, 404, 539, 627, 739.5, 826, 900.5, 973, and 1010 C, respectively.
82	1438	Tye, R. P.	1968	L	351-1295	3	Similar to the above specimen but electrical resistivity 4.32 μohm cm at 294 K.
83	1438	Tye, R. P.	1968	L	390-1280	4	98.2 Be, 1.7 BeO, 0.13 Fe, 0.12 Al, 0.12 C, 0.04 Si, 0.03 Mg, 0.01 Mn, and 0.04 others; same dimensions and fabrication method as the above specimen; density 1.853 g cm^{-3}; electrical resistivity 4.50, 6.51, 12.32, 15.20, 24.09, 29.92, 39.1, and 44.1 μohm cm at 22.2, 98.3, 276, 368.5, 591.3, 737.1, 885, and 976 C, respectively.
84	1438	Tye, R. P.	1968	L	333-1166	5	Cut from the same stock in the same form as the above specimen; electrical resistivity 4.39 μohm cm at 294 K.
85*	1438	Tye, R. P.	1968	L	361-1301	6	98.46 Be, 1.60 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.03 Si, 0.01 Mg, 0.01 Mn, and 0.04 others; same dimensions and fabrication method as the above specimen; density 1.86 g cm^{-3}; electrical resistivity 4.61, 6.88, 10.18, 15.15, 20.42, 25.72, 30.12, 37.1, and 44.9 μohm cm at 25.6, 101.3, 210.4, 357, 496, 635, 726, 848, and 985 C, respectively.
86*	1438	Tye, R. P.	1968	L	347-1277	7	Cut from the same stock in the same form as the above specimen; electrical resistivity 4.50 μohm cm at 294 K.
87*	1438	Tye, R. P.	1968	L	377-1250	8	Similar to the above specimen but electrical resistivity 4.25, 7.1, 10.74, 14.42, 18.93, 24.52, 28.12, 35.5, and 45.3 μohm cm at 22, 123, 233.3, 341.2, 473.3, 612.2, 699.9, 840.5, and 1003 C, respectively.

* Not shown in figure.

TABLE 11. THERMAL CONDUCTIVITY OF BERYLLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
88	1438	Tye, R.P.	1968	L	351-1284	9	98.41 Be, 1.64 BeO, 0.12 C, 0.12 Fe, 0.09 Al, 0.03 Si, 0.01 Mg, 0.01 Mn, and 0.04 others; same dimensions and fabrication method as the above specimen; density 1.86 g cm^{-3}; electrical resistivity 4.72, 7.4, 10.95, 16.95, 19.6, 25.15, 28.81, 32.4, 38.3, 42.2, and 45.6 μohm cm at 24.3, 120, 227.5, 392.5, 466.3, 603.3, 686.3, 772.5, 860, 935, and 995 C, respectively.
89*	1438	Tye, R.P.	1968	L	398-1252	10	Cut from the same stock in the same form as the above specimen; electrical resistivity 4.59 μohm cm at 294 K.
90*	1438	Tye, R.P.	1968	L	355-1247	11	Similar to the above specimen but electrical resistivity 4.70, 7.43, 10.82, 15.03, 20.41, 24.83, 36.2, 40.9, and 44.8 μohm cm at 24.5, 123, 222, 353.5, 505.2, 616, 834.5, 899, and 993 C, respectively.
91*	1438	Tye, R.P.	1968	L	395-1249	12	Similar to the above specimen but electrical resistivity 4.69 μohm cm at 294 K.
92	1439	Tye, R.P. and Quinn, J.E.	1968	L	385-865	1	The same specimen No. 1 as for curve No. 25; electrical resistivity 4.56, 4.64, 7.1, 7.73, 8.92, 9.55, 12.23, 12.58, and 24.2 μohm cm at 20, 20, 110, 131, 168, 188, 258, 277, and 586 C, respectively.
93*	1439	Tye, R.P. and Quinn, J.E.	1968	L	330-884	2	The same specimen No. 2 as for curve No. 26; electrical resistivity 4.66, 4.73, 6.24, 8.54, 10.3, 13.2, 15.3, 16.0, 16.8, 18.7, 22.8, and 24.6 μohm cm at 20, 20, 94, 193, 209, 297, 341, 368, 390, 443, 535, and 597 C, respectively.
94*	1439	Tye, R.P. and Quinn, J.E.	1968	L	297-807	3	The same specimen No. 3 as for curve No. 27; electrical resistivity 4.66, 8.45, 9.1, 14.1, 14.1, 19.02, and 22.4 μohm cm at 20, 159.5, 174, 289, 369, 445, and 534 C, respectively.
95*	1439	Tye, R.P. and Quinn, J.E.	1968	L	304-853	5	The same specimen No. 5 as for curve No. 29; electrical resistivity 4.58, 4.88, 16.0, 17.0, 20.2, and 23.3 μohm cm at 20, 30.5, 355, 401, 482, and 552 C, respectively.
96	1543	White, G.K. and Woods, S.B.	1955	L	8.7-132		98 Be, 2 Mg, and trace of Fe; cylindrical specimen 5 mm dia; supplied by Brush Co.; residual electrical resistivity ρ_0 = 1.11 μohm cm; electrical resistivity 1.05, 1.06, 1.06, 1.08, 1.08, 1.09, 1.10, 1.10, 1.09, 1.09, 1.11, 1.15, 1.15, 1.16, 1.16, and 5.08 μohm cm at 0.6, 1.5, 2.2, 3.3, 5.0, 8.5, 10.7, 21.5, 26.1, 31.1, 36.5, 62.0, 77.9, 84.7, 90.0, and 295 K, respectively.

Bismuth

The room-temperature thermal conductivity of bismuth is lower than any metal, except probably some of the transuranium elements. It is the most diamagnetic and has the highest Hall effect of all metals.

Many determinations of the thermal conductivity of bismuth have been reported and these values spread over a fairly wide band of values. Part of this spread is probably due to a certain amount of preferred crystal orientation being present in the samples investigated, since at normal temperatures the thermal conductivity perpendicular to the trigonal axis is about 70 percent greater than for the direction parallel to this axis. Also many determinations have related to the influence of magnetic fields of varying strength and orientation.

Over the range from about 20 K to the melting point 544.592 K, smooth curves based on the available data have been drawn to approximate the most probable values for these two crystal directions and for polycrystalline bismuth. At lower temperatures the data become less definite owing to the fact that some earlier workers failed to fully specify the samples studied.

The highest of the above mentioned curves has, for the present, been extrapolated to fit the highest of the single crystal data in the thermal conductivity maximum region, that of Shalyt [1294] (curve 1), and has been extended to lower temperatures. Manchon [879] has obtained higher values for two samples (curves 137–139) over the temperature range 1.3 to 2.0 K. At 1.3 K he considers the electronic conduction component to be only of the order of 10 percent, phonons being responsible for the major component; boundary scattering also occurs. More work is required on well characterized samples of bismuth of high purity.

Of the six sets of values available for the thermal conductivity of molten bismuth, that of Powell and Tye [1131] (curve 4) yields Lorenz functions that exceed the theoretical value by less than 5 percent; the others exceed it by up to 60 percent at 573 K, except for the values of Yurchak and Filippov [1591] (148) derived from thermal diffusivity measurements, which at their maximum temperature of 1023 K give a Lorenz function of 2.20×10^{-8} V^2 K^{-2} (10 percent below the theoretical value). In order to give some weight to these higher values, the recommended curve has been drawn to give a Lorenz function which decreases from about 2.87×10^{-8} V^2 K^{-2} at 573 K to 2.51×10^{-8} at 1273 K.

The proposed curve indicates that at the melting point the ratio of the thermal conductivity of liquid to solid bismuth is of the order of 1.9, a ratio considerably greater than that of 1.56 suggested for antimony, an element often regarded as rather similar to bismuth.

There are, therefore, good grounds for suggesting that further work would be in order to establish whether bismuth does have a Lorenz function well into the molten state of above or below the theoretical value, and for further study of the behavior of bismuth and antimony near their melting points.

The tabulated values are for well-annealed high-purity bismuth. The probable uncertainty of the recommended values (those above 20 K) is of the order of ±5 to ±10 percent for the solid state at room temperature and above, increasing to ±15 to ±20 percent for the molten state. The values below 20 K are merely typical values for the low-temperature thermal conductivity of well-annealed high-purity bismuth.

TABLE 12. Recommended thermal conductivity of bismuth†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

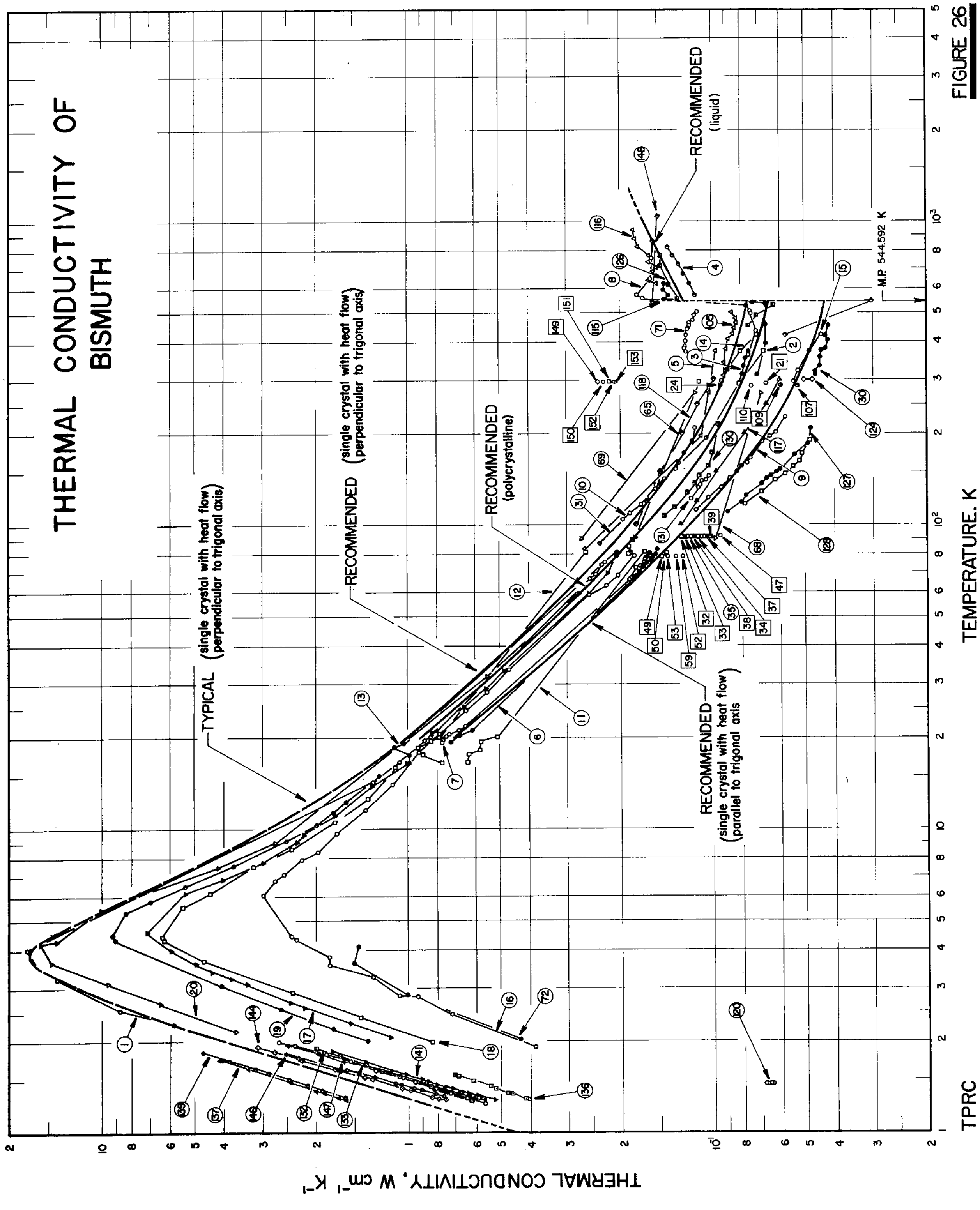
Solid

T	‖ to trigonal axis k	⊥ to trigonal axis k	Poly-crystalline k
0		0	
1		0.452*	
2		3.94	
3		11.8	
4		17.1	
5		11.9	
6		7.98	
7		5.77	
8		4.40	
9		3.50	
10		2.88	
11		2.45	
12		2.11	
13		1.85	
14		1.65	
15		1.48	
16		1.36	
18		1.15	
20	0.700	1.00	0.900
25	0.538	0.780	0.695
30	0.434	0.635	0.568
35	0.364	0.536	0.478
40	0.311	0.465	0.414
45	0.272	0.410	0.365
50	0.243	0.367	0.326
60	0.199	0.303	0.268
70	0.168	0.260	0.231
80	0.148	0.230	0.203
90	0.131	0.206	0.182
100	0.119	0.188	0.165
123.2	0.0994	0.159	0.138
150	0.0826	0.136	0.118
173.2	0.0739	0.123	0.107
200	0.0667	0.112	0.0969
223.2	0.0612	0.105	0.0904
250	0.0581	0.0995	0.0854
273.2	0.0554	0.0953	0.0820
298.2	0.0530	0.0919	0.0789
300	0.0528	0.0915	0.0787
323.2	0.0510	0.0890	0.0763
350	0.0491	0.0860	0.0739
373.2	0.0481	0.0844	0.0722
400	0.0469	0.0822	0.0704
473.2	0.0446	0.0784	0.0669
500	0.0438	0.0775	0.0663
544.592	0.0429	0.0761	0.0650

Liquid

T	k
544.592	0.124
573.2	0.128
600	0.131
673.2	0.138
700	0.141
773.2	0.148
800	0.150
873.2	0.157
900	0.159
973.2	0.166
1000	0.168
1073.2	0.172*
1100	0.175*
1173.2	0.179*
1200	0.182*
1273.2	0.185*
1300	0.188*

†The values are for well-annealed high-purity bismuth, and those below 20 K are merely typical values.
*Extrapolated.


THERMAL CONDUCTIVITY OF BISMUTH
TYPICAL (single crystal with heat flow perpendicular to trigonal axis)
RECOMMENDED (single crystal with heat flow perpendicular to trigonal axis)
RECOMMENDED (polycrystalline)
RECOMMENDED (single crystal with heat flow parallel to trigonal axis)
RECOMMENDED (liquid)
M.P. 544.592 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 26

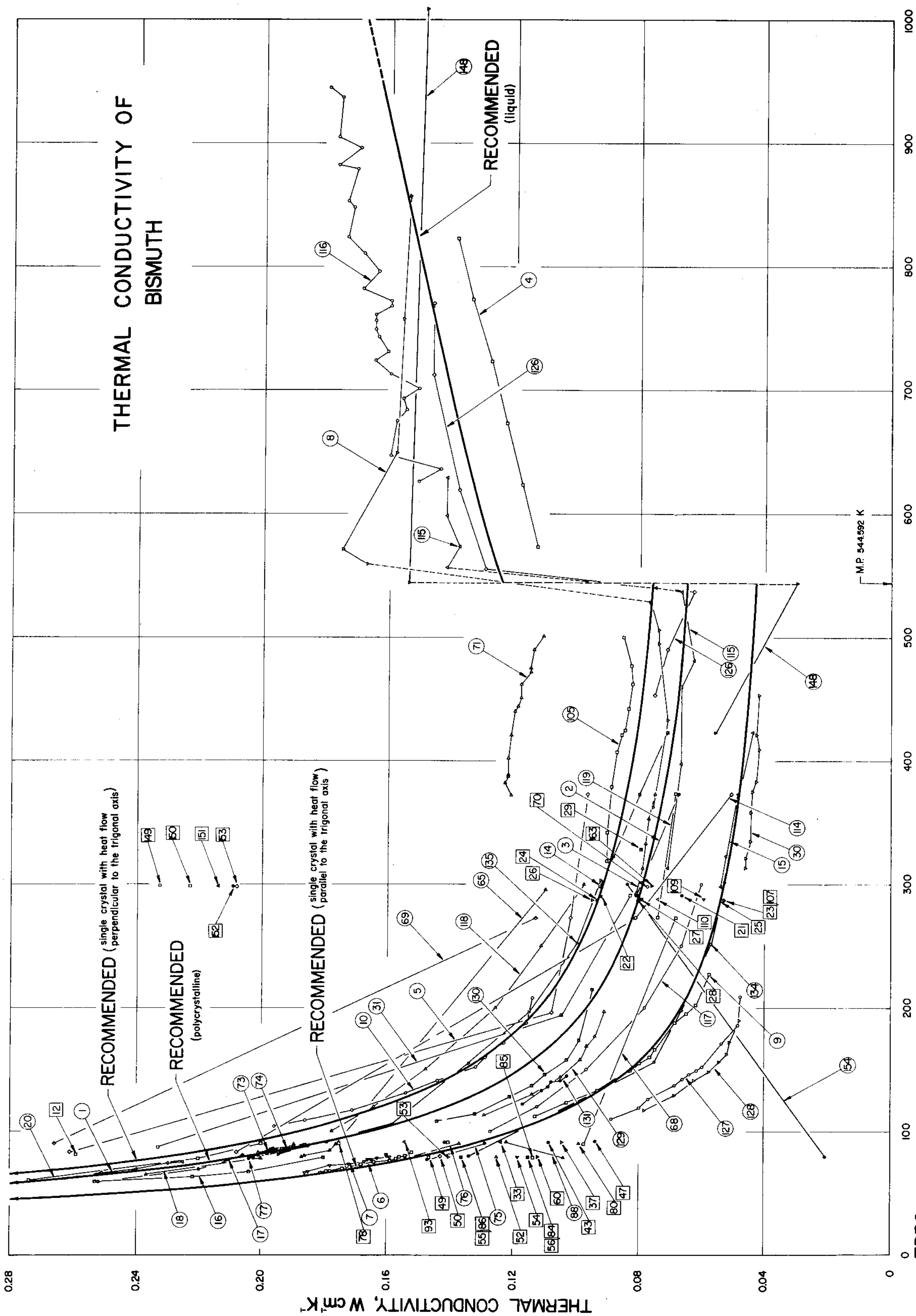

THERMAL CONDUCTIVITY OF
BISMUTH
RECOMMENDED (single crystal with heat flow perpendicular to the trigonal axis)
RECOMMENDED (polycrystalline)
RECOMMENDED (single crystal with heat flow parallel to the trigonal axis)
RECOMMENDED (liquid)
M.P. 544.592 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TPRC

FIGURE 27

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1294	Shalyt, S.	1944	L	2.3-76		Highly purified; single crystal; cylindrical specimen of 7.5 cm length and 0.1 cm^2 cross-sectional area; supplied by Hilger Co.; electrical resistivity ratio $\rho(T)/\rho(0C)$ = 0.320, 0.0725, 0.039 and 0.019 at 77.35, 20.4, 14.1 and 4.2 K, respectively.
2	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373		Impurities, < 0.03 total of Pb and Fe; cast wire; 8.95 cm long, 1.795 cm dia; density 9.78 g cm^{-3} at 18 C; electrical conductivity at 18 and 100 C being 0.840 and 0.624 x 10^4 ohm^{-1} cm^{-1}, respectively.
3	1247, 281	Sawyer, R.B. and Clifford, J.M.	1955	F	293-373		Pure; cast from granular bismuth; electrical conductivity 7360, 6760, 6330, 5920, and 5500 ohm^{-1} cm^{-1} at 293, 313, 333, 353, and 373 K, respectively.
4	1131	Powell, R.W. and Tye, R.P.	1957	C	573-823		High purity; molten metal; contained in a cavity 3.5 in. long, 0.94 in. dia; electrical resistivity 128.6, 131.1, 133.6, 136.0, and 138.5 μohm cm at 300, 350, 400, 450, and 500 C respectively; stainless steel used as comparative material.
5	481	Gehlhoff, G. and Neumeier, F.	1913	L	83-373		Pure; electrical conductivity reported as 2.640, 1.190, 0.915, and 0.612 x 10^4 ohm^{-1} cm^{-1} at -190, -77, 0, and 100 C, respectively.
6	338	deHaas, W.J., Gerritsen, A.N., and Capel, W.H.	1936	L	19-83	PZ 2	99.997 Bi; 0.002 Ag, traces of Pb and Cu; single crystal; length 3 cm, cross-sectional area 0.1 cm^2; crystal grown from 'Bi 9506 bismuth' supplied by Adam Hilger Ltd., London; heat flow parallel to trigonal axis; electrical resistivity ratio $\rho(T)/\rho(0C)$ = 0.0711, 0,0634, and 0.0452 at 20.37, 18.47, and 14.15 K, respectively.
7	338	deHaas, W.J. et al.	1936	L	19-81	PZ 4	99.998 Bi; 0.001 Ag; trace of Pb; single crystal; length 3 cm, cross-sectional area 0.1 cm^2; crystal grown from 'Bi 10283 bismuth' supplied by Adam Hilger Ltd., London; heat flow parallel to trigonal axis; $\rho(T)/\rho(0C)$ = 0.244, 0.0540, 0.0474, and 0.0324 at 70.85, 20.37, 18.47, and 14.15 K, respectively.
8	778	Konno, S.	1919	L	362-857		Cylindrical specimen.
9	1209	Rodine, M.T.	1934	L	112-228	No. 1	High purity; single crystal; specimen 1.231 cm in length and cross-section roughly triangular in shape with dimensions ~3 mm on a side; specimen prepared at California Institute of Technology; heat flow parallel to trigonal axis; measured in vacuum of 10^{-6} mm Hg.
10	1209	Rodine, M.T.	1934	L	105-208	No. 2	High purity; single crystal; specimen 1.3 cm long and similar in form to No. 1; specimen prepared at California Institute of Technology; heat flow perpendicular to trigonal axis; measured in a vacuum of 10^{-6} mm Hg.
11	335	deHaas, W.J. and Capel, W.H.	1934	L	17-81	P	99.995 Bi; major impurity, Ag; single crystal; specimen consisted of two rods each of size 28 x 5 x 5 mm; grown from H.S. Brand, Laboratory No. 8016 bismuth, supplied by Adam Hilger Ltd., London; heat flow parallel to trigonal axis (the specimen axis).
12	336	deHaas, W.J. and Capel, W.H.	1934	L	17-81	S_1	99.995 Bi; major impurity, Ag; single crystal; specimen consisted of two rods each of size 28 x 5.8 x 4.5 mm; grown from material supplied by Adam Hilger Ltd., London; material melted and pressed into mould to be in contact with a seed crystal, then cooled slowly to crystallize; heat flow parallel to a binary axis.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	336	deHaas, W.J. and Capel, W.H.	1934	L	17-81	S_2	Similar to the above specimen except heat flow parallel to a bisectrix between two binary axes.
14	720	Kaye, G.W.C.	1939	L	298-423	Bi-1	High purity; spectroscopic examination showing traces of Pb and Cu; single crystal; specimen cut in the form of disks 25 mm in dia and 2 mm thick from a large crystal grown by Bridgman's method; supplied by Kahlbaum; density 9.78 g cm^{-3}; at room temp; electrical resistivity reported as 114 μohm cm at 25 C; heat flow perpendicular to trigonal axis. (Data extracted from smooth curve.)
15	720	Kaye, G.W.C.	1939	L	298-423	Bi-2	Similar to the above specimen except electrical resistivity 144 μohm cm at 25 C and heat flow parallel to trigonal axis.
16	1543	White, G.K. and Woods, S.B.	1955	L	2-80	Bi-1	99.97 pure when received; specimen 2 mm dia, 6 mm long; it contained columnar crystals penetrating to the center of the rod, 16 to 18 crystals being exposed on the circular section; metal supplied by Mining and Chemical Products (London); cast and cooled quickly; residual electrical resistivity ρ_0 = 104 μohm cm; ρ(295 K) = 136 μohm cm.
17	1543	White, G.K. and Woods, S.B.	1955	L	2-91	Bi-2	99.99 pure; 6 columnar crystals per circular section; specimen 3 mm dia, 6 cm long; granular bismuth supplied by the General Chemical Division of Allied Chemical and Dye Corp.; cast in a brass former; cooled slowly, residual electrical resistivity ρ_0 = 5.9 μohm cm; ρ (295 K) = 120 μohm cm.
18	1551	White, G.K. and Woods, S.B.	1958	L	2-78	Bi-3	99.999 pure; crystals about 1 cm long and had the lateral dimensions of the rod; specimen about 3.5 mm dia, 6 cm long; bismuth supplied by Varlacoid Chemical Co. of New York; zone-refined and annealed for several days at a temp just below melting point; residual electrical resistivity ρ_0 = 2.07 μohm cm; ρ (295 K, assumed) = 118 μohm cm.
19	1551	White, G.K. and Woods, S.B.	1958	L	2-79	Bi-4	99.999 pure; specimen contained about 3 crystals; it had a triangular cross-section of sides 5,5, and 2.5 mm, 6 cm long; cut from zone-refined bar; supplied by Varlacoid Chemical Co.; residual electrical resistivity ρ_0 = 1.70 μohm cm; ρ (295 K, assumed) = 118 μohm cm.
20	1551	White, G.K. and Woods, S.B.	1958	L	2-91	Bi-5	Cut from the same bar as the above specimen; contained crystals 2 to 4 mm wide and 1 to 2 cm long; square cross-section 6 x 6 mm; residual electrical resistivity ρ_0 = 2.4 μohm cm; ρ (295 K, assumed) = 118 μohm cm.
21	724	Kaye, G.W.C. and Roberts, J.K.	1923	L	219		0.02 Pb, trace of Fe; single crystal; 1.842 x 1.023 x 0.168 cm; annealed; heat flow parallel to trigonal axis.
22	724	Kaye, G.W.C. and Roberts, J.K.	1923	L	219		Similar to above specimen except dimensions 1.843 x 1.022 x 0.167 cm and heat flow perpendicular to trigonal axis.
23	1037	Nishioka, S.	1949	L	287.2	1	Pure single crystal; 0.9114 cm cubic specimen; bismuth supplied by Merch; heat flow parallel to trigonal axis.
24	1037	Nishioka, S.	1949	L	287.2	1	The above specimen; heat flow perpendicular to the trigonal axis.
25	1037	Nishioka, S.	1949	L	287.2	2	Similar to the above specimen except heat flow parallel to the trigonal axis.
26	1037	Nishioka, S.	1949	L	287.2	2	The above specimen; heat flow perpendicular to the trigonal axis.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
27	1037	Nishioka, S.	1949	L	287.2	3	Pure; polycrystalline; cubic specimen 0.93 x 0.93 x 0.93 cm; bismuth supplied by Merch.
28	1037	Nishioka, S.	1949	L	287.2	4	Similar to the above specimen.
29	1327	Smith, A. W.	1925	L	328.2		Total impurities <0.03; specimen 10 cm long, 1.9 cm in dia; bismuth from Baker's Analyzed Metal; electrical conductivity 0.84 x 10^4 ohm^{-1} cm^{-1} at 22 C.
30	970	Mikryukov, V. E. and Tyapunina, N.A.	1956	E	313–453		99.997 pure.
31	491	Giebe, E.	1903	L	87–291		Pure; density 9.67, 10.04 and 10.44 g cm^{-3} at 18, -79, and -186 C, respectively; electrical conductivity 0.861, 1.196 and 2.452 x 10^4 ohm^{-1} cm^{-1} at 18, -79, and -179 C, respectively. (Note: the paper gives electrical conductivity as 10^5 ohm^{-1} cm^{-1} which is probably an error.)
32	558	Grüneisen, E. and Gielessen, J.	1937	L	91.5	Bi 66	Pure; single crystal; the angle between rod axis and trigonal axis $\Phi = 2°$.
33	558	Grüneisen, E. and Gielessen, J.	1937	L	91.5	Bi 66	The above specimen measured in a magnetic field approx parallel to the z-axis and the xz-plane (z-axis coincident with the trigonal axis; x-axis parallel to a diagonal, which does not intersect with the trigonal axis of one face of the crystal (i.e.), parallel to a two-fold secondary axis, with strength H = 650 oersteds.
34	558	Grüneisen, E. and Gielessen, J.	1937	L	91.6	Bi 66	The above specimen measured at H = 650 oersteds approx parallel to x-axis.
35	558	Grüneisen, E. and Gielessen, J.	1937	L	91.4–91.5	Bi 66	The above specimen measured at H = 1500 oersteds (H in xz-plane) and at ψ (angle between H and z-axis) ranging from 0 to -10°.
36*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.5	Bi 66	The above specimen measured at H= 2520 oersteds (H parallel to xz-plane) and at $\psi = 0°$.
37	558	Grüneisen, E. and Gielessen, J.	1937	L	91.7	Bi 66	The above specimen measured at H = 2520 oersteds (H parallel to xz-plane) and at $\psi = 90°$.
38	558	Grüneisen, E. and Gielessen, J.	1937	L	91.6	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to xz-plane) and at $\psi = 0°$.
39	558	Grüneisen, E. and Gielessen, J.	1937	L	91.7	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to xz-plane) and at $\psi = 0°$.
40*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.5–91.7	Bi 66	The above specimen measured at H = 6100 oersteds (H parallel to xz-plane) and at ψ ranging from 0 to -20°.
41*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.5	Bi 66	The above specimen measured without magnetic field.
42*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.6	Bi 66	The above specimen measured in a magnetic field parallel to the yz-plane with H =650 oersteds and $\psi = 10°$ (H approx parallel to the trigonal axis).
43	558	Grüneisen, E. and Gielessen, J.	1937	L	91.8	Bi 66	The above specimen measured at H = 650 oersteds (H parallel to yz-plane) and at $\psi = 100°$ (H approx parallel to y-axis).
44*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.7–92.0	Bi 66	The above specimen measured at H = 1500 oersteds (H parallel to yz-plane) and at ψ ranging from 10 to -80°.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
45*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.37–91.40	Bi 66	The above specimen measured at H = 2520 oersteds (H parallel to yz-plane) and at ψ ranging from 10 to 100°.
46*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.8	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to yz-plane) and at ψ = 10°.
47	558	Grüneisen, E. and Gielessen, J.	1937	L	92.0	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to yz-plane) and at ψ = 100°.
48*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.8–92.0	Bi 66	The above specimen measured at H = 6100 oersteds (H parallel to yz-plane) and at ψ ranging from 10 to -20°.
49	558	Grüneisen, E. and Gielessen, J.	1937	L	79.2	Bi 66	The above specimen measured without magnetic field.
50	558	Grüneisen, E. and Gielessen, J.	1937	L	80.8	Bi 66	The above specimen measured without magnetic field.
51*	558	Grüneisen, E. and Gielessen, J.	1937	L	79.2	Bi 66	The above specimen measured at H = 650 oersteds (H parallel to yz-plane) and at ψ = 10°.
52	558	Grüneisen, E. and Gielessen, J.	1937	L	79.3	Bi 66	The above specimen measured at H = 650 oersteds (H parallel to yz-plane) and at ψ = 100°.
53	558	Grüneisen, E. and Gielessen, J.	1937	L	79.1	Bi 66	The above specimen measured at H = 1500 oersteds (H parallel to yz-plane) and at ψ = 10°.
54	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 1500 oersteds (H parallel to yz-plane) and at ψ = 100°.
55*	558	Grüneisen, E. and Gielessen, J.	1937	L	79.3	Bi 66	The above specimen measured at H = 2520 oersteds (H parallel to yz-plane) and at ψ = 10°.
56	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 2520 oersteds (H parallel to yz-plane) and at ψ = 100°.
57*	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to yz-plane) and at ψ = 10°.
58*	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 4850 oersteds (H parallel to yz-plane) and at ψ = 100°.
59	558	Grüneisen, E. and Gielessen, J.	1937	L	79.2	Bi 66	The above specimen measured at H = 6100 oersteds (H parallel to yz-plane) and at ψ = 10°.
60	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 6100 oersteds (H parallel to yz-plane) and at ψ = 100°.
61*	558	Grüneisen, E. and Gielessen, J.	1937	L	79.4	Bi 66	The above specimen measured at H = 6100 oersteds (H parallel to yz-plane) and at ψ = -80°.
62*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.2	Bi 51	Pure, single crystal; the angle between rod axis and trigonal axis Φ = 86°.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
63*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.2-91.5	Bi 51	The above specimen measured in a magnetic field parallel to the plane containing the trigonal axis (z-axis) and the rod axis with strength H = 2520 oersteds and at ψ' (angle between field direction and a line such that at $\psi' = 7^\circ$, H perpendicular z-axis and at $\psi' = 97^\circ$, H parallel z-axis) ranging from 8 to -10°.
64*	558	Grüneisen, E. and Gielessen, J.	1937	L	91.6-91.8	Bi 51	The above specimen measured at H = 6100 oersteds (H parallel to the plane containing z-axis and the rod axis) and at ψ' ranging from 7 to -5°.
65	1187	Reddemann, H.	1934	L	80-297	Bi 9	Single crystal; 0.55 cm dia x 3.6 cm long; the angle between rod axis and trigonal axis about 80°; electrical resistivity reported as 46.95, 48.32, 49.41, 103.6, and 112.2 μohm cm at -193.92, -188.19, -183.62, 0, and 21.02 C, respectively.
66*	1187	Reddemann, H.	1934	L	81.1	Bi 9	The above specimen measured in a transverse magnetic field (H perpendicular to rod axis) with H (field strength) = 5900 gauss and at θ (the angle between field and rod axis) ranging from 25 to 170°; electrical resistivity at -194.5 C reported as 601, 620, and 458 μohm cm at θ = 25, 35, and 170°, respectively.
67*	1187	Reddemann, H.	1934	L	89.4-90.5	Bi 9	The above specimen measured in a transverse magnetic field; H = 5900 gauss and θ ranging from 35 to 170°; electrical resistivity at -183.5 C reported as 510, 408, and 391 μohm cm at θ = 35, 95 and 170°, respectively.
68	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystal with fine grains; electrical conductivity 2.61 and 9.29 x 10^3 ohm^{-1} cm^{-1} at 90 and 273 K respectively.
69	406	Eucken, A. and Neumann, O.	1924	L	90, 273		Polycrystal with coarse grains; electrical conductivity 2.55 and 8.98 x 10^3 ohm^{-1} cm^{-1} at 90 and 273 K respectively.
70	60	Amirkhanov, Kh. I., Daibov, A. Z., and Zhuze, V. P.	1954	L, C	298.2		Fine-crystalline extruded specimen; 15 mm in dia and 1 to 3 mm thick; concentration of current carriers 8.8 x 10^{18} $ohm^{-1} cm^{-1}$; electrical conductivity 6760 $ohm^{-1} cm^{-1}$ at 25 C.
71	969	Mikryukov, V. E. and Rabotnov, S. N.	1944	E	372-501		Pure; polycrystal; electrical resistivity 179.20 to 277.00 μohm cm at 372.3 to 501.1 K.
72	538	Grenier, C. G., Reynolds, J. M., and Sybert, J. R.	1961	L	2.1-4.1		Very pure; single crystal; prepared from spectroscopically pure bismuth; right parallelepiped 24.3 x 6.9 x 2.5 mm; obtained from Johnson Matthey and Co.; crystal resistance ratio R(300 K)/R(4.2 K) ≈40.
73	560	Grüneisen, E., Rausch, K., and Weiss, K.	1950	L	82-90	$Bi-S_4$	Single crystal; rod axis perpendicular to the trigonal axis and approx parallel to one of the two-fold secondary axes (one side of the base triangle); electrical resistivity reported as 39.93 and 99.4 μohm cm at -187.5 and 0 C, respectively.
74	560	Grüneisen, E. et al.	1950	L	83-89	$Bi-S_7$	Single crystal; rod axis perpendicular to trigonal axis and perpendicular to one of the two-fold secondary axes (one side of the base triangle); electrical resistivity reported as 40.18 and 100.7 μohm cm at -187.5 and 0 C, respectively.
75	557	Grüneisen, E. and Gielessen, J.	1936	L	78, 90	Bi 66	Pure; single crystal; the angle between trigonal axis and rod axis $\phi = 2^\circ$; 3 mm dia x 4~5 cm long; electrical resistivity reported as 36.1, 41.0 and 127.4 μohm cm at -195.39, -182.98 and 0 C, respectively.
76	557	Grüneisen, E. and Gielessen, J.	1936	L	78, 90	Bi 13	Pure; single crystal; $\phi = 16^\circ$; 3 mm dia x 4~5 cm long; electrical resistivity reported as 37.4, 42.0, 86.6, and 125.6 μohm cm at -194.84, -183.20, -78.36, and 0 C, respectively.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
77	557	Grüneisen, E. and Gielessen, J.	1936	L	78, 90	Bi 51	Pure; single crystal; $\phi = 86^\circ$; 3 mm dia x 4~5 cm long; electrical resistivity reported as 37.0, 40.4, and 99.1 μohm cm at -194.78, -183.49 and 0 C, respectively.
78	557	Grüneisen, E. and Gielessen, J.	1936	L	90.0	Bi 72	Pure; single crystal; $\phi = 85.5^\circ$; 3 mm dia x 4~5 cm long; electrical resistivity reported as 43.0 and 102.9 μohm cm at -183.13 and 0 C, respectively.
79*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.8	Bi 66	Pure; single crystal; $\phi = 2^\circ$; 0.0898 cm^2 x 2.23 cm long.
80	557	Grüneisen, E. and Gielessen, J.	1936	L	92.2	Bi 66	The above specimen measured in a transverse magnetic field (H perpendicular to rod axis) with strength H = 2520 oersteds and field orientation θ (the angle between field direction and a line perpendicular to the rod axis such that at $\theta \simeq -12^\circ$, H is parallel to the x-axis and at $\theta \simeq 78^\circ$, H is parallel to the y-axis) = -161°; x-axis parallel to one of the two-fold secondary axes; z-axis coincided with the trigonal axis.
81*	557	Grüneisen, E. and Gielessen, J.	1936	L	79.6	Bi 66	The above specimen measured without magnetic field.
82*	557	Grüneisen, E. and Gielessen, J.	1936	L	79.8	Bi 66	The above specimen measured at H = 1500 oersteds and at $\theta = 108^\circ$.
83*	557	Grüneisen, E. and Gielessen, J.	1936	L	79.9	Bi 66	The above specimen measured at H = 2520 oersteds and at $\theta = -41^\circ$.
84	557	Grüneisen, E. and Gielessen, J.	1936	L	79.9	Bi 66	The above specimen measured at H = 4850 oersteds and at mean θ (averaged from values which varied from 15-30°).
85	557	Grüneisen, E. and Gielessen, J.	1936	L	79.9	Bi 66	The above specimen measured at H = 6100 oersteds and at mean θ.
86	557	Grüneisen, E. and Gielessen, J.	1936	L	91.0	Bi 13	Pure; single crystal; the angle between trigonal axis and rod axis $\phi = 16^\circ$; 0.1452 cm^2 x 3.10 cm long.
87*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.2	Bi 13	The above specimen measured in a transverse magnetic field (H perpendicular to rod axis) with strength H = 2460 oersteds and field orientation at $\theta = 4$ and 38°, where θ is the angle between field direction and a line perpendicular to the rod axis such that at $\theta \simeq 6^\circ$; H approx parallel to x-axis.
88	557	Grüneisen, E. and Gielessen, J.	1936	L	79, 91	Bi 13	The above specimen measured at H = 6100 oersteds and at mean θ (averaged from values which varied from 15-30°).
89*	557	Grüneisen, E. and Gielessen, J.	1936	L	78.5	Bi 13	The above specimen measured without magnetic field.
90*	557	Grüneisen, E. and Gielessen, J.	1936	L	78.7	Bi 13	The above specimen measured at H = 2460 oersteds and at $\theta = -4$ and 38°.
91*	557	Grüneisen, E. and Gielessen, J.	1936	L	78.7	Bi 13	The above specimen measured at H = 6100 oersteds and at $\theta = 38^\circ$.
92*	557	Grüneisen, E. and Gielessen, J.	1936	L	79, 91	Bi 51	Pure; single crystal; the angle between trigonal axis and rod axis $\phi = 86^\circ$; 0.0749 cm^2 x 2.18 cm long.
93	557	Grüneisen, E. and Gielessen, J.	1936	L	91.1	Bi 51	The above specimen measured in a transverse magnetic field (H perpendicular to rod axis) with strength H = 2520 oersteds and field orientation at $\theta = -152^\circ$; where θ is the angle between field direction and a line perpendicular to the rod axis such that at $\theta \simeq 35^\circ$; H parallel to negative x-axis and at $\theta = -55^\circ$; H parallel to z-axis.
94*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.4	Bi 51	The above specimen measured at H = 4900 oersteds and at $\theta = -152^\circ$.
95*	557	Grüneisen, E. and Gielessen, J.	1936	L	79.3	Bi 51	The above specimen measured at H = 2520 oersteds and at mean θ (averaged from values which varied from 15-30°).

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
96*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.3	Bi 72	Pure; single crystal; the angle between trigonal axis and rod axis $\phi = 85.5^\circ$; 0.0907 cm^2 x 2.51 cm long.
97*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.3	Bi 72	The above specimen measured in a transverse magnetic field (H perpendicular to rod axis) with strength H = 650 oersteds and field orientation $\theta = 2^\circ$, where θ is the angle between field direction and a line perpendicular to the rod axis such that at $\theta = 8^\circ$, H is parallel to negative z-axis and at $\theta = 98^\circ$, H is perpendicular to z-axis.
98*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.3	Bi 72	The above specimen measured at H = 650 oersteds and at $\theta = -124^\circ$.
99*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.2-91.4	Bi 72	The above specimen measured at H = 1500 oersteds and at θ ranging from 2 to -34°.
100*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.2	Bi 72	The above specimen measured at H = 2520 oersteds and at $\theta = 2^\circ$.
101*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.3	Bi 72	The above specimen measured at H = 2520 oersteds and at $\theta = -124^\circ$.
102*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.6	Bi 72	The above specimen measured at H = 4900 oersteds and at $\theta = 2^\circ$.
103*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.6	Bi 72	The above specimen measured at H = 4900 oersteds and at $\theta = -124^\circ$.
104*	557	Grüneisen, E. and Gielessen, J.	1936	L	91.3-91.5	Bi 72	The above specimen measured at H = 6100 oersteds and at θ ranging from 2 to -34°.
105	971	Mikryukov, V. E., Tyapunina, N. A., and Cherpakov, V. P.	1956		320-500		Pure; electrical conductivity reported as 0.744, 0.684, 0.602, 0.544, 0.516, 0.509, 0.477, 0.446, 0.421, and 0.380 x 10^4 ohm^{-1} cm^{-1} at 46.7, 69.1, 105.8, 134.6, 148.7, 152.1, 169.0, 188.8, 203.8, and 227.0 C, respectively.
106*	266	Cherpakov, V. P.	1957		373.2		Pure.
107	1037	Nishioka, S.	1949	L	287.2		Pure; single crystal; bismuth plate, 2 x 9.3 x 9.3 mm; supplied by Merch; θ (the angle between the trigonal axis of the crystal and the direction of heat flow) = 0°.
108*	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 14.7^\circ$.
109	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 27.2^\circ$.
110	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 50.7^\circ$.
111*	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 67.9^\circ$.
112*	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 74.3^\circ$.
113*	1037	Nishioka, S.	1949	L	287.2		Similar to the above specimen except $\theta = 89.0^\circ$.
114	482	Gehlhoff, G. and Neumeier, F.	1913	L	83-373		Pure; cylindrical specimen; made from bismuth supplied by C. A. F. Kahlbaum; bismuth powder pressed at 5000 kg cm^{-2} for 1 hr; density 1% less than cast bismuth; electrical conductivity reported as 3.5, 3.8, and 3.2 x 10^3 ohm^{-1} cm^{-1} at -190, 0, and 100 C, respectively.
115	1066, 1067	Pashaev, B. P.	1961	L	313-630		Measurements made on solid specimen and molten specimen (from same source as the solid specimen); container 3 mm in dia, 64 mm long used to determine data in liquid state; melting point 544.2 K.
116	1063	Nikol'skii, N.A., Kalakutskaya, N.A., Pchelkin, I.M., Klassen, T.V., and Vel'tishcheva, V.A.	1959	L	626-945		In liquid state; melting point 271 C.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
117	470	Gallo, C., Chandrasekhar, B.S., and Sutter, P.H.	1962	L	100–300		99.999 pure; single crystal; specimen 2 x 2 x 10 mm; provided by American Smelting and Refining Co.; as received; electrical resistivity 34.2, 42.4, 85.3, and 134.8 μohm cm at 79, 100, 200, and 300 K, respectively; heat flow parallel to trigonal axis.
118	470	Gallo, C., et al.	1962	L	100–300		Similar to the above specimen except electrical resistivity 32.5, 39.0, 73.1, and 111.7 μohm cm at 81, 100, 200, and 300 K, respectively; heat flow perpendicular to trigonal axis.
119	859	Lorenz, L.	1881	L	273, 373		Density 9.74 g cm^{-3}; electrical conductivity 0.929 and 0.630 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively.(electrical conductivity reported as 0.929 and 0.63 x 10^5 ohm^{-1} cm^{-1}, probably a typographical error).
120	52	Alsup, D. L.	1964	L	1.46		Single crystal with rhombohedral structure; 16.8 x 4.55 x 2.0 mm, with trigonal axis parallel to the small dimension and bisectrix parallel to the large dimension; specimen taken from cylindrical ingot supplied by Texas Instruments Corp.; electrical resistivity reported as 1.1 and 1.2 μohm cm at 1.12 and 4.2 K, respectively; $\rho(298.2)/\rho(4.2)$ reported as 94.2; measured with the magnetic field directed along the trigonal axis, and the heat flow along the large dimension; magnetic field ranging from 1.02 to 17.98 kilogauss.
121*	722	Kaye, G.W.C. and Higgins, W.F.	1929	L	300.2		Single crystal; disk specimen 25 mm in dia and 2 mm thick; heat flow perpendicular to the trigonal axis; measured in magnetic fields (H) ranging from 2499 to 10554 gauss perpendicular to the trigonal axis.
122*	722	Kaye, G.W.C. and Higgins, W.F.	1929	L	300.2		Similar to the above specimen except measured in magnetic fields parallel to the trigonal axis ranging from 0 to 10773 gauss.
123*	722	Kaye, G.W.C. and Higgins, W.F.	1929	L	300.2		Single crystal; disk specimen 25 mm in dia and 2.0 mm thick; heat flow parallel to the trigonal axis; measured in magnetic fields perpendicular to the trigonal axis ranging from 0 to 11161 gauss.
124	722	Kaye, G.W.C. and Higgins, W.F.	1929	L	300.2		Similar to the above specimen except disk 2.02 mm thick and measured in magnetic fields ranging from 5071 to 9847 gauss.
125*	722	Kaye, G.W.C. and Higgins, W.F.	1929	L	300.2		The above two specimens combined together (4.02 mm thick); measured in the same conditions as above with magnetic fields ranging from 4997 to 9973 gauss.
126	383	Dutchak Ya. I. and Panasyuk, P.V.	1967	C	453–770		The molten specimen placed in a hole 21 mm in dia drilled in an asbestos cement cylinder of 30 mm height; steel 1Kh18N9T used as comparative material.
127	1209, 1210	Rodine, M.T.	1934	L	110~209	1	Single crystal; specimen length 1.231 cm cross-section roughly triangular in shape with dimensions about 3 mm on a side; trigonal axis parallel to the length; supplied by Prof. A. Goetz of CIT; measured in a vacuum of 10^{-6} mm Hg, and in a magnetic field of 7800 gauss parallel to one of the binary axes; heat flow along the trigonal axis.
128	1209, 1210	Rodine, M.T.	1934	L	117–190	1	The above specimen measured with the magnetic field perpendicular to one of the binary axes.

*Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
129	1209, 1210	Rodine, M. T.	1934	L	114–198	2	Single crystal; specimen length 1.3 cm, cross-section roughly triangular in shape with dimensions about 3 mm on a side; trigonal axis perpendicular to the length; measured in a vacuum of 10^{-6} mm Hg and in a magnetic field of 7800 gauss perpendicular to the trigonal axis; heat flow perpendicular to the trigonal axis.
130	1209, 1210	Rodine, M. T.	1934	L	108–216	2	The above specimen measured with the magnetic field parallel to the trigonal axis.
131	1209, 1210	Rodine, M. T.	1934	L	122–145	2	The above specimen measured with the magnetic field at 45° to the trigonal axis.
132	155	Bhagat, S. M. and Manchon, D. D., Jr.	1967	→	1.3–1.9	Sample 3	99.9999 pure; single crystal; specimen 1.57 x 3.1 mm in cross-section; specimen axis along the bisectrix; electrical resistivity ratio $\rho(300)/\rho(4.2) = 140$; thermal conductivity values calculated from heat capacity, velocity and effective mean free path.
133	155	Bhagat, S. M. and Manchon, D. D., Jr.	1967	→	1.3–2.0	Sample 5	99.9999 pure; single crystal; specimen 3.8 x 3.85 mm in cross-section; specimen axis along the trigonal; electrical resistivity ratio $\rho(300)/\rho(4.2) = 104$; thermal conductivity values calculated from heat capacity, velocity and effective mean free path.
134	1585	Yim, W. M. and Stofko, E. J.	1967	L	80–301		Single crystal; 0.4 x 0.2 x 0.2 in.; electrical resistivity reported as 0.0349, 0.0472, 0.0680, 0.0854, 0.113, and 0.134 milliohm cm at 80, 112, 160, 198, 253, and 299 K, respectively; heat flow along the trigonal axis.
135	1585	Yim, W. M. and Stofko, E. J.	1967	L	81–303		Single crystal; 0.4 x 0.2 x 0.2 in.; electrical resistivity reported as 0.0324, 0.0445, 0.0602, 0.0727, 0.0950, and 0.116 milliohm cm at 77, 115, 156, 193, 249, and 298 K, respectively; heat flow along one of the binary axes.
136	879	Manchon, D. D., Jr.	1967	→	1.3–1.6	Sample 2A	99.9999 pure; single crystal; grown from melt in an open graphite boat under a vacuum of $\sim 10^{-5}$ torr; specimen 2.41 x 3.15 mm in cross section and effective length 1.90 cm; specimen axis along the bisectrix direction; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 85$; thermal conductivity values calculated from heat capacity, velocity and effective mean free path.
137	879, 156	Manchon, D. D., Jr.	1967	→	1.3–1.8	Sample 4A	Similar to above except specimen 3.30 x 2.95 mm in cross section and effective length 2.38 cm; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 320$; electrical resistivity 7.32, 7.45, 7.59, 7.79, 8.09, 8.27, 8.61, 8.87, 9.28, 9.45, 9.69, and 10.04 μohm cm at 1.15, 1.47, 1.80, 2.10, 2.40, 2.59, 2.89, 3.20, 3.49, 3.70, 3.90, and 4.18 K, respectively.
138*	879, 156	Manchon, D. D., Jr.	1967	→	1.3–1.8	Sample 4B	Similar to the above specimen.
139	879, 156	Manchon, D. D., Jr.	1967	→	1.3–1.8	Sample 4BH	The above specimen measured in a transverse magnetic field of 500 Oe.
140*	879, 156	Manchon, D. D., Jr.	1967	→	1.3–2.0	Sample 6A	Same purity and fabrication method as the above specimen; 3.80 x 3.85 mm in cross section and effective length 2.22 cm; specimen axis along the trigonal direction; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 104$; same measuring method as above.
141	879, 156	Manchon, D. D., Jr.	1967	→	1.3–1.8	Sample 6AH	The above specimen measured in a transverse magnetic field of 500 Oe.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
142*	879, 156	Manchon, D. D., Jr.	1967	→	1.3-2.0	Sample 6B	Similar to the above specimen but no magnetic field applied.
143*	879, 156	Manchon, D. D., Jr.	1967	→	1.3-1.9	Sample 6BH	The above specimen measured in a transverse magnetic field of 500 Oe.
144	879, 156	Manchon, D. D., Jr.	1967	→	1.3-1.9	Sample 7A	Same purity and fabrication method as the above specimen; 3.30 x 3.60 mm in cross section and effective length 1.92 cm; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 370; electrical resistivity reported as 6.31, 6.43, 6.65, 6.83, 7.14, 7.35, 7.65, 7.91, 8.15, 8.43, 8.72, and 9.43 μohm cm at 1.17, 1.49, 1.80, 2.09, 2.40, 2.59, 2.89, 3.19, 3.50, 3.69, 3.89, and 4.19 K, respectively; same measuring method as above.
145*	879, 156	Manchon, D. D., Jr.	1967	→	1.3-1.9	Sample 7B	Similar to above.
146	879, 156	Manchon, D. D., Jr.	1967	→	1.3-1.8	Sample 7BH	The above specimen measured in a transverse magnetic field of 500 Oe.
147	879, 156	Manchon, D. D., Jr.	1967	→	1.3-2.0	Sample 5AH	The same specimen as reported in curve No. 133 measured in a transverse magnetic field of 500 Oe.
148	1591	Yurchak, R. P. and Filippov, L. P.	1964	P	423-1035		In solid and liquid states; electrical resistivity reported as 294.2, 276.1, 274.0, 270.7, 131.9, 132.4, 133.3, 138.4, 139.3, 143.7, 146.0, and 155.1 μohm cm at 20, 169, 195, 227, 292, 305, 320, 425, 455, 510, 575, and 725 C, respectively.
149	210	Bridgman, P. W.	1926	L	298.2		Single crystal; 6 mm dia x 10 cm long; crystal axis nearly perpendicular to specimen axis; obtained from U.S. Metals Refining Co.; cast; electrical resistivity 109.0 μohm cm at room temp; reported thermal conductivity value uncorrected for heat losses.
150	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 109.4 μohm cm at room temp and the crystal axis inclined at a smaller angle to specimen axis.
151	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 109.9 μohm cm and the crystal axis inclination still smaller.
152	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 111.6 μohm cm and the crystal axis inclination still smaller.
153	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 112.9 μohm cm and the crystal axis inclination still smaller.
154	870	Luyckx, A., Issi, J-P., Streydio, J. M., Michenand, J. P., and Coopmans, P.	1964	L	80, 300	TC 1	Pure; polycrystalline; annealed; electrical resistivity 37.4, 41.6, 59.2, 78.9, 98.8, 112.6, 124.6, and 138.9 μohm cm at 80.5, 90.6, 140.7, 196.0, 240.0, 273.0, 300.0, and 330.5 K, respectively.
155*	560	Grüneisen, E., Rausch, K., and Weiss, K.	1950	L	85.7	$Bi\text{-}S_7{}^{x}$	Single crystal; 3 to 4 mm in dia and ~5 cm long; specimen axis perpendicular to the principal axis and to one of the binary crystallographic axes; grown by Hasler's method; electrical resistivity 40.18 and 100.7 μohm cm at 85.7 and 273.2 K, respectively; measured in magnetic fields at a direction $\theta = -5°$ to the specimen axis ranging from 1.0 to 10.2 kOe.
156*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_7{}^{x}$	The above specimen with $\theta = -95°$.
157*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_7{}^{x}$	The above specimen with $\theta = -120°$.
158*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_7{}^{x}$	The above specimen with $\theta = -143°$.

* Not shown in figure.

TABLE 13. THERMAL CONDUCTIVITY OF BISMUTH - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
159*	560	Grüneisen, E., Rausch, K., and Weiss, K.	1950	L	85.7	$Bi\text{-}S_4\ ^x$	Single crystal; 3 to 4 mm in dia and ~5 cm long; specimen axis perpendicular to the principal axis and at 2.3° to one of the binary crystallographic axes; grown by Hasler's method; electrical resistivity 39.93 and 99.4 μohm cm at 85.7 and 273.2 K, respectively; measured in magnetic fields at θ = +12 ° ranging from 1.5 to 10.2 kOe.
160*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_4\ ^x$	The above specimen with θ = -12°.
161*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_4\ ^x$	The above specimen with θ = -39°.
162*	560	Grüneisen, E., et al.	1950	L	85.7	$Bi\text{-}S_4\ ^x$	The above specimen with θ = -93°.
163	227	Bursuc, I.	1960	P	298.2		20 mm dia x 15 cm long; thermal conductivity value calculated from measured thermal diffusivity using a density value of 9.80 g cm^{-3} and a specific heat capacity value of 0.029 cal g^{-1} C^{-1} (measuring temp assumed 25 C).
164*	227	Bursuc, I.	1958	P	313.2		19 mm dia x 22 cm long; thermal conductivity value calculated from measured thermal diffusivity using specific heat and density values taken from Kohlrausch, F. (Practische Physik, 1935).
165*	227	Bursuc, I.	1958	P	313.2		The above specimen measured in a transverse magnetic field of 9800 Oe.
166*	227	Bursuc, I.	1958	P	313.2		The above specimen measured in a longitudinal magnetic field of 1800 Oe.
167*	44	Aliev, M.I., Veliev, M.I., and Kerimov, I.G.	1961	L	82-287		Polycrystalline; 0.8 cm long and 0.6 cm^2 in cross section.

*Not shown in figure.

Boron

Slack [1321] has determined the thermal conductivity from 3 to 300 K for two polycrystalline samples (curves 7 and 8) of the β-rhombohedral form and containing columnar crystallites, the form normally produced when crystals are grown from the melt. He considers that the fairly large differences between his values and those of Thompson and McDonald [1407] (curves 1–6) for single crystals of the β-form must be due to sample differences, possibly to impurities or faults in the single crystals. Slack's data of low temperatures are preferred as representing the typical thermal conductivity of high-purity boron.

Petrov, et al. [1085] have made determinations over the range 80 to 1035 K for three samples of about 99.99 percent boron (curves 11–13). Up to about 400 K their results agree with Slack's and decrease approximately as T^{-2}, but above 700 K their values become almost independent of temperature and indicate that an appreciable second conducting mechanism needs to be considered. The measured thermal conductivity is only about 2 to 2.5 percent of that indicated by the Leibfried-Schlömann theory [834] and the low thermal conductivity of boron is believed to be due to its complex structure: phonons of long wave length can account for the contribution varying as T^{-2} and phonons of short wave length and a different temperature dependence of their mean free path can explain this second contribution. Any contributions from radiation, electrons, and ambipolar mechanisms are regarded as much too small.

The recommended curve from 200 to 300 K has been fitted to the experimental data of Slack, it then continues to meet the highest curve of Petrov, et al. near 500 K and follows their data for this sample to about 1100 K. Further measurements are thought to be desirable before values are given to higher temperatures. No information is available for molten boron.

The tabulated values are for well-annealed high-purity polycrystalline boron. The recommended values (those above 200 K) are probably accurate to within ±10 to ±15 percent. The values below 200 K are merely typical values.

TABLE 14. Recommended thermal conductivity of boron†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	123.2	1.35
1	0.0150*	150	0.935
2	0.0781*	173.2	0.718
3	0.198	200	0.551
4	0.375	223.2	0.454
5	0.588	250	0.371
6	0.826	273.2	0.318
7	1.07	298.2	0.274
8	1.31	300	0.270
9	1.54	323.2	0.240
10	1.77	350	0.209
11	1.98	373.2	0.188
12	2.19	400	0.168
13	2.39	473.2	0.133
14	2.58	500	0.125
15	2.76	573.2	0.109
16	2.93	600	0.106
18	3.22	673.2	0.0994
20	3.46	700	0.0981
25	3.92	773.2	0.0964
30	4.21	800	0.0960
35	4.30	873.2	0.0966
40	4.28	900	0.0969
45	4.19	973.2	0.0980
50	4.04	1000	0.0985
60	3.63	1073.2	0.100
70	3.10	1100	0.101
80	2.63		
90	2.24		
100	1.90		

†The values are for well-annealed high-purity boron, and those below 200 K are merely typical values.
*Extrapolated.

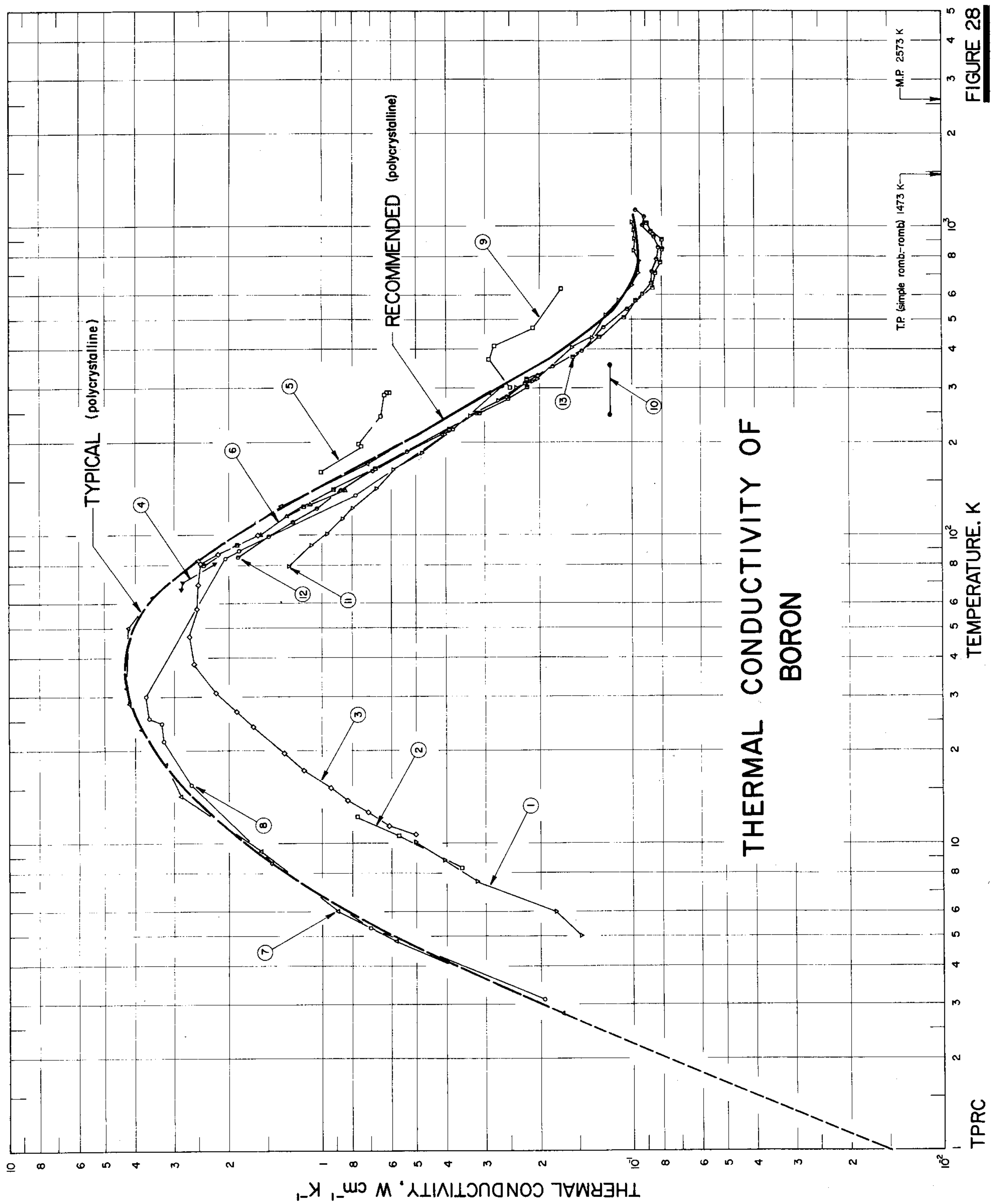

THERMAL CONDUCTIVITY OF
BORON
TYPICAL (polycrystalline)
RECOMMENDED (polycrystalline)
T.P. (simple romb.-romb.) 1473 K
M.P. 2573 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 28

TABLE 15. THERMAL CONDUCTIVITY OF BORON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1407	Thompson, J.C. and McDonald, W.J.	1963	L	5-10		99.9 B (by difference), 0.1 C; cylindrical specimen 0.26 cm average dia 3.8 cm long; made from single crystal of the beta-rhombohedral phase, provided by Texaco Experiment Inc.; density 2.342 ± 0.005 g cm^{-3}; electrical resistivity > 5 x 10^6 ohm cm at room temp; Debye temp 1219 K.
2	1407	Thompson, J.C. and McDonald, W.J.	1963	L	8-12		Rerun of the above specimen.
3	1407	Thompson, J.C. and McDonald, W.J.	1963	L	10-100		Rerun of the above specimen.
4	1407	Thompson, J.C. and McDonald, W.J.	1963	L	67-80		Rerun of the above specimen.
5	1407	Thompson, J.C. and McDonald, W.J.	1963	L	162-290		Rerun of the above specimen.
6	1407	Thompson, J.C. and McDonald, W.J.	1963	L	100-140		Rerun of the above specimen.
7	1321	Slack, G.A.	1965	L	2.8-291	R 4	Major impurities: 10 x 10^{19} Si, 20 x 10^{18} Al, 20 x 10^{18} Mn, 6 x 10^{18} Ti, and 4 x 10^{18} Cu atoms cm^{-3}, also about 0.1% (by volume) of precipitated particles 5-50μ in dia (probably of boron nitride, silicon inclusions or small voids); polycrystalline with numerous columnar crystals of β-rhombohedral phase 1 cm long 0.3 cm avg dia; specimen 3.8 cm long 0.7 cm avg dia grown from partially purified boron by General Electric Research Lab.; density 2.33 g cm^{-3}.
8	1321	Slack, G.A.	1965	L	3.1-305	R 46	Major impurities: 0.8 x 10^{18} Si, 0.3 x 10^{18} Al, < 0.3 x 10^{18} Ti, and 0.04 x 10^{18} Cu atom cm^{-3}; composed of columnar crystallites 2 cm long 0.1cm avg dia; specimen 2.6 cm long, 0.6 cm avg dia; provided by Eagle-Picher Research Lab. Miami, Okla. (crystal reference No. M6005CP); grown from the melt by floating zone process.
9	991	Morris, R.G.	1965		300-630		No details reported.
10	1386	Talley, C.P.	1959	R	293-353		99^+ B and 0.02 total of Ca, Cu, Fe, Mg, and Si; polycrystalline specimen 1 mm in dia and several cm long with a 0.025 mm; tungsten filament at the center amounting to about 0.7% by weight; prepared by the reduction of boron tribromide by hydrogen near the tungsten filament at about 1250 C; data reported here are 10 times of author's original data, which are assumed to be wrongly given.
11	1085	Petrov, A.V., Germaidze, M.S., Golikova, O.A., Kiskachi, A.Yu., and Matveev, V.N.	1969	L, C	79-1035	Sample 267	β-boron; <0.01 Mg, <0.001 each of Al, Bi, Cu, Fe, and Si; prepared by the zone-melting method; electrical resistivity 1.5-1.8 x 10^6 ohm cm at 300 K.
12	1085	Petrov, A.V., et al.	1969	L, C	83-1130	Sample 315	Similar to the above specimen.
13	1085	Petrov, A.V., et al.	1969	L, C	80-1050	Sample 303	Similar to the above specimen.

Bromine

No information is available for the thermal conductivity of solid bromine. The thermal conductivities of the other physical states are discussed separately below.

Saturated Liquid

The only experimental data located for the thermal conductivity of saturated liquid bromine were some experimental measurements from 283 to 323 K [256]. In addition, a correlation for saturated liquid and vapor diatomic substances [1257] was considered.

Intercomparison of the measurements and the correlation showed good agreement below 305 K but progressively increasing disagreement at higher temperatures. The trend of the measured data is to predict a critical temperature far below other estimates. Possibilities to explain the discrepancy are association in the liquid phase, partial vaporization or an experimental effect similar to that observed with Keyes [748] data for liquid krypton. It was decided to base the recommended values on a smooth curve which followed the correlation for temperatures near and at the critical point.

Based upon the disagreement noted above and the errors possible in the extrapolated critical point thermal conductivity, the recommended values are subject to an uncertainty of some fifteen percent below about 500 K and an unknown amount at higher temperatures.

Saturated Vapor

No experimental data were located for the thermal conductivity of saturated bromine vapor. The correlation of Schaefer and Thodos [1257] was used to construct a graph of the thermal conductivity as a function of temperature and it was found that this agreed very closely with values for atmospheric pressure gas in the region 310 to 350 K. However, the latter values depend on a single experimental data point of uncertain accuracy. The proposed values, derived from the plot of the correlation [1257], must therefore be regarded as provisional. Their accuracy could possibly be within about ten percent below 450 K, fifteen percent from 450 to 550 K and unknown at higher temperatures. Due to the complete lack of experimental data for the saturated vapor, no departure plot is given.

Gas

Only one experimental value is available for the thermal conductivity of gaseous bromine, that of Franck [454] for 276 K, 65 mm Hg. Lenoir [839] has calculated values at 255, 283, and 311 K. Interpolation of these values at 276 K gives a value ten percent lower than that of Franck. No information is given as to the pressure for which the Lenoir values are valid. The tabulated values were generated by parallel displacement of the Lenoir values to coincide with the single experimental data point. Due to the paucity of experimental data no departure plot or recommendation as to accuracy is possible.

TABLE 16. Recommended thermal conductivity of bromine

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor		Gas	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		300	0.047*	250	0.038*
266	1.31*	310	0.049*	260	0.040*
270	1.30*	320	0.051*	270	0.042*
280	1.27	330	0.053*	280	0.044*
290	1.25	340	0.055*	290	0.046*
300	1.22	350	0.057*	300	0.048*
310	1.20	360	0.059*	310	0.049*
320	1.18	370	0.061*	320	0.051*
330	1.16*	380	0.063*	330	0.053*
340	1.14*	390	0.065*	340	0.055*
350	1.11*	400	0.068*	350	0.057*
360	1.09*	410	0.070*		
370	1.06*	420	0.072*		
380	1.04*	430	0.075*		
390	1.02*	440	0.078*		
400	0.99*	450	0.080*		
410	0.97*	460	0.084*		
420	0.94*	470	0.087*		
430	0.92*	480	0.091*		
440	0.89*	490	0.095*		
450	0.87*	500	0.099*		
460	0.84*	510	0.104*		
470	0.82*	520	0.109*		
480	0.79*	530	0.116*		
490	0.76*	540	0.128*		
500	0.73*	550	0.144*		
510	0.70*	560	0.16*		
520	0.66*	570	0.19*		
530	0.63*	580	0.23*		
540	0.59*	584	0.28*‡		
550	0.55*				
560	0.50*				
570	0.44*				
580	0.35*				
584	0.28*‡				

*Estimated or extrapolated, hence provisional.
‡Pseudo-critical value.

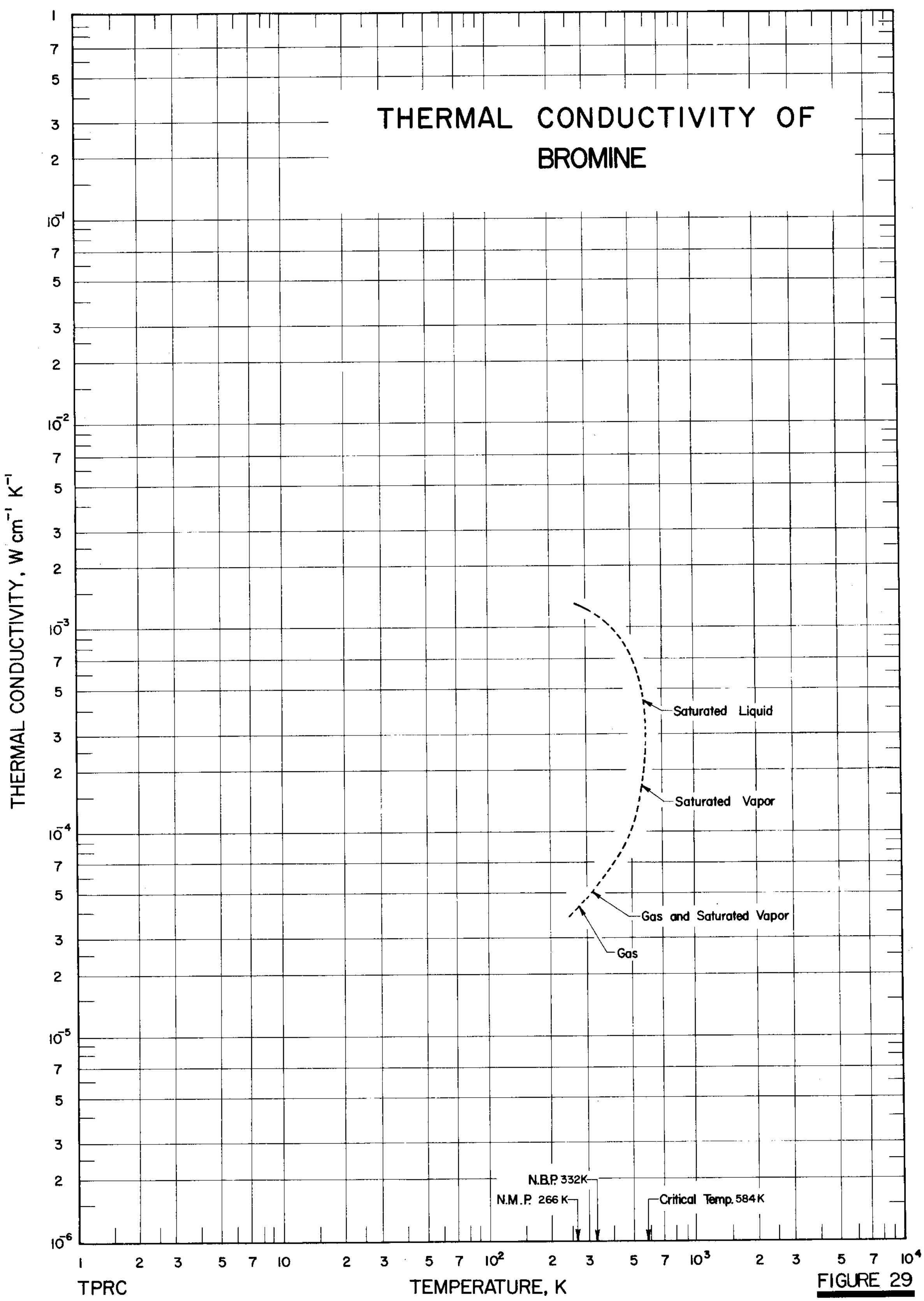
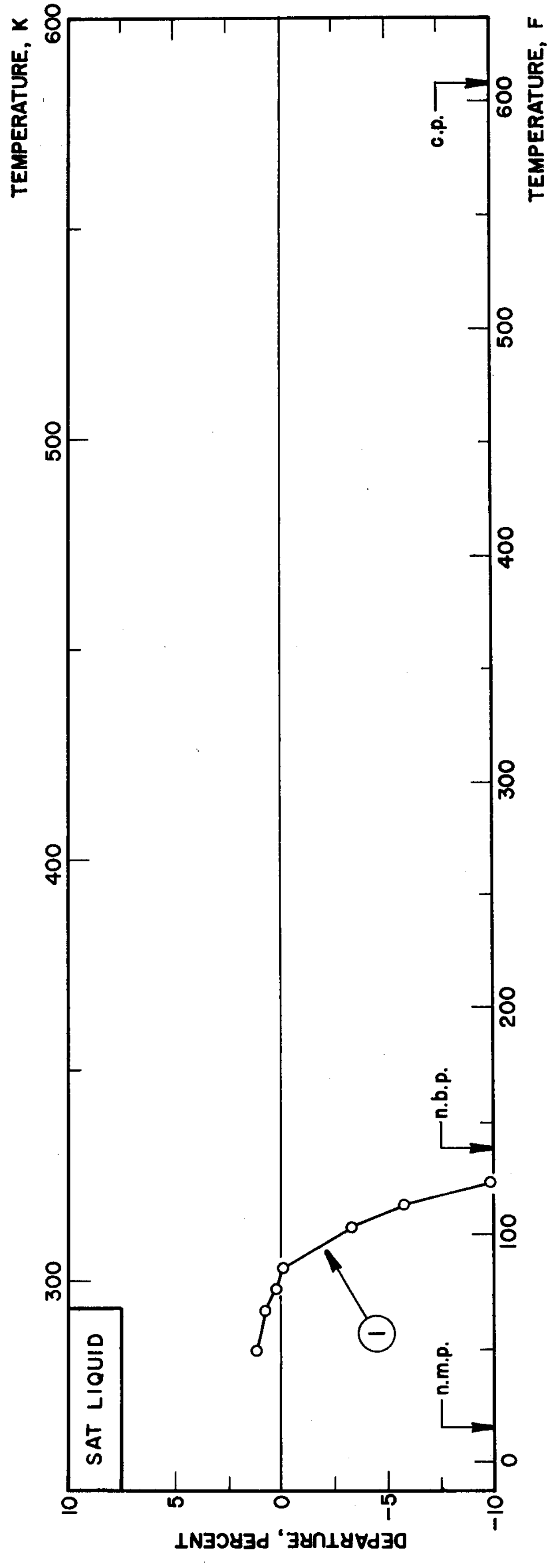

THERMAL CONDUCTIVITY OF
BROMINE
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Saturated Liquid
Saturated Vapor
Gas and Saturated Vapor
Gas
N.B.P. 332K
N.M.P. 266 K
Critical Temp. 584 K
TPRC

FIGURE 29

FIGURE 30. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID BROMINE



Curve	Reference
1	256

Cadmium

The four curves available for the thermal conductivity of cadmium at low temperatures in 1968 [608] have been supplemented by ten further curves from the works of Bogaard and Gerritsen [178] (curves 43–45, and 48) and of Bogaard [177] (curves 49–54) and two by Rowe [1227] (curves 46 and 47). These last, however, are not discussed, since they involve uncertainties. Of the nine sets of data which now include the thermal conductivity maximum, all but one (curve 52) can be reasonably well satisfied by a straight line (in a log-log graph) passing through the maxima and having an m-value of 5.0 but n varies from 2.2 to 4.5 and increases as β decreases which is unusual since for other metals n is practically a constant. Curve 52, for a single-crystal sample containing 0.006 percent zinc and having the heat flow directed along the a-axis, and hence for the $k_\perp$ direction, had a maximum displaced to a lower temperature. This result may probably be an indication that, as in the case of zinc, an effect of the anisotropy is for cadmium single crystals with different impurities to have different families of curves for each crystal direction. This possibility is however being ignored for the present, pending more conclusive information.

On the assumption that one family of curves applies to all crystal directions, and using $m = 5.0$ and $n = 4.5$, the values of α'' was derived for curve 43 with $\beta = 0.0055$, which is a slight modification (for a better fit) of the value 0.006 given by the authors. Using $\beta = 0.0055$ a recommended curve for $k_\parallel$ was derived up to 3 K, which links smoothly with curve 43 and follows it to about 20 K. Bogaard's measured values for samples giving $k_\perp$ all lie below this curve, but it seems reasonable to assume this to result from their lower purities and to accept the earlier conclusion [608] that $k_\perp/k_\parallel$ is 1.31 at low temperatures. This was based on measurements for the two crystal directions at 0.53 K by Zavaritskii [1601] (curves 15 and 16), and the support given by a value of 1.25 at 293 K due to Goens and Grüneisen [502] (curves 12–14). By using $k_\perp/k_\parallel = 1.31$ at 0.53 K, the β-value for the corresponding curve for $k_\perp$ has been calculated to be 0.0042 and the curve for $k_\perp$ derived using the same constants, m, n, and α'' as for $k_\parallel$. The recommended curve for k_{poly} has been derived on the assumption that $k_{poly} = 1/3\ (k_\parallel + 2k_\perp)$.

The recommended low-temperature curves have been smoothly extended to higher temperatures. That for the perpendicular direction at first approximates curve 8, and then follows Goens and Grüneisen's derived values for k to about 300 K. It is continued smoothly to the melting point. The curve for the parallel direction is derived from this on the basis of $k_\parallel = k_\perp/1.25$ and that for the polycrystalline sample is again derived on the assumption that $k_{poly} = 1/3\ (k_\parallel + 2k_\perp)$.

Although these curves have been drawn with no minimum in the immediate sub-normal temperature region, the possibility of a slight minimum should not totally be dismissed. The measurements of Wright [1580] (curve 25) were only regarded as having an accuracy of 10 percent, but these do indicate a small minimum at about 110 K. Moreover, this possibility of a minimum receives support from the results of three other sets of workers, Eucken and Gehlhoff [405] (curve 1), Bailey [106] (curve 4), and Brown [219] (curve 6), all of which give positive temperature coefficients at temperatures near normal.

It is of interest that those workers who had included measurements of electrical resistivity report Lorenz functions that agree to within a few percent of the theoretical value at near normal temperatures.

Two sets of data are available for a short temperature range in the liquid state. The early measurements of Brown [219] (curve 6) have a positive temperature coefficient and agree to within about 4 percent with values derived from the electrical resistivity data of Matuyama [903] and an equation recommended by Powell [1120]

$$k = 0.012 + 2.32 \times 10^{-8}\ T\ \rho^{-1}.$$

On the other hand Yurchak and Filippov [1591] (curve 31) report thermal conductivity values with a small negative temperature coefficient and a lower and decreasing Lorenz function. The curve at present proposed for liquid cadmium has been drawn in a mean position and only extends to about 300 K above the melting point. Even so, a difference of about 40 percent will be noted, which would increase rapidly at higher temperatures. It is clear that further measurements on molten cadmium are required.

The recommended values are for well-annealed high-purity cadmium and are thought to be accurate to within ±4 percent at moderate temperatures and ±6 percent near the melting point. At temperatures below 100 K the values are highly conditioned by impurity and imperfection, and the recommended values for $k_\parallel$, $k_\perp$, and k_{poly} are applicable only to specimens having $\rho_0 = 0.000134$, 0.000103, and 0.000112 $\mu\Omega$ cm, respectively. Since, however, the location of the thermal conductivity maxima have not yet been well defined experimentally, the uncertainties of the values below 20 K are probably as high as ±20 percent. The values for molten cadmium are provisional and they are probably good to ±12 percent near the melting point but the uncertainty is considerably larger at higher temperatures.

TABLE 17. Recommended thermal conductivity of cadmium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k
0	0	0	0
1	182	239	220
2	343	442	409
3	354	432	406
4	264	314	297
5	157	167	164
6	73.8	76.8	75.8
7	40.0	42.8	41.9
8	24.6	26.2	25.7
9	16.3	17.6	17.2
10	11.5	12.5	12.2
11	8.68	9.50	9.23
12	6.74	7.44	7.21
13	5.44	6.05	5.85
14	4.48	5.01	4.83
15	3.76	4.26	4.09
16	3.23	3.67	3.52
18	2.50	2.88	2.75
20	2.07	2.44	2.32
25	1.59	1.92	1.81
30	1.37	1.67	1.57
35	1.23	1.51	1.42
40	1.13	1.41	1.32
45	1.07	1.34	1.24
50	1.03	1.28	1.20
60	0.970	1.21	1.13
70	0.930	1.16	1.08
80	0.905	1.13	1.06
90	0.892	1.11	1.04
100	0.883	1.10	1.03
123.2	0.872	1.09	1.02
150	0.864	1.08	1.01
173.2	0.856	1.07	1.00
200	0.851	1.06	0.993
223.2	0.846	1.05	0.987
250	0.840	1.05	0.980
273.2	0.835	1.04	0.975
298.2	0.830	1.04	0.969
300	0.830	1.04	0.968
323.2	0.826	1.03	0.963
350	0.821	1.03	0.958
373.2	0.816	1.02	0.953
400	0.811	1.01	0.947
473.2	0.793	0.990	0.928
500	0.786	0.980	0.920
573.2	0.760	0.951	0.891
594.258	0.751	0.942	0.880

Liquid

T	k
594.258	0.368
600	0.370
673.2	0.389
700	0.396
773.2	0.414
800	0.420
873.2	0.434
900	0.439

†The values are for well-annealed high-purity cadmium. Those below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having ρ_0=0.000134, 0.000103, and 0.000112 $\mu\Omega$ cm, respectively. The values for molten cadmium are provisional.

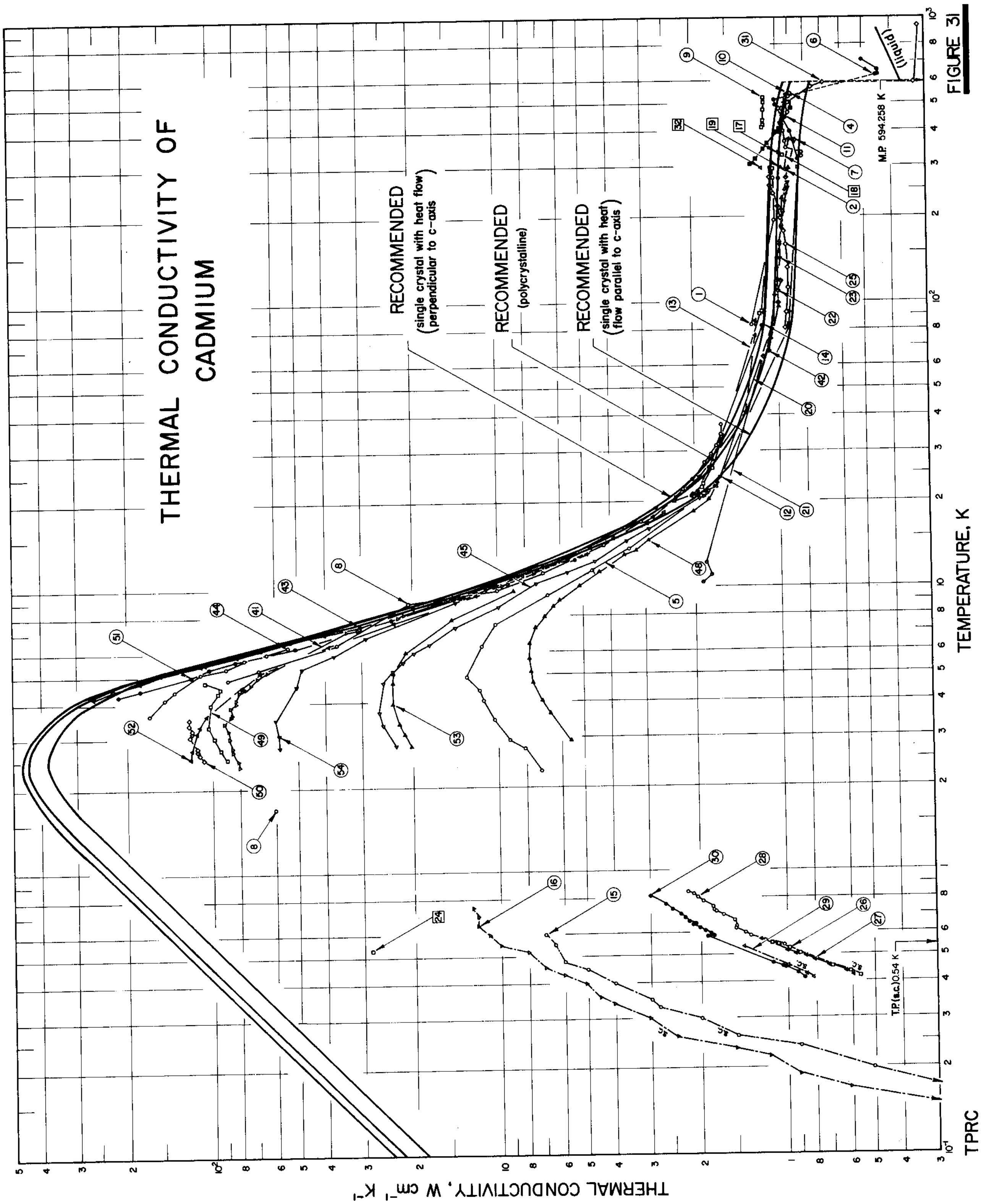

THERMAL CONDUCTIVITY OF CADMIUM
RECOMMENDED (single crystal with heat flow perpendicular to c–axis)
RECOMMENDED (polycrystalline)
RECOMMENDED (single crystal with heat flow parallel to c–axis)
(liquid)
M.P. 594.258 K
T.P.(s.c.) 0.54 K
TPRC
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹

FIGURE 31

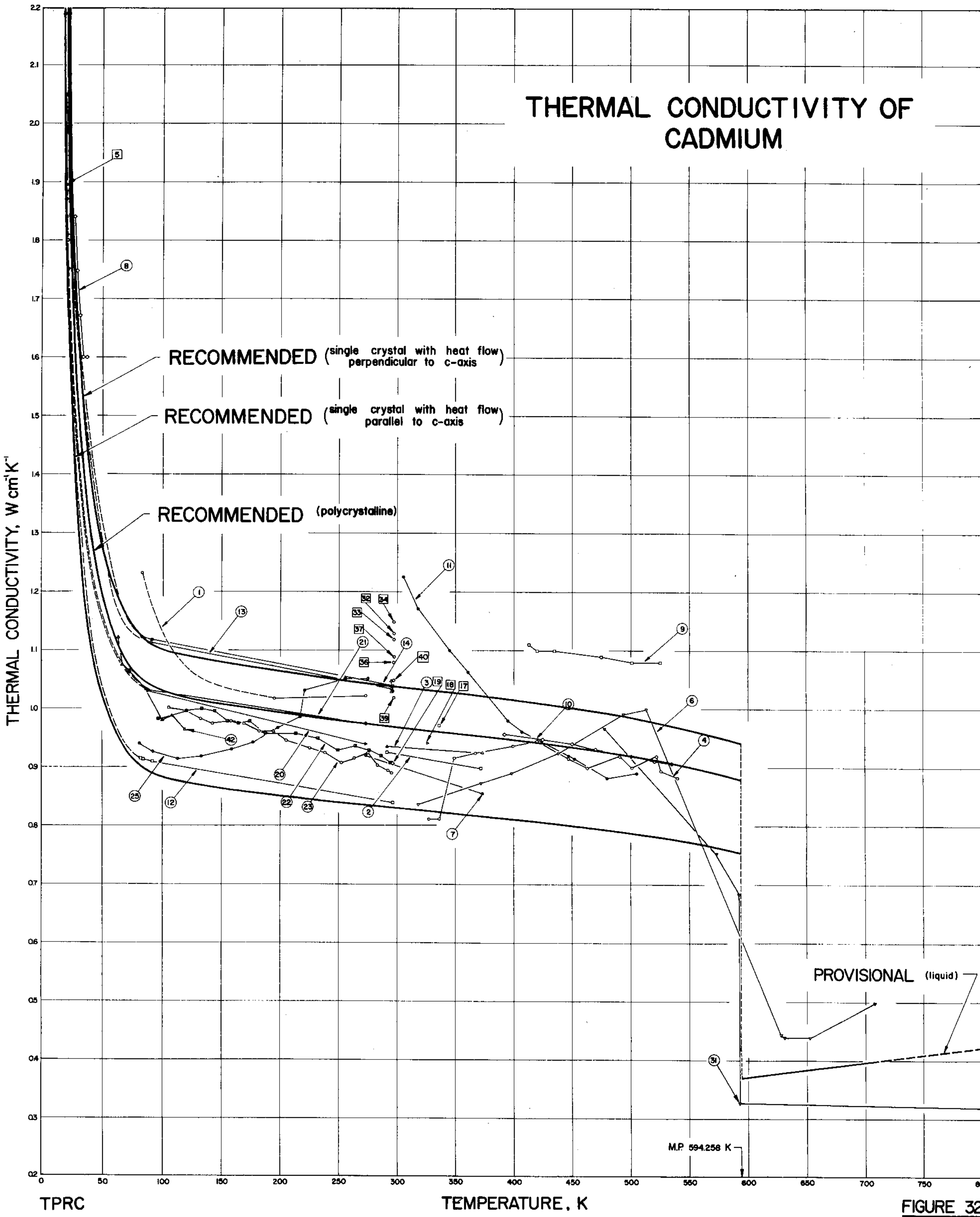

THERMAL CONDUCTIVITY OF CADMIUM
RECOMMENDED (single crystal with heat flow perpendicular to c-axis)
RECOMMENDED (single crystal with heat flow parallel to c-axis)
RECOMMENDED (polycrystalline)
PROVISIONAL (liquid)
M.P. 594.258 K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 32

TABLE 18. THERMAL CONDUCTIVITY OF CADMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	405	Eucken, A. and Gehlhoff, G.	1912	L	83-273		Specimen 2-3 cm in dia; electrical conductivity 5.05, 1.835, and 1.289 x 10^5 ohm^{-1} cm^{-1} at -190, -79, and 0 C, respectively.
2	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373		<0.05 (Fe + Pb + Zn); density 8.63 g cm^{-3} at 18 C; electrical conductivity 13.13 and 9.89 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
3	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373		Similar to the above specimen but drawn into a wire; electrical conductivity 13.25 and 10.18 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
4	106	Bailey, L.C.	1931	L	327-540		Specimen prepared from "pure redistilled cadmium"; density 8.64 g cm^{-3} at 21 C; same specimen as used by Lees (curves 22 and 23).
5	937	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-21	Cd 1	99.9999 pure; polycrystalline; form factor = 160; cast in glass; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 50.4.
6	219	Brown, W.B.	1923	L	318-708		Specimen 1.5 cm in dia and 12 cm long; melting point 320 C.
7	859	Lorenz, L.	1881	L	273,373		Density 8.62 g cm^{-3}; electrical conductivity 14.41 and 10.18 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively. (The paper reported 14.41 and 10.18 x 10^5 ohm^{-1} cm^{-1}, obviously a typographical error.)
8	1220	Rosenberg, H.M.	1955	L	1.7-37	Cd 2	99.995 pure; single crystal; with heat flow at 79° to the hexagonal axis.
9	969	Mikryukov, V.E. and Rabotnov, S.N.	1944	E	414-526		Single crystal; electrical resistivity 10.08, 10.33, 10.90, 12.23, 13.20, and 14.10 μohm cm at 140.6, 146.9, 162.4, 202.0, 228.6, and 252.4 C, respectively.
10	969	Mikryukov, V.E. and Rabotnov, S.N.	1944	E	393-536		Polycrystal; electrical resistivity 11.84, 13.22, 14.34, 15.22, 16.65, 17.59, and 18.30 μohm cm at 119.6, 152.8, 177.2, 196.9, 228.2, 248.8, and 262.6 C, respectively.
11	971	Mikryukov, V.E., Tyapunina, N.A., and Cherpakov, V.P.	1956	E	306-506		Pure; electrical conductivity 12.89, 11.11, 9.51, 8.38, 7.60, and 7.32 x 10^4 ohm^{-1} cm^{-1} at 32.5, 72.2, 122.2, 174.3, 207.5, and 232.6 C, respectively.
12	502	Goens, E. and Grüneisen, E.	1932	L	21-297	Cd 53	Single crystal; specimen 0.1475 cm^2 in cross-sectional area and 6.70 cm long; angle between rod axis and hexagonal axis ϕ = 14°; electrical resistivity 0.185, 2.001, 7.65, and 8.27 μohm cm at -252, -190, 0, and 20 C, respectively.
13	502	Goens, E. and Grüneisen, E.	1932	L	22-295	Cd 47a	Single crystal; specimen 0.1009 cm^2 in cross-sectional area and 4.48 cm long; ϕ = 84°; electrical resistivity 0.1352, 1.63, 6.38, and 6.89 μohm cm at -252, -190, 0, and 20 C, respectively.
14	502	Goens, E. and Grüneisen, E.	1932	L	21-297	Cd 47b	Similar to the above specimen except 0.0914 cm^2 in cross-sectional area and 6.65 cm long.
15	1601	Zavaritskii, N.V.	1960	L	0.10-0.60	Cd-1	Single crystal; heat flow along the hexagonal axis; in normal and superconducting states.
16	1601	Zavaritskii, N.V.	1960	L	0.10-0.75	Cd-3	Single crystal; heat flow perpendicular to the hexagonal axis; in normal and superconducting states.
17	1327	Smith, A.W.	1925	L	336.2		Impurities <0.03; specimen in rod form 0.3 cm^2 in cross-sectional area and 5 to 6 cm long; electrical conductivity 13.76 x 10^4 ohm^{-1} cm^{-1} at 23 C.

TABLE 18. THERMAL CONDUCTIVITY OF CADMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	830	Smith, A. W.	1925	L	326.2		Similar to the above specimen except 1.9 cm in dia and 10 cm long.
19	869	Lussana, S.	1918	L	296.9		Specimen 1.1 cm in dia; supplied by Erba; measured in air at atmospheric pressure.
20	1268	Schott, R.	1916	L	20-273		Purified; specimen ~0.5 cm in dia and 5 cm long; electrical conductivity 622.0, 52.5, and 14.5 x 10^4 ohm^{-1} cm^{-1} at 20.4, 87.0, and 273 K, respectively.
21	1268	Schott, R.	1916	L	20-273		Chemically pure (Kahlbaum); specimen ~0.5 cm in dia and 5 cm long; electrical conductivity 678.9, 53.58, and 14.6 x 10^4 ohm^{-1} cm^{-1} at 20.4, 87.0, and 273 K, respectively.
22	830	Lees, C. H.	1908	L	96-297		Turned from a cast stick of "pure redistilled cadmium" as used in cadmium-cell; specimen 0.585 cm in dia and 7-8 cm long; density 8.64 g cm^{-3} at 21 C; electrical resistivity 2.22, 2.56, 4.18, 5.05, 5.46, 6.38, 6.96, and 7.78 μohm cm at -178.1, -165.9, -105.8, -75.1, -59.9, -25.2, -5.7, and 22.8 C, respectively; first experiment.
23	830	Lees, C. H.	1908	L	105-295		The above specimen, second experiment.
24	1601	Zavaritskii, N. V.	1960	L	0.53	Cd-2	Single crystal; heat flow perpendicular to the hexagonal axis; transition point 0.53 K.
25	1580	Wright, W. H.	1960	L	82-276		99.95 pure; specimen 0.1877 in. dia x 2.255 in. long; turned from a cast stick obtained from A. D. Mackay; data corrected for rise in temp during measurement.
26	1299	Sharma, J. K. N.	1967	L	0.42-0.55	Run 38	99.999 pure; polycrystalline; supplied by Johnson, Matthey and Co., Ltd; Lab. No. 137; specimen form factor (ℓ/a) = 1.94 x 10^4 cm^{-1}; measurements taken just after extruding the wire; in superconducting state.
27	1299	Sharma, J. K. N.	1967	L	0.42-0.57	Run 38	The above specimen in normal state.
28	1299	Sharma, J. K. N.	1967	L	0.53-0.85	Run 38	The above specimen measured in a magnetic field of 80 Oe; in normal state.
29	1299	Sharma, J. K. N.	1967	L	0.42-0.54	Run 39	The above specimen annealed in the cryostat itself in a vacuum of 10^{-5} mm Hg for 7 days at room temp; in superconducting state; run No. 39.
30	1299	Sharma, J. K. N.	1967	L	0.42-0.82	Run 39	The above specimen measured in a magnetic field of 40 Oe for the normal state results below 0.58 K.
31	1591	Yurchak, R. P. and Filippov, L. P.	1964	P	478-929		In solid and liquid states; thermal conductivity values calculated from measured thermal diffusivity data with density and specific heat data taken from Slavinskii, M. P. ("Physicochemical Properties of Elements," Moscow, 1952).
32	210	Bridgman, P. W.	1926	L	298.2		Single crystal; 6 mm dia x 10 cm long; crystal axis nearly perpendicular to specimen axis; obtained from Kahlbaum; electrical resistivity 6.92 μohm cm at room temp; datum uncorrected for heat losses.
33	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 7.03 μohm cm at room temp and the crystal axis inclined at a smaller angle to specimen axis.
34	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 7.14 μohm cm at room temp and the crystal axis inclination still smaller.
35*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 7.20 μohm cm at room temp and the crystal axis inclination still smaller.

* Not shown in figure.

TABLE 18. THERMAL CONDUCTIVITY OF CADMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
36	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 7.39 μohm cm at room temp and the crystal axis inclination still smaller.
37	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 7.77 μohm cm at room temp and the crystal axis inclination still smaller.
38*	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 8.14 μohm cm at room temp and the crystal axis inclination still smaller.
39	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 8.20 μohm cm at room temp and the crystal axis inclination still smaller.
40	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 8.31 μohm cm at room temp and the crystal axis almost parallel to specimen axis.
41	1222	Rosenberg, H.M.	1957	L	2.4-14	Cd 5	99.995 pure; single crystal with the hexagonal axis at 40 degrees to the specimen axis; prepared from a batch of Hilger VPS 8670.
42	296	Cooper, M.H.	1964	L	65-119		99.95 pure; cut from the same batch as the specimen used by Wright, W.H. (see curve No. 25); machined to a 0.25 in. rod.
43	178, 177	Bogaard, R.H. and Gerritsen, A.N.	1969	L	4.2-18	Cd C1	0.0007 Ca, ≤0.0005 Ta, <0.0005 Sn, 0.0004 Cl, 0.0003 C, 0.0003 Li, <0.0003 In, 0.0002 each of N, O, and K, <0.0002 Au, <0.0002 Te, <0.00007 Tl, <0.00007 Th, 0.00006 Ti, <0.00006 Ag, <0.00006 W, <0.00005 Ba, and 0.00002 Cr; single crystal; supplied by Harshaw Chemical Co.; 20 x 2 x 1.90 mm; specimen axis parallel to the hexagonal orientation; annealed at 200 C for 6 hrs; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K) \sim 50\,000$; residual thermal resistance parameter $\beta = 0.006$.
44	178, 177	Bogaard, R.H. and Gerritsen, A.N.	1969	L	3.7-6.3	Cd C2	The above specimen etched to 0.70 mm in width; $\beta = 0.016$.
45	178, 177	Bogaard, R.H. and Gerritsen, A.N.	1969	L	2.8-20	CdZnC	Approx 0.049 Zn; single crystal; specimen 1.14 mm wide with axis parallel to the hexagonal orientation; prepared by electroplating zinc onto a pure single crystal Cd blank, allowing diffusion at 200 C for several days, etching off the surface residue, and annealing at 200 C for a wk; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K) \sim 3100$.
46*	1227	Rowe, V.A.	1967	L	2.0-259		99.9999 pure; single crystal; grown in the author's laboratories (M.S.U.) using a horizontal zone technique developed by Abele, J.C.; specimen cross-sectional area 0.0453 cm^2 and 6.80 cm long; electrical resistivity ratio $\rho(297K)/\rho(4.2K) = 24\,000$; measured in a vacuum of 5×10^{-6} mm Hg; heat flow perpendicular to c-axis. (Author regarded values as of low accuracy.)
47*	1227	Rowe, V.A.	1967	L	2.3-275		Similar to the above specimen except cross-sectional area 0.0501 cm^2 and 6.096 cm long; electrical resistivity ratio $\rho(297K)/\rho(4.2K) = 44\,000$; heat flow parallel to c-axis. (Author regarded values as of low accuracy.)
48	178	Bogaard, R.H. and Gerritsen, A.N.	1969	L	2.9-23	CdZnA	~0.35 Zn; single crystal; specimen 1.00 mm wide with axis perpendicular to the hexagonal orientation; prepared by electroplating zinc onto a pure single crystal Cd blank, diffusing at 200 C for several days, etching off the surface residue, annealing at 200 C for a week; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K) \sim 500$.
49	177	Bogaard, R.H.	1970	L	2.6-4.8	Cd C3	The specimen Cd C2 for curve No. 44 etched to 0.45 mm in width.
50	177	Bogaard, R.H.	1970	L	2.6-71	CdZnC2	Approx 0.006 Zn; single crystal; specimen 1.03 mm wide with axis parallel to the hexagonal orientation; supplied by AREMCO Products Inc.; commerically alloyed; annealed at 200 C for 6 hrs; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K) = 18\,000$.

* Not shown in figure.

TABLE 18. THERMAL CONDUCTIVITY OF CADMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
51	177	Bogaard, R. H.	1970	L	4.3-13	CdA1	0.0007 Ca, ≤0.0005 Ta, < 0.0005 Sn, 0.0004 Cl, 0.0003 C, 0.0003 Li, <0.0003 In, 0.0002 each of N, O, and K, < 0.0002 Au, < 0.0002 Te, <0.00007 Tl, < 0.00007 Th, 0.00006 Ti, < 0.00006 Ag, < 0.00006 W, <0.00005 Ba, and 0.00002 Cr; single crystal; supplied by Harshaw Chemical Co.; about 25 mm long, 2.15 mm wide, and 1.5 mm thick; heat flow along the a-axis.
52	177	Bogaard, R. H.	1970	L	2.6-86	CdZnA2	Approx 0.006 Zn; single crystal; about 25 mm long, 1.12 mm wide, and 1.5 mm thick; supplied by AREMCO Products Inc.; commercially alloyed; annealed at 200 C for 6 hrs; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K)$ = 19000; heat flow along the a-axis.
53	177	Bogaard, R. H.	1970	L	2.8-9.8	CdZnA3	Approx 0.055 Zn; single crystal; about 25 mm long, 1.16 mm wide, and 1.5 mm thick; prepared by electroplating zinc onto a pure single crystal cadmium blank, allowing diffusion at 200 C for several days, etching off the surface residue, and homogenizing at 200 C for 1 wk; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K)$ = 2700; heat flow along the a-axis.
54	177	Bogaard, R. H.	1970	L	2.8-19	CdSnA1	Approx 0.15 Sn; single crystal; about 25 mm long, 1.04 mm wide, and 1.5 mm thick; electrical resistivity ratio $\rho(r.t.)/\rho(1.4K)$ = 7700; heat flow along the a-axis.

Calcium

The thermal conductivity of calcium has been listed in the 1948 and 1961 Editions of Metals Handbook [56] published by the American Society for Metals as 0.3 cal s^{-1} cm^{-1} C^{-1} (1.25 W cm^{-1} C^{-1}) at 20 C, but no source of this value can be located. Indeed the thermal conductivity of calcium does not appear to have been measured at any temperature. Furthermore, according to Frank and Jepperson [459] the electrical resistivity of calcium at room temperature is 3.60 ± 0.03 $\mu\Omega$ cm, which, together with the listed thermal conductivity, leads to the low value of about 1.5 × 10^{-8} V^2 K^{-2} for the Lorenz function. This would suggest that the listed value could only apply to a very impure sample of calcium, and that the thermal conductivity of a sample having the above electrical resistivity would be nearer 2.0 W cm^{-1} K^{-1} at normal temperature.

In order to extend the estimation to higher temperatures a similar use has been made of the electrical resistivity data of Smith, Carlson, and Vest [1333]. These workers covered the range 293 to 973 K but, as their sample gave values that were greater by about 0.5 $\mu\Omega$ cm at room temperature, this quantity has been subtracted from each of their values, and the resistivity value obtained in this way used for the derivation of thermal conductivities to higher temperatures. The dashed curve shown in the figure was derived in this way, and should serve to give provisional values to within 20 percent, pending the availability of experimental determinations, for the thermal conductivity of calcium.

Calcium is clearly a metal for which thermal conductivity determinations should be made over a wide range of temperatures.

TABLE 19. Provisional thermal conductivity of calcium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1} K^{-1})

Solid			
T	*k*	*T*	*k*
0	0	673.2	1.76*
200	2.22*	700	1.76*
223.2	2.15*	737	1.76*
250	2.09*	773.2	1.62*
273.2	2.06*	800	1.53*
298.2	2.01*	873.2	1.34*
300	2.00*	900	1.27*
323.2	1.97*	973.2	1.33*
350	1.93*	1000	1.28*
373.2	1.91*		
400	1.88*		
473.2	1.82*		
500	1.81*		
573.2	1.79*		
600	1.78*		

†For well-annealed high-purity calcium.
*Estimated.

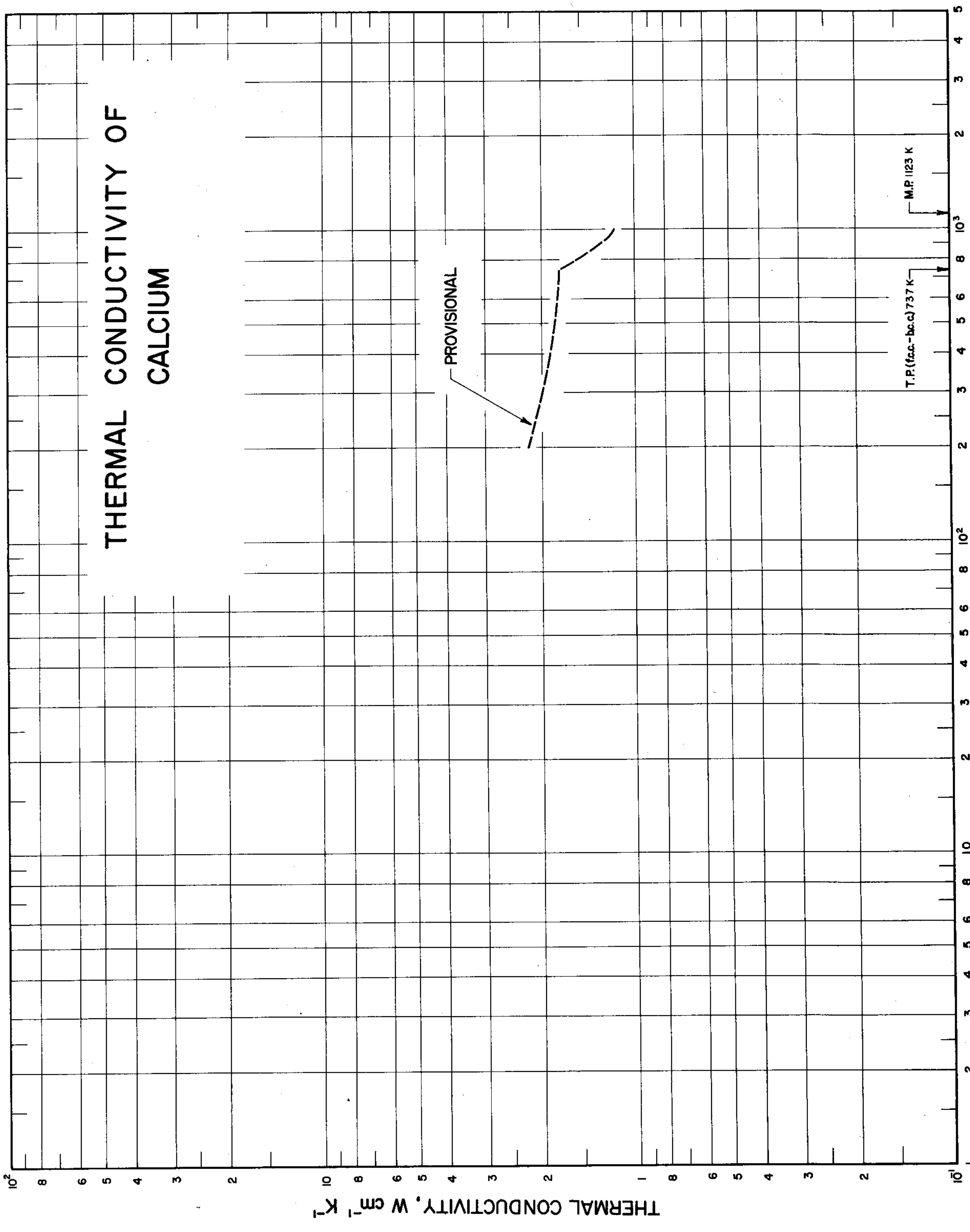

THERMAL CONDUCTIVITY OF CALCIUM
PROVISIONAL
M.P. 1123 K
T.P. (f.c.c.-b.c.c.) 737 K
TEMPFRATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 33

Californium

No information is available for the thermal or electrical conductivity of californium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidence shows that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of californium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Carbon

Carbon exists in nature in three allotropic forms: amorphous, which is black; graphite, also black; and diamond, which is colorless. A fourth form, known as "white" carbon which is a transparent birefringent crystal, is now thought to exist.

Amorphous carbon is stable at temperatures below about 1500 K, and transforms gradually to graphite when heated at higher temperatures. With increase in temperature the extent of the graphitization increases and is accompanied by the growth of larger crystallites. The temperature and rate of the transformation are both influenced by the presence of impurities. Diamond is one of the hardest known materials while graphite is one of the sofest. Graphite exists in two forms: hexagonal (alpha) form and rhombohedral (beta) form. Natural graphite is reported to contain as much as 30 percent of the rhombohedral form, whereas artificial graphite contains only the hexagonal form. The hexagonal form can be converted to the rhombohedral by mechanical treatment, and the rhombohedral form reverts to the hexagonal on heating above 1300 K. The new allotropic form, "white" carbon, was produced in 1969 during the sublimation of pyrolytic graphite at high temperatures and low pressures. Under free-vaporization conditions above about 2550 K, "white" carbon forms as small transparent crystals on the edges of the basal planes of graphite.

The thermal conductivities of amorphous carbon, diamond, and graphite are discussed separately in the following subsections.

Carbon (Amorphous)

Amorphous carbon includes a variety of materials such as petroleum coke, lampblack, carbon black, etc. Its density is about 1.8 to 2.1 g cm^{-3}. Amorphous carbon sublimes at about 3925 to 3970 K.

Much less attention has been given to the determination of the thermal conductivity of amorphous carbon than to that of graphite. Pandorf, Chen, and Daunt [1061] have reported the thermal conductivities of several carbon resistors for a temperature range of about 3 to 120 K (curves 54–56, 58, 59). At 100 K their values range from 0.0055 to 0.0140 W cm^{-1} K^{-1}, and, since higher values can probably be attributed to some departure of the carbon from the amorphous form, a most probable curve for amorphous carbon has been drawn approximately as the mean for the two lowest conductivity curves of Pandorf, et al.

At temperatures above normal, the approximate range 300 to 1100 K has been covered by Burr [224] (curve 2), who made measurements on a sample taken from a petroleum coke electrode using a radial heat-flow method and by Meyers and Koyama [951] (curves 25 and 26) who derived appreciably larger values from thermal diffusivity determinations made on small carbon disks, when flash heated by a xenon lamp. Powell and Schofield [1128], from observations of the radial gradients established in several electrically heated samples of 80 percent petroleum coke combined with 20 percent lampblack, obtained values at temperatures from 1023 to over 2000 K (curves 3–7). Graphitization, and consequent departure from the amorphous carbon form, probably commenced at about 1500 K. Over the short temperature range common to the determinations of Burr the latter are higher by about 20 percent. Another set of measurements by Jones (curve 64) for the range 320 to 520 K are referred to by Powell and Schofield [1128] and these lie some 10 to 13 percent below the values of Burr. The aforementioned most probable curve for the thermal conductivity of amorphous carbon has been smoothly extended from about 120 K to pass through the curve of Jones and then continued to follow at higher temperatures the trend of the curve of Burr to pass through the data of Powell and Schofield. It is weighted towards the latter since these were direct thermal conductivity determinations and were made on three different specimens believed to be free of any graphite. This curve stops at 1500 K, about the upper temperature limit at which carbon exists in the amorphous form and above which the observed increases in conductivity can be attributed to partial graphitization.

The recommended values are for high-purity amorphous carbon and are thought to be accurate to within ±10 to ±20 percent above room temperature. Values below room temperature are provisional and their uncertainty is considerably larger.

TABLE 20. Recommended thermal conductivity of carbon (amorphous)†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Amorphous			
T	k	T	k
0	0	250	0.0140
1		273.2	0.0150
2	0.0000361	298.2	0.0159
3	0.0000859	300	0.0160
4	0.000155	323.2	0.0168
5	0.000236	350	0.0176
6	0.000325	373.2	0.0182
7	0.000419	400	0.0189
8	0.000514	473.2	0.0202
9	0.000610	500	0.0206
10	0.000705	573.2	0.0216
11	0.000795	600	0.0219
12	0.000890	673.2	0.0226
13	0.000982	700	0.0229
14	0.00107	773.2	0.0235
15	0.00117	800	0.0237
16	0.00126	873.2	0.0242
18	0.00143	900	0.0244
20	0.00160	973.2	0.0250
25	0.00200	1000	0.0253
30	0.00239	1073.2	0.0262
35	0.00276	1100	0.0267
40	0.00312	1173.2	0.0279
45	0.00345	1200	0.0284
50	0.00377	1273.2	0.0297
60	0.00440	1300	0.0302
70	0.00500	1373.2	0.0318
80	0.00558	1400	0.0324
90	0.00614	1473.2	0.0341
100	0.00668	1500	0.0348
123.2	0.00798		
150	0.00938		
173.2	0.0106		
200	0.0118		
223.2	0.0129		

†The values are for high-purity amorphous carbon, and those below room temperature are provisional.

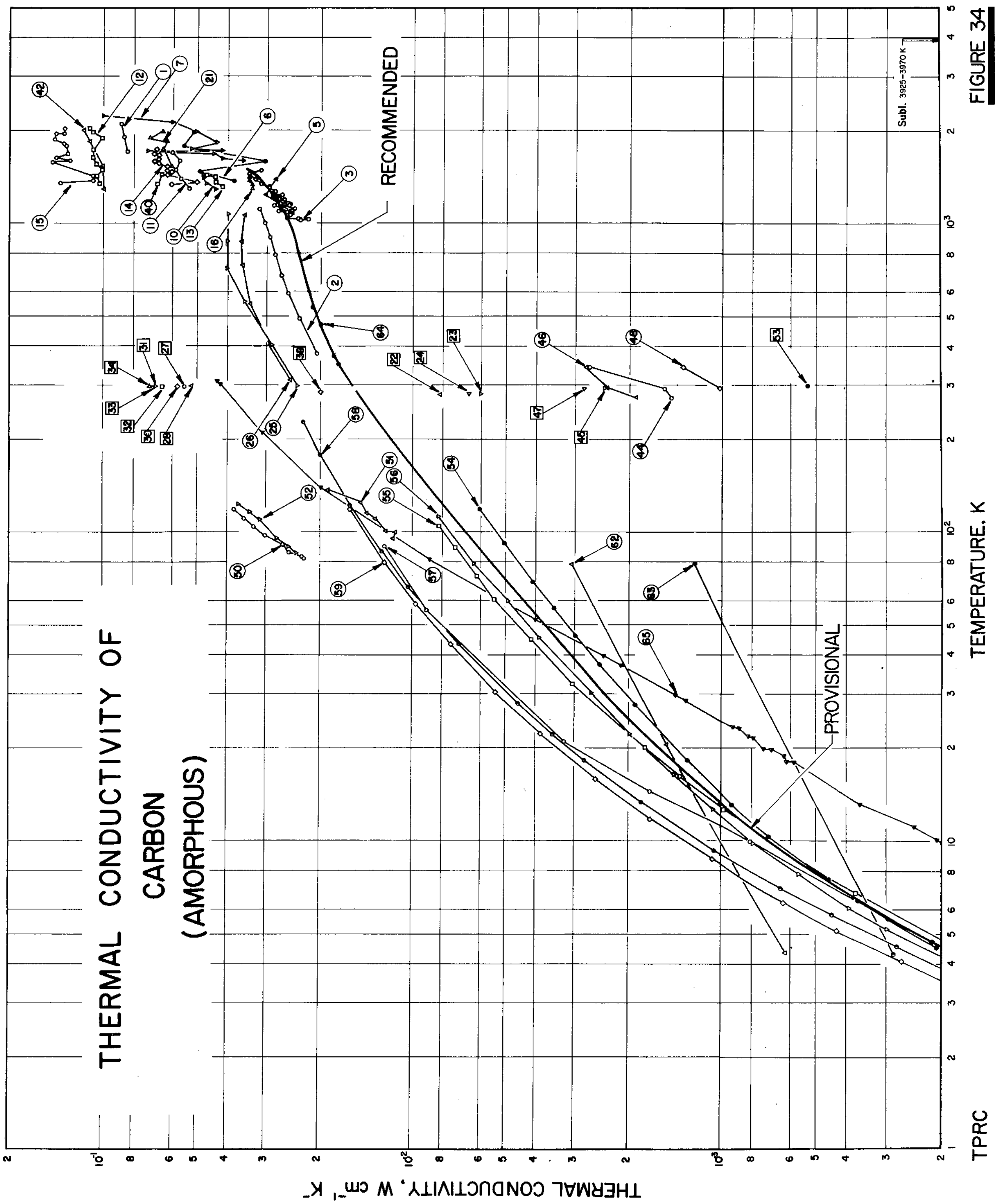

THERMAL CONDUCTIVITY OF
CARBON
(AMORPHOUS)
RECOMMENDED
PROVISIONAL
Subl. 3925–3970 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 34

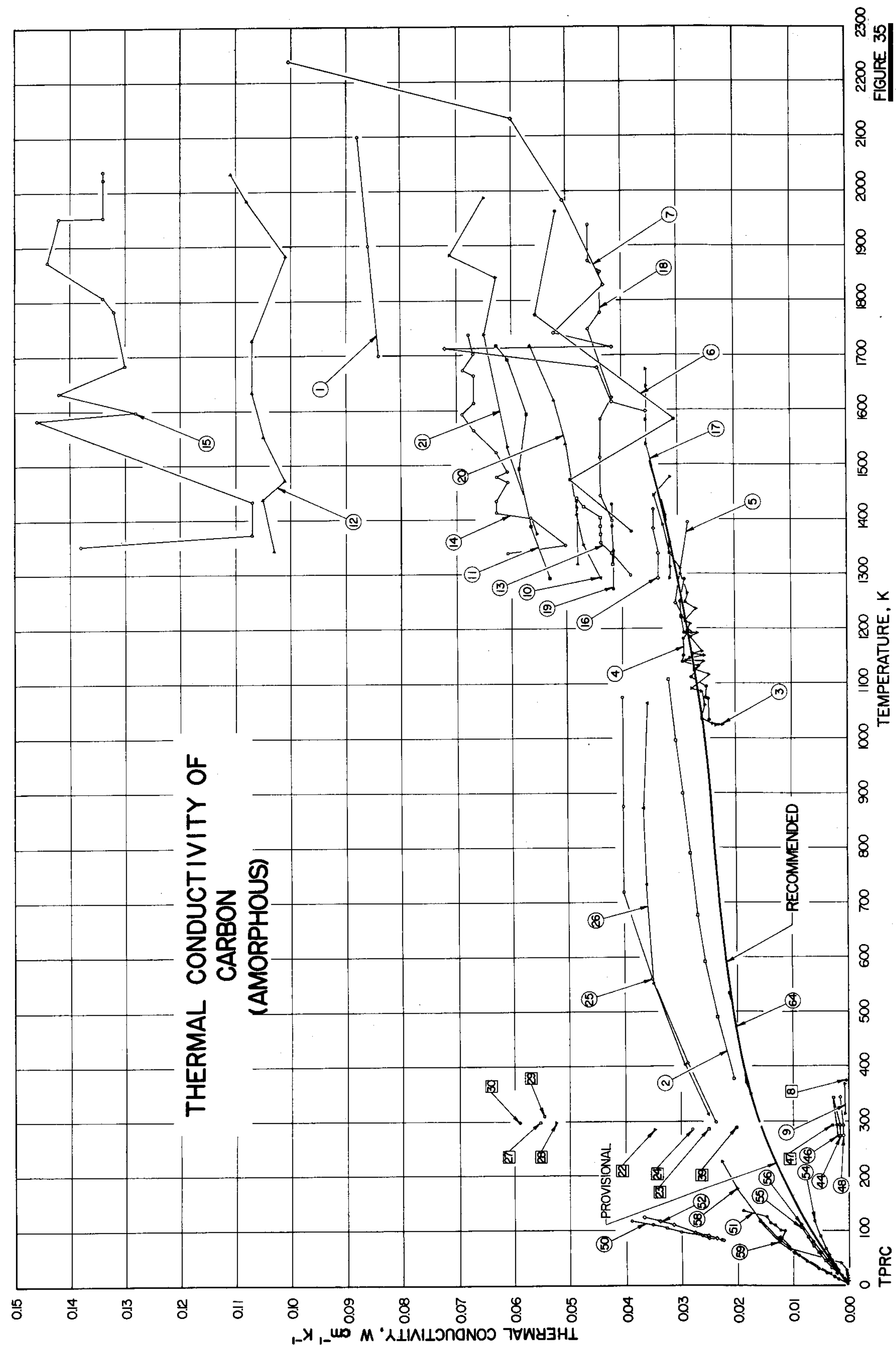

THERMAL CONDUCTIVITY OF
CARBON
(AMORPHOUS)
RECOMMENDED
PROVISIONAL
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 35

TABLE 21. THERMAL CONDUCTIVITY OF CARBON (AMORPHOUS) - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1579	Worthing, A. G.	1914	E	1700-2100		Pure; untreated carbon filament.
2	224	Burr, A. C.	1951	R	377-1107	Petroleum coke	Petroleum coke electrode; tubular, 6 in. O.D., 1.5 in. I.D., 2.25 in. long.
3	1128	Powell, R. W. and Schofield, F. H.	1939	R	1023-1477	1	80% petroleum coke, 20% lampblack; baked at approx 1100 C.
4	1128	Powell, R. W. and Schofield, F. H.	1939	R	1033-1290	2	Similar to the above specimen.
5	1128	Powell, R. W. and Schofield, F. H.	1939	R	1076-1394	3	Similar to the above specimen.
6	1128	Powell, R. W. and Schofield, F. H.	1939	R	1373-1963	4	Similar to the above specimen.
7	1128	Powell, R. W. and Schofield, F. H.	1939	R	1598-2238	5	Similar to the above specimen.
8	1340	Snyder, T. M. and Kamm, R. L.	1955	L	373.2	Lampblack	Compressed under 10 lb in.$^{-2}$ from 0.375 in. to 0.25 in. thick; specimen previously used in a high temp neutron absorption experiment.
9	1397	Taylor, T. S.	1920	L	313,368	Lampblack	Specimen 0.476 in. thick; specific gravity 0.165; prepared from Eagle brand Germantown lampblack.
10	1006	Mrozowski, S., Andrew, J. F., Juul, N., Sato, S., Strauss, H. E., and Tsuzuku, T.	1963	R	1293-1433		Prepared by mixing 50 parts 65/100 mesh and 50 parts <200 mesh soft filler (soft Texas coke), and 40 parts soft binder (M-30 pitch); extruded to 0.5 in. dia; baked for 4 days to 1000 C; heat-treated at 1200 C for 10 min; density after baking 1.55 g cm^{-3}; measured in an argon atm (approx one atm pressure).
11	1006	Mrozowski, S., et al.	1963	R	1293-1718		The above specimen heat-treated at 1500 C for 10 min.
12	1006	Mrozowski, S., et al.	1963	R	1343-2033		The above specimen heat-treated at 1800 C for 10 min.
13	1006	Mrozowski, S., et al.	1963	R	1318-1438		Prepared by mixing 50 parts 65/100 mesh and 50 parts 200/270 mesh soft filler (soft Texas coke), and 35 parts hard binder (phenol benzaldehyde); extruded to 0.5 in. dia; baked for 4 days to 1000 C; heat-treated at 1200 C for 10 min; density after baking 1.56 g cm^{-3}; measured in an argon atm (approx one atm pressure).
14	1006	Mrozowski, S., et al.	1963	R	1338-1738		The above specimen heat-treated at 1500 C for 10 min.
15	1006	Mrozowski, S., et al.	1963	R	1353-2038		The above specimen heat-treated at 1800 C for 10 min.
16	1006	Mrozowski, S., et al.	1963	R	1293-1415		Prepared by mixing 50 parts 100/150 mesh and 50 parts <270 mesh hard filler (phenol formaldehyde), and 48 parts soft binder (M-30 pitch); extruded to 0.5 in. dia; baked for 4 days to 1000 C; heat-treated at 1200 C for 10 min; density after baking 1.14 g cm^{-3}; measured in an argon atm (approx one atm pressure).
17	1006	Mrozowski, S., et al.	1963	R	1293-1675		The above specimen heat-treated at 1500 C for 10 min.
18	1006	Mrozowski, S., et al.	1963	R	1298-1938		The above specimen heat-treated at 1800 C for 10 min.
19	1006	Mrozowski, S., et al.	1963	R	1273-1428		Prepared by mixing 50 parts 100/150 mesh and 50 parts <270 hard filler (phenol formaldehyde), and 43 parts hard binder (phenol benzaldehyde); extruded to 0.5 in. dia; baked for 4 days to 1000 C; heat-treated at 1200 C for 10 min; density after baking 1.22 g cm^{-3}; measured in an argon atm (approx one atm pressure).

TABLE 21. THERMAL CONDUCTIVITY OF CARBON (AMORPHOUS) - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	1006	Mrozowski, S., Andrew, J. F., Juul, N., Sato, S., Strauss, H. E., and Tsuzuku, T.	1963	R	1318-1718		The above specimen heat-treated at 1500 C for 10 min.
21	1006	Mrozowski, S., et al.	1963	R	1373-1988		The above specimen heat-treated at 1800 C for 10 min.
22	246	Cellier, L.	1898	P	281.0	Bogenlichtkohle	Obtained from Paris; 0.495 cm dia x 2.33 cm long; density 1.567 g cm^{-3}; thermal conductivity value calculated from measured data of thermal diffusivity, density, and specific heat capacity.
23	246	Cellier, L.	1898	P	282.2	Bogenlichtkohle	From Siemens and Halske; 0.599 cm dia x 2.329 cm long; density 1.467 g cm^{-3}; same measuring method as above.
24	246	Cellier, L.	1898	P	282.2	Retortenkohle	2.298 x 0.533 x 0.525 cm; density 1.627 g cm^{-3}; same measuring method as above.
25	951	Meyers, C. and Koyama, K.	1968	P	298-1074	B205; 1-E	Disk specimen 0.5 in. in dia and 0.045 in. thick; density 1.516 g cm^{-3}; heat flow perpendicular to molding pressure; thermal conductivity values calculated from the measurement of thermal diffusivity (measured by xenon-flash technique), specific heat and density.
26	951	Meyers, C. and Koyama, K.	1968	P	312-1064	B205; 1-C	Similar to the above specimen except heat flow parallel to molding pressure.
27	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-A	Heat-treated at 1300 C; density 1.503 g cm^{-3}; electrical resistivity 5.58 milliohm cm.
28	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-A	The above specimen irradiated by 0.5 x 10^{19}nvt at 150-200 C; electrical resistivity 5.89 milliohm cm.
29	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-A	Similar to above but irradiated by a flux of 0.85 x 10^{19} nvt and electrical resistivity 5.89 milliohm cm.
30	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-A	Similar to above but irradiated by a flux of 2.0 x 10^{19} nvt and electrical resistivity 5.65 milliohm cm.
31	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-B	Heat-trated at 2000 C; density 1.483 g cm^{-3}; electrical resistivity 4.56 milliohm cm.
32	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-B	The above specimen irradiated by 0.5 x 10^{19} nvt at 150-200 C; electrical resistivity 4.55 milliohm cm.
33	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-B	Similar to above but irradiated by 0.85 x 10^{19} nvt and electrical resistivity 4.57 milliohm cm.
34	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-B	Similar to above but irradiated by 2.0 x 10^{19} nvt and electrical resistivity 4.56 milliohm cm.
35*	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-C	Heat-treated at 3000 C; density 1.458 g cm^{-3}; electrical resistivity 4.49 milliohm cm.
36*	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-C	The above specimen irradiated by 0.5 x 10^{19} nvt at 150-200 C; electrical resistivity 4.49 milliohm cm.
37*	1304	Shimada, T. and Kikuchi, T.	1964		298.2	GC-C	Similar to above but irradiated by 0.85 x 10^{19} nvt and electrical resistivity 4.48 milliohm cm.

* Not shown in figure.

TABLE 21. THERMAL CONDUCTIVITY OF CARBON (AMORPHOUS) - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
38*	1588	Yoshikawa, H.H.	1964		298.2	L-14	Prepared by National Carbon Co. from lampblack filler and pitch binder; 0.426 in. dia x 4 in. long; heat-treated at 1400 C; density 1.55 g cm^{-3}; electrical resistivity 6.0 milliohm cm at room temp.
39	1369	Störmer, R.	1934	E	286.2		Amorphous; 0.5 cm in dia and 3 5o 4 cm long; obtained from Siemens-Plania-Werke; electrical resistivity 8.905 milliohm cm.
40	1370	Strauss, H.E.	1963	E	1367, 1449		0.5 in. dia cylindrical specimen prepared from a mixture of soft filler and soft binder, extruded, baked to 1000 C; heat-treated at 1200 C for 5 min; electrical resistivity 3.56 and 3.50 milliohm cm at 1030 and 1168 C, respectively.
41*	1370	Strauss, H.E.	1963	E	1595, 1735		The above specimen again heat-treated to 1500 C; electrical resistivity 3.31, 3.24, 3.19, and 3.14 milliohm cm at 1019, 1221, 1341, and 1440 C, respectively.
42	1370	Strauss, H.E.	1963	E	1301-2015		The above specimen again heat-treated to 1800 C; electrical resistivity 2.83, 2.63, 2.53, and 2.37 milliohm cm at 1044, 1398, 1544, and 1732 C, respectively.
43*	247	Cerceo, J.M.	1963	L	1189		Density 0.51 g cm^{-3}.
44	1316	Simonova, L.K.	1943	P	273-343	1	Granulated specimen; density 0.474 g cm^{-3}; measured by a transient method.
45	1316	Simonova, L.K.	1943	P	293.2	1	The above specimen powdered; density 0.686 g cm^{-3}; same measuring method as above.
46	1316	Simonova, L.K.	1943	P	273-343	2	Granulated specimen; density 0.700 g cm^{-3}; same measuring method as above.
47	1316	Simonova, L.K.	1943	P	293.2	2	The abpve specimen ground to powder; density 0.810 g cm^{-3}; same measuring method as above.
48	1316	Simonova, L.K.	1943	P	273-343	3	Granulated specimen; density 0.513 g cm^{-3}; same measuring method as above.
49*	1316	Simonova, L.K.	1943	P	293.2	3	The above specimen ground to powder; density 0.630 g cm^{-3}; same measuring method as above.
50	899	Masuyama, T.	1966	L	82-118	Hard carbon (polymer-carbon)	Specimen 0.25 in. in dia and 4 in. long.
51	899	Masuyama, T.	1966	L	86-125		The above specimen irradiated in General Electri's Ballecitos Atomic Laboratories at 205 C with the irradiation dose of 1.76×10^{20} nvt (thermal neutron) = 7.6×10^{18} nvt (fast neutron E >2.9 MeV).
52	899	Masuyama, T.	1966	L	86-124		The above specimen measured after annealed at 1200 C.
53*	1336	Smith, N.D., Fun, F., and Visokey, R.M.	1967	C	298.2	Porous carbon	Specimen ~1 in. in dia and 0.5 in. long; aluminum used as comparative material; assume measured at room temp.
54	1061	Pandorf, R.C., Chen, C.Y., and Daunt, J.G.	1962	L	4.5-119		Allen Bradley carbon resistor 10 ohm 1/2 W; 0.24 cm in dia and 0.65 cm long; measured in vacuo.
55	1061	Pandorf, R.C., et al.	1962	L	2.8-105		Allen Bradley carbon resistor 10 ohm 1 W; 0.37 cm in dia and 1.1 cm long; measured in vacuo.
56	1061	Pandorf, R.C., et al.	1962	L	3.1-113		Allen Bradley carbon resistor 100 ohm 0.5 W; 0.25 cm in dia and 0.69 cm long.

*Not shown in figure.

TABLE 21. THERMAL CONDUCTIVITY OF CARBON (AMORPHOUS) - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
57	138	Berman, R.	1952	L	2.8-90		L. A. B. carbon resistor 33 ohm 0.5 W.
58	1061	Pandorf, R. C., Chen, C. Y., and Daunt, J. G.	1962	L	2.4-227		Ohmite carbon resistor 100 ohm 2 W; 0.58 cm in dia and 1.38 cm long; measured in vacuum.
59	1061	Pandorf, R. C., et al.	1962	L	2.4-118		Ohmite carbon resistor 3900 ohm 2 W; 0.58 cm in dia and 1.4 cm long; measured in vacuum.
60*	1168	Rafalowicz, J.	1966	R	1.8-2.2	A	500 ohm carbon resistor; supplied by Speer Resistor Co.
61*	1168	Rafalowicz, J.	1966	R	2.2-3.5	B	Similar to the above specimen.
62	265	Chen, C. Y.	1962	L	4.4-79		Allen Bradley carbon resistor 100 ohm 0.5 W.
63	265	Chen, C. Y.	1962	L	4.3, 79		Allen Bradley carbon resistor 10 ohm 0.5 W.
64	1128	Powell, R. W. and Schofield, F. H.	1939	R	350-534		Specimen taken from a batch of 80/20 carbon; electrical resistivity 0.0066 ohm cm at 20 C; measurements made by Jones, D. E. A.
65	1171	Rasor, J. S. and Smith, A. W.	1954	E	9.0-309		Index rod made from gas-baked coke (ungraphitized AGOT); extruded; room temp properties 1.56 g cm^{-3}, electrical resistivity 43 milliohm cm, and orientation factor $(\rho_{max}/\rho_{min}) = 1.8$.

* Not shown in figure.

Diamond

Diamond has the highest Debye temperature of all solids and, therefore, has the distinction to have the highest thermal conductivity of all solids at normal temperatures, since these two are proportional.

The water-white diamonds are divided into types I and II, according to whether the ultraviolet absorption by the diamond is pronounced at wavelengths near 3000 Å or 2200 Å, respectively [1204, 254]. Type II diamonds are in turn subdivided into two kinds: type IIa which refers to the electrically insulating variety and type IIb to the good conductors of electricity. Berman [138a] has found that the distinction between the type I and type II samples measured by him and his co-workers [143] was due to the nitrogen content of the former, and that the type I measured had about 5×10^{19} nitrogen atoms per cubic centimeter.

There are 12 sets of data available for diamond as shown in figures 36 and 37. Only for type I does more than one experimental curve exist. Moreover, most of the measurements have been made at the Clarendon Laboratory, Oxford [147, 143], and for type I the workers concerned regarded the newer measurements (curve 7) as being more accurate. The proposed curves for types I, IIa, and IIb have been smoothly drawn through their data and extrapolated to 400 K. These are considered only as typical curves serving to indicate the general trend of the thermal conductivity, since the exact location of the curve for a particular sample highly depends on its purity, lattice defect, crystal size, surface finish, and other factors.

TABLE 22. Typical thermal conductivity of diamond†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid							
	Type I	Type IIa	Type IIb		Type I	Type IIa	Type IIb
T	k	k	k	T	k	k	k
2	0.0138*	0.0331*	0.0200*	40	29.4	65.9	44.0
3	0.0461	0.111	0.0676	45	32.9	79.3	52.3
4	0.108	0.261	0.160	50	35.3	92.1	59.1
5	0.206	0.494	0.307	60	37.4	112	67.5
6	0.344	0.820	0.510	70	36.9	119	69.1
7	0.523	1.24	0.778	80	35.1	117	65.7
8	0.762	1.77	1.12	90	32.7	109	60.0
9	1.05	2.41	1.53	100	30.0	100	54.2
10	1.40	3.17	2.03	123.2	24.2	79.2	41.8
11	1.79	4.00	2.58	150	19.5	60.2	32.5
12	2.24	5.00	3.22	173.2	16.6	49.3	27.0
13	2.76	6.10	3.96	200	14.1	40.3	22.6
14	3.33	7.32	4.77	223.2	12.5	34.7	19.7
15	3.96	8.65	5.66	250	11.0	29.7	17.0
16	4.65	10.0	6.62	273.2	9.94	26.2	15.2
18	6.15	13.2	8.75	298.2	9.00	23.2	13.6
20	7.87	16.8	11.2	300	8.95	23.0	13.5
25	12.9	27.1	18.2	323.2	8.26*	20.7*	12.3*
30	18.8	38.9	26.5	350	7.55*	18.5*	11.1*
35	24.5	51.8	35.0	373.2	7.03*	17.0*	10.2*
				400	6.50*	15.4*	9.32*

†The three sets of values only represent typical curves for the thermal conductivity of the three types of diamond.
*Extrapolated.

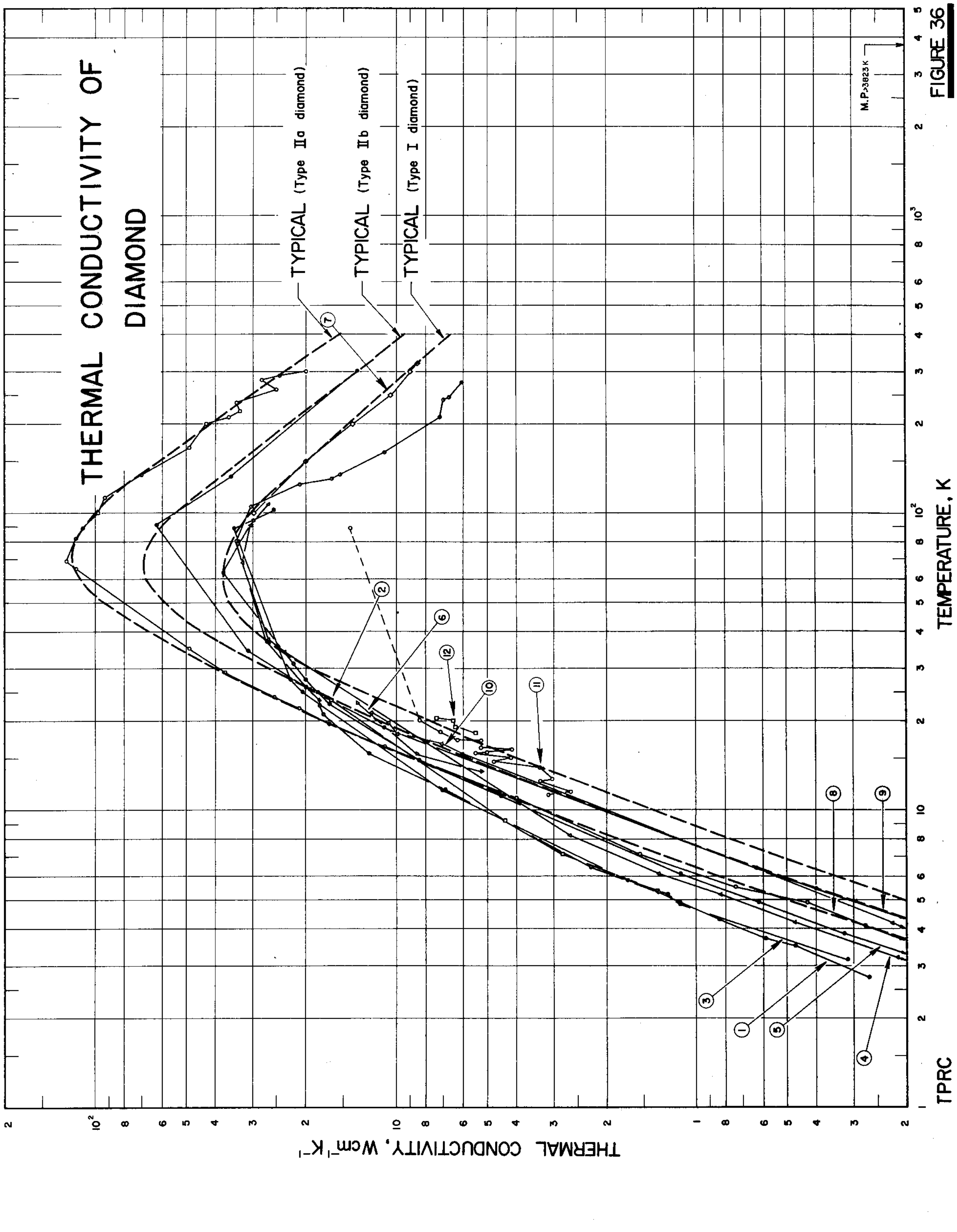

THERMAL CONDUCTIVITY OF DIAMOND
TYPICAL (Type IIa diamond)
TYPICAL (Type IIb diamond)
TYPICAL (Type I diamond)
M.P.≥3823 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 36

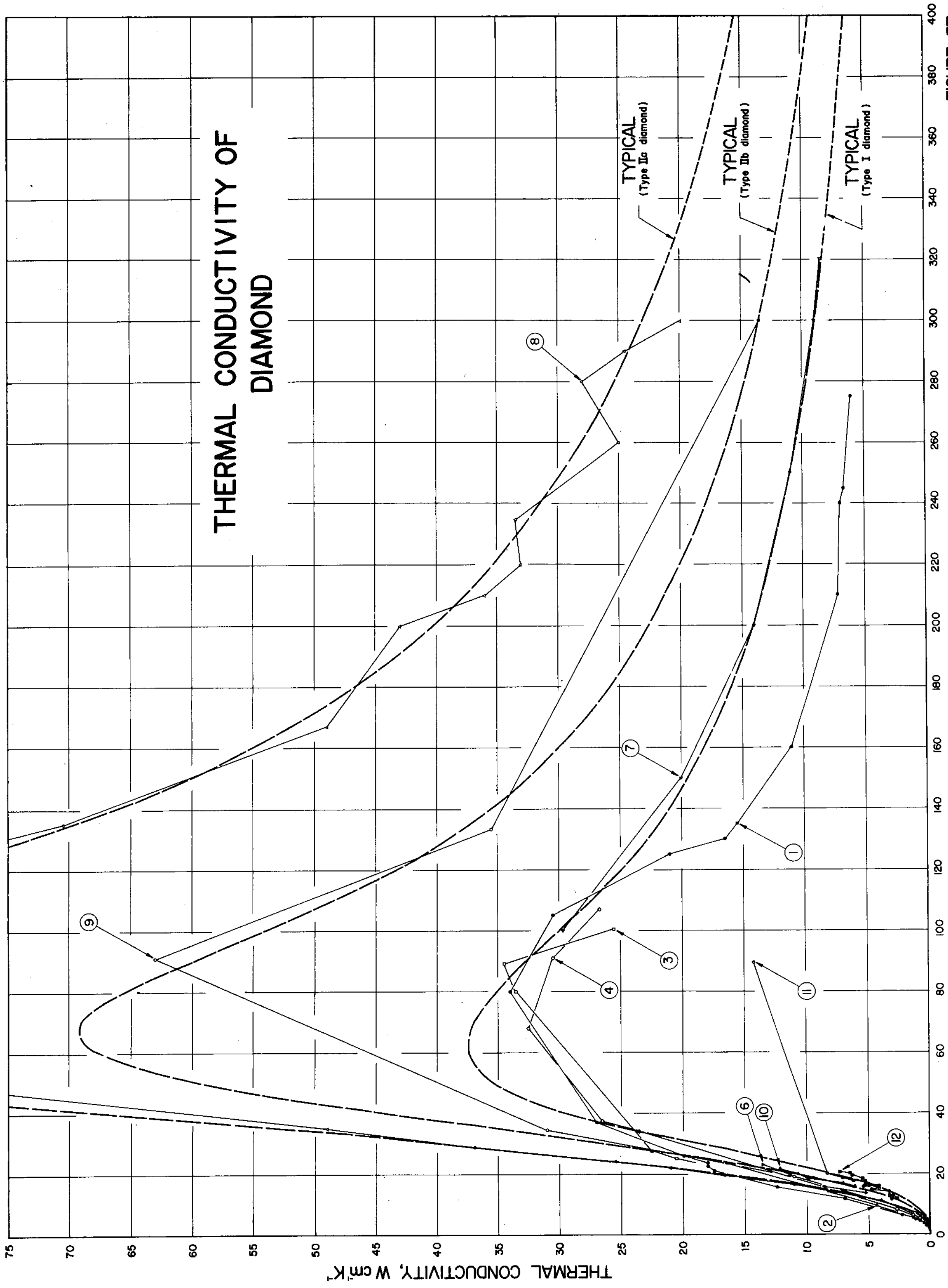

THERMAL CONDUCTIVITY OF DIAMOND
TYPICAL (Type IIa diamond)
TYPICAL (Type IIb diamond)
TYPICAL (Type I diamond)
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1}K^{-1}
TPRC

FIGURE 37

TABLE 23. THERMAL CONDUCTIVITY OF DIAMOND - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	147	Berman, R., Simon, F. E., and Ziman, J. M.	1953	L	2. 8-275	Type I	Type I stone (gem quality); as classified according to its ultra-violet transparency limit; 3. 9 x 3. 9 x 10. 9 mm; measuring length 6. 8 mm.
2	147	Berman, R., et al.	1953	L	5. 4-24	Type I	The above specimen; measuring length 5. 8 mm.
3	147	Berman, R., et al.	1953	L	3. 2-100	Type I	The above specimen sawn and ground to 3. 1 x 3. 1 mm in cross-section.
4	147	Berman, R., et al.	1953	L	2. 4-107	Type I	The above specimen sawn and ground to 1. 7 x 1. 7 mm in cross-section.
5	147	Berman, R., et al.	1953	L	2. 8-94	Type I	The above specimen sawn and ground to 1. 1 x 1. 1 mm in cross-section; measuring length 6. 9 mm.
6	147	Berman, R., et al.	1953	L	14-23	Type I	The above specimen; measuring length 5. 2 mm.
7	143	Berman, R. and Foster, E. L.	1956	L	100-320	Type I	Type I stone; approx 1. 1 x 1. 1 x 11 mm in size.
8	143	Berman, R. and Foster, E. L.	1956	L	2. 7-300	Type IIa	Type IIa stone; approx 0. 7 x 1. 25 x 10 mm.
9	143	Berman, R. and Foster, E. L.	1956	L	3. 0-300	Type IIb	Type IIb stone; approx 1. 1 x 1. 2 x 7 mm.
10	333	de Haas, W. J. and Biermasz, Th.	1938	L	3. 0-22		Specimen 6 mm long and 0. 59 mm^2 in triangular cross-section; supplied by I. J. Asscher, Amsterdam.
11	333	de Haas, W. J. and Biermasz, Th.	1938	L	11-89		The above specimen remounted.
12	333	de Haas, W, J. and Biermasz, Th.	1938	L	18-21		9 mm long; cross-sectional area 0. 82 mm^2; supplied by I. J. Asscher, Amsterdam.

Graphite

Graphite falls into two categories: natural graphite and artificial graphite. Natural graphite exists in two allotropic forms: hexagonal and rhombohedral. Although all artificial graphite has a hexagonal crystalline structure, it is not a specific material but includes a great variety of materials of different types and grades. Graphite of the hexagonal form has a theoretical density of 2.26 g cm^{-3} at 293 K, but the artificial graphites normally have much lower densities.

Since graphite includes a large family of materials and since the hexagonal crystal of graphite is highly anisotropic due to its two-dimensional layer structure, the thermal conductivity of graphite covers a very wide range.

In the category of artificial graphites, pyrolytic graphite distinguishes itself from pitch-bonded artificial graphite for its well-oriented crystalline structure such that the thermal conductivity of treated pyrolytic graphite measured both parallel and perpendicular to the layer planes approaches the values for ideal graphite single crystal [630]. Due to the lack of sufficiently large single crystals of graphite and the difficulty in handling them, information on graphite single crystals can best be obtained through the study of pyrolytic graphite. Experimental evidence indicates that the anisotropy of the thermal conductivity of pyrolytic graphite is far greater than that of natural graphite. The highest thermal conductivity so far measured is for a pyrolytic graphite in the direction parallel to the layer planes. At temperatures above 100 K it is higher than the thermal conductivity of all known solids except diamond. In contrast, the thermal conductivity of pyrolytic graphite in the direction perpendicular to the layer planes is comparable with that of the insulators. In between these two extremes lie the whole familv of thermal conductivity curves of pitch-bonded graphite varieties and natural graphites, the location of the curves depending upon the combined effect of various parameters such as impurity, imperfection (defects), the orientation and size and the degree of ordering of the grains and of the crystallites, the degree of graphitization, i.e., the ratio of the amount of the crystalline graphite to that of the cross-linking intercrystalline carbon, the nature of the raw material, porosity and the size, shape, number, and distribution of the pores, and so forth.

In graphite at temperatures below about 2000 K, heat is conducted primarily by lattice vibrations (phonons). This is evidenced by the facts that the Lorenz function of graphite is highly dependent on temperature and on the type of graphite and at room temperature it is two hundred to several hundred times the value for good metallic conductors, that the thermal conductivity of graphite above room temperature varies approximately as T^{-1}, which is typical for a nonmetallic crystal in which the phonon-phonon (Umklapp) scattering is predominant, and that the low temperature dependence of the thermal conductivity of graphite is different from that of metals. At very high temperatures (above 2000 K), however, the thermal conductivity of graphite varies much more slowly than T^{-1}, and becomes nearly temperature independent at least up to 3000 K. This behavior has been explained by Kaspar [719] in terms of ambipolar (electrons and holes) thermal conduction in graphite at very high temperatures. He showed that, in this high temperature region, the Wiedemann-Franz law holds for graphite with a Lorenz number of about $9(\kappa/e)^2$, in consequence of the established ambipolar electrical conduction in graphite.

At low temperatures the phonons are scattered mainly by the boundaries of crystallites, and according to Casimir's theory [243], the thermal conductivity should be proportional to the average size of the crystallites and to the specific heat. It has been experimentally verified that at low temperatures the thermal conductivity of graphite is indeed roughly proportional to the crystallite size (see, e.g., [136, 675]). However, the thermal conductivity of graphite at low temperatures does not have the same temperature dependence as the specific heat (T^2 dependence), but rather varies more rapidly with temperature (as great as $T^{2.7}$) (see, e.g., [138, 1177, 1329, 1443]).

The unusual T^2 dependence of the specific heat of graphite has been explained by many authors. This theoretical understanding gives information on the lattice vibration spectrum of graphite, and hence on the lattice thermal conduction. In the work of Komatsu and Nagamiya [777] and of Gurney [569], they assumed that in the layer-type structure of graphite each layer can be treated separately as a two-dimensional crystal, thus yielding a T^2 dependence of the specific heat of graphite at low temperatures instead of the familiar T^3 law for most solids. From another approach, by employing a semirigorous analysis of the normal mode problem for the transverse vibrations, Krumhansl and Brooks [790] showed the T^2 dependence of the specific heat to be a consequence of the elastic anisotropy of graphite. Experimentally this T^2 dependence has been confirmed by the measurements of DeSorbo and Tyler [349] in the temperature range from 13 to 54 K. Measurements by Keesom and Pearlman [725] also confirmed this T^2 dependence for temperatures between 10 and 20 K, though both theory [776] and experiment [134, 349, 725, 1456] showed that the T^2 law does not hold below 10 K and that eventually the T^3 law predominates.

The anomaly of the thermal conductivity of graphite, which increases with temperature faster than does the specific heat at low temperatures has been explained by Klemens [770] in terms of a mean free path for waves in the hexagonal plane, which, as a consequence of the crystallite geometry, is considerably larger for longitudinal than for transverse waves, resulting in an increased contribution of the former to the thermal conductivity.

Another explanation for this anomaly was proposed by Hove and Smith [637] in terms of a two-medium theory, which is based on their assumption that the pitch-bonded artificial graphite is comprised of two media: the graphite particles (each of which is made up of many single crystallites) and the intergranular ungraphitized carbon (pitch residue). They considered the thermal conductivity of graphite particles as having a T^2 dependence while that of the ungraphitized carbon, which is assumed to be an isotropic thermal conductor, is considered to have a T^3 dependence, and the latter can be taken in series with the former to obtain the total conductivity. In this way, as they claimed, the anomalous temperature dependence of the artificial graphite can be immediately explained.

This two-medium theory has, however, been criticized by Klein and Holland and their co-workers [623, 769] on the ground that, while magnetic susceptibility results [438] imply that there is little if any nongraphitic carbon in pyrolytic graphite, experimental results indicate that the thermal conductivity of pyrolytic graphite at low temperatures is not proportional to T^2, but rather varies more rapidly than T^2 also.

Klein and Holland [769] found that across the layer planes the thermal conductivity of turbostratic [a] pyrolytic graphite below 20 K is nearly proportional to $T^{2.3}$. Slack [1318] also reported a similar temperature variation for a sample of pyrolytic graphite deposited at 2250 C. It was concluded that heat transfer across the layer planes proceeds entirely through the lattice vibrations.

Along the layer planes, Klein and Holland's results [769] indicate that the thermal conductivity of turbostratic pyrolytic graphite varies as $T^{2.5}$ from about 10 to 80 K. On another sample of pyrolytic graphite that had been heat-treated at 3250 C [623], their thermal conductivity data above 10 K exhibit a $T^{2.7}$ dependence that accords with Berman's measurements on a natural graphite crystal [138].

At temperatures below 10 K the thermal conductivity of pyrolytic graphite along the layer plane falls much less rapidly than it does above 10 K,[b] leading to the conclusion that electrons are involved in the layer-plane heat transport at very low temperatures [767]. Thus the thermal conductivity along the layer planes of pyrolytic graphite below 10 K can be evpressed [769] as a sum of two terms: $aT + bT^n$, where aT represents the electronic contribution, bT^n the phonon contribution, and $n \approx 2.6$ as predicted from a long-wave-length treatment of the "effective" phonon velocity, which shows that the in-plane modes of lattice vibrations are seriously enhanced relative to the part they play in the lattice specific heat.

Because of the large anisotropy of graphite crystals, the over-all thermal conduction of conventional graphite will be mainly determined by the basal-plane behavior. Therefore, to sum up the discussions on the low temperature region, the thermal conductivity of graphite should vary as $T^{2.5 \pm 0.2}$ above 10 K and as $aT + bT^{2.5 \pm 0.2}$ below 10 K.

It has been observed that in the low temperature region there seems to be a trend for the thermal conductivity of pitch-bonded graphite that the higher the curve the steeper is its slope. Probably this can be explained as the direct result of the aforementioned fact that the thermal conductivity of graphite crystal along the basal plane varies with temperature more rapidly than that across the basal plane, in addition to the difference in magnitude due to anisotropy.

The anisotropy of pitch-bonded graphite results from preferred orientation of the grains. When the calcined petroleum coke is crushed or milled to obtain the dry aggregate, the individual particles, although irregular in shape, tend to have one dimension larger than the other two. This results from the fact that, in the coking process, the aromatic molecules tend to be oriented with the planes of the benzene rings parallel to the cellular walls of the coke. These walls usually fracture so that the length of coke particles is in the direction of the layer planes of the ultimate graphite crystalline structure. In the process of forming, the long axes of the particles tend to take a preferred orientation: either parallel to the direction of extrusion or perpendicular to the direction of molding pressure. The final graphite product retains the same pattern of grain orientation. The with-the-grain direction is parallel to the direction of extrusion in extruded graphite and perpendicular to the direction of molding pressure in the molded piece. The across-the-grain direction is perpendicular to this. Therefore, it is apparent that the low-temperature thermal conductivity of pitch-bonded graphite measured in the with-the-grain direction is not only higher (due to inherent anisotropy) than that measured in the across-the-grain direction but also varying more rapidly with temperature (due to inherent difference in temperature dependence). Bacon [103] has devised an x-ray method for the determination of the degree of preferred grain orientation.

For a group of different graphite samples measured in the same direction, say, in the direction with-the-grain, it is also apparent that the higher the curve the steeper is its slope. Since, other things being equal, higher thermal conductivity implies higher degree of ordering and better alignment of the axes, and therefore the contribution to the total heat flow from conduction in the basal-plane direction is higher.

It has also been observed that many of the maxima of the thermal conductivity curves seem to fall approximately on a straight line (in the logarithmic plot). There are, however, exceptions, notably the curves for samples of Canadian natural graphite [1328, 1329] and many of the lower conductivity curves. The information available for this correlation of thermal conductivity maxima is extremely sparse due to the termination near room temperature of almost all the low temperature curves of pitch-bonded graphite before reaching their maxima. It is

[a] Pyrolytic graphite whose adjacent basal planes are randomly rotated with respect to one another and thus do not display evidence of three-dimensional ordering.

[b] The thermal conductivity of pitch-bonded artificial graphite behaves also in the same manner, see, for example, Deegan's results [324].

therefore highly desirable to have systematic measurements extending from low to high temperatures for a set of selected graphite samples with thermal conductivity covering a wide range. While knowing that the thermal conductivity maxima falling on a straight line in logarithmic plot is a characteristic feature of the thermal conductivity of a metallic element [248, 249, 250] and therefore is not necessarily true for graphite, the following tentative equation has been derived for this line:

$$k_m = 4.64 \times 10^{10}\, T_m^{-4.35},$$

where T_m is the temperature corresponding to the thermal conductivity maximum k_m. This line (a curve in linear plot) is intended mainly for the pitch-bonded graphite varieties.

Pitch-bonded artificial graphite is a mixture of crystalline graphite and cross-linking intercrystalline carbon which may have also been graphitized or partially graphitized, and is usually of high purity but low density, with numerous pores distributed throughout. Its thermal conductivity (or thermal resistivity) is the result of contributions from all sources and is therefore affected by many factors. In order to understand some of the factors affecting its thermal conductivity, the production process is here briefly reviewed [307, 1451]. In manufacturing the pitch-bonded graphite, the raw material such as calcined petroleum coke is first crushed or milled to obtain fine particles, which are then combined with coal tar pitch to make the plastic mix. This mixture is heated to assure homogeneity and is then formed into pieces by extrusion or molding. The formed pieces are then heated by gas to a temperature of 750 to 900° C in a kiln to coke the pitch binder in the pieces to develop an infusible carbon bond (the so-called first bake). In order to improve the density and other properties of the final product, the baked pieces are pitch-impregnated at this stage. Finally the impregnated pieces are heated in an electric furnace to a temperature in the 2600–3000° C range to convert carbon into graphite, known as graphitizing.

First of all, the thermal conductivity of pitch-bonded artificial graphite is affected by the nature of the starting raw material. Cokes from different sources behave differently with respect to the shapes of the crushed particles. Some yield longer and more splintery particles than others and each coke source tends to have a different particle eccentricity, which affects the degree of alignment on molding or extrusion. The other major difference among petroleum cokes is the graphiticity, or perfection attained by the graphite crystals after heating to 2600 to 3000° C, which affects greatly the properties of the final products. Besides the difference in the attainable perfection of graphitization, some petroleum cokes are also graphitized more easily than the others and require lower graphitizing temperature. Thus the sensitivity of thermal conductivity to thermal history can vary considerably with graphites of different coke sources. Therefore, graphite samples of the same composition and manufactured under identical process conditions but from different coke sources might have different anisotropy ratios and different thermal conductivities.

Purity of the sample is an important factor affecting thermal conductivity. The purity of artificial graphite is usually high, higher than that of the natural graphite [1025]. This is partly because, during the graphitization process, a large fraction of the impurities, which are present in the original materials to the extent of about 1 percent, distill away, since the temperatures involved are higher than the boiling points of most of the impurity compounds.

Density or porosity is another important factor. Results on the variation of thermal conductivity of graphite with bulk density obtained by workers at Battelle Memorial Institute and reported by Cacciotti [282] showed that the thermal conductivities of a series of samples of graphite measured parallel to the direction of extrusion with densities 1.41, 1.55, 1.65, 1.70, and 1.75 g cm^{-3} are, respectively, 0.795, 1.21, 1.46, 1.88, and 2.34 W cm^{-1} K^{-1}. The conductivity versus density curve is nearly linear in the density range from 1.41 to 1.65 g cm^{-3} and also in the range from 1.65 to 1.75 g cm^{-3} with a gradual change of slope around 1.65 g cm^{-3}. Thus in the density range from 1.41 to 1.65 g cm^{-3}, samples with 1 percent difference in density would have about 5 percent difference in thermal conductivity, while in the range 1.65 to 1.75 g cm^{-3}, 1 percent difference in density would cause about 10 percent difference in thermal conductivity. The dependence of thermal conductivity and other properties of graphite on porosity has also been discussed by Hutcheon and Price [649]. It should be noted that besides the bulk density or total porosity, the size, shape, number, and the way of distribution of the pores also have effect on thermal conductivity. In the same graphite stock, thermal conductivity and density can vary not only from piece to piece but also within a piece of graphite. In many cases in a large piece of graphite thermal conductivity and density are the highest near the surface and are the lowest at the center of the piece, with intermediate values gradually decreasing from the surface to the central region. Consequently, specimens cut out of the same piece of graphite may not have the same thermal conductivity and density.

As mentioned before, the thermal conductivity of graphite is roughly proportional to the size of the crystallites, which make up the grains (graphites particles). Thus the crystallite size is a very important factor influencing thermal conductivity. Due to the large anisotropy of graphite crystals, thermal conductivity is affected also by the degree of ordering of the crystallites. Another important factor is the crystal imperfection; the type and the concentration of defects are of important influence. The effect of lattice defects on the thermal conductivity of graphite has been extensively studied (see, e.g., [324, 381, 443, 508, 629, 776, 894, 947, 1176, 1281]) by investigating the effects of irradiation damage on thermal conductivity. The thermal conductivity of graphite is drastically reduced by irradiation, which produces lattice defects, and it can be recovered by annealing. Smith and Rasor [1330] found that neutron irradiation causes the thermal conductivity of graphite to decrease markedly at a rate that decreases with exposure time and also the exponent of the temperature dependence decreases with exposure. Mason and Knibbs [894] found that when the crystallite size of graphite is so small (<100 Å) that the number of crystal layers per unit volume is greater than the number of displaced atoms, clusters of interstitial atoms cannot form and the increase in thermal resistivity is directly proportional to the irradiation dose and independent of crystallite size, as in the case of vacancies, and that when the crystallite size is large (>100 Å), so that the diameter is greater than the separation distance between clusters, the number of clusters is independent of crystallite size and the increase in thermal resistivity varies only as the square root of the dose. Unpublished work by Meyer [947] indicated that the irradiation effect of thermal conductivity is inversely proportional to the irradiation temperature from room temperature to 1400° C.

The thermal conductivity of graphite is affected by the size of the graphite particles (grain size). However, this effect is different with different types of graphites, and no general conclusion can therefore be drawn. As discussed in detail before, due to the planar shape of the calcined petroleum coke particles, in the forming process the long axes of the particles tend to take a preferred orientation: either parallel to the direction of extrusion or perpendicular to the direction of molding pressure, and the final graphite product retains the same pattern of grain orientation. Therefore, the thermal conductivity is highly dependent on the grain orientation and also on the degree of ordering of the grains.

The graphitizing temperature has a tremendous effect on thermal conductivity. During graphitization, the thermal conductivity of the material can increase by a factor of the order of twenty-five [307]. This is due to the increased perfection, growth, and rearrangement of the graphite crystallites, these being quite small and in random arrangement in the gas-baked carbon piece. The thermal conductivity of any piece of graphite is, therefore, directly dependent upon the highest temperature reached in graphitization. The higher the graphitizing temperature, the greater the temperature uniformity and the longer the graphitizing time, the higher is the thermal conductivity of the end product. Consequently, the thermal cycling associated with measurements on a sample of graphite reaching a temperature higher than its graphitizing temperature may increase its thermal conductivity. It should be noted, as mentioned before, that some petroleum cokes are graphitized more easily than others and therefore the sensitivity of thermal conductivity to thermal history can vary considerably.

The thermal conductivity of graphite from room temperature to about 2000 K decreases gradually and monotonically with increasing temperature and varies roughly as T^{-1}, in accord with the theory of phonon conduction. Above 2000 K the thermal conductivity varies much more slowly than T^{-1} and in fact becomes nearly independent of temperature due to the contribution of ambipolar electronic thermal conduction, as discussed earlier. However, at very high temperatures approaching the sublimation temperature of graphite, the thermal conductivity of pitch-bonded graphite decreases abruptly, falling by about an order of magnitude in a relatively small temperature interval [409, 1179]. Euler [408] regarded this as being due to the loosening of the graphite structure at these very high temperatures, and a consequent large irreversible drop in density. However, Rasor and McClelland [1179] found no permanent change in density from their measurements. Since the specific heat of graphite measured by them had an abrupt and large decrease, they explained this striking feature as being due to the formation of thermally produced lattice defects — vacant lattice sites, and suggested a vacancy concentration of about 0.5 atomic percent at the sublimation temperature and an energy of formation of 7.7 ± 0.5 eV for the vacancies.

Golovina and Kotova [514] have demonstrated that when graphite is heated in a gaseous reagent such as carbon dioxide or oxygen at high temperatures above 2300 K, unsteady-state internal diffusion within the graphite specimen occurs such that carbon atoms diffuse from within the solid to the surface on which the reaction with the gas takes place. The density of the graphite decreases, and that of the surface layer reduces to about one half of the original density. With increase in temperature and reaction time the carbon atoms are removed from ever deeper layers of the graphite specimen and the depth of loosening increases. However, the density at the surface changes only insignificantly and remains at about one half of the original density for a wide range of temperatures and for various degrees of removal of graphite mass of 15 to 30 percent. The conditions of Golovina and Kotova differed from those of Euler [408, 409] and of Rasor and McClelland [1179], furthermore, Anacker and Mannkopff [63] report experiments which yielded no marked drop in thermal conductivity, so more studies near the upper temperature limit of graphite are required.

A correlation between the thermal and electrical conductivities of graphite was first proposed by Powell in 1937 [1109]. For Acheson graphite from room temperature to 1073 K he suggested the following equation for the variation of the Lorenz function with temperature:

$$L = \frac{0.123}{T^{1.8}},$$

or

$$k = \frac{0.123\sigma}{T^{0.8}},$$

where L is the Lorenz function, k the thermal conductivity in W cm^{-1} K^{-1}, σ the electrical conductivity in Ω^{-1} cm^{-1}, and T the temperature in K. Based upon further available data, Powell [1117] later proposed the equation

$$k = 0.18 + \frac{2.2\sigma}{T^{1.8}},$$

for the Ceylon and Hilger and Acheson graphites and

$$k = 0.25 + \frac{3.1\sigma}{T^{1.3}}$$

for the Cumberland graphites.

Currie, Hamister, and MacPherson [307] derived an empirical relationship between the room-temperature thermal conductivity and the room-temperature electrical resistivity of pitch-bonded artificial graphite based upon the data of Powell [1109], Powell and Schofield [1128], Johnson [683], Neubert [1024], and of Micinski [960]. They claimed that the following equation would yield the thermal conductivity of graphite at 25° C accurate to within 5 percent:

$$k = \frac{0.0013}{\rho},$$

where the thermal conductivity, k, is in W cm^{-1} K^{-1} and the electrical resistivity, ρ, is in Ω cm and measured at 25° C.

Mason and Knibbs [895] demonstrated that for a given graphite the thermal resistivity varies linearly with electrical resistivity when either the orientation or the crystallinity varies. They attributed this correlation to the fact that the flow of both heat and electricity is restricted essenially to the crystal layer planes and that in both cases the flow is controlled by scattering at crystal boundaries. They derived the following relationship, applicable at 20° C,

$$k = \frac{1}{707\,\rho + 0.0813},$$

which was shown to hold fairly well for over forty graded graphites and enables the thermal conductivity to be estimated from electrical measurements to within ±15 percent.

The theory and measurement of the thermal conductivity of graphite have been reviewed by Kelly [731] and the thermal conductivity and many other properties of graphite have been treated in a book by Reynolds [1192a].

Although there are over 1000 sets of data available for the thermal conductivity of graphites, yet most of the measurements are for low and/or moderate temperatures and many are for unidentified graphite specimens. It is found that no graphite has available thermal conductivity data covering the full range of temperature.

As discussed in the following subsections the available thermal conductivity data for a number of graphites have been analyzed. They include Acheson graphite,[c] AGOT graphite, ATJ graphite, AWG graphite, pyrolytic graphite, 875S graphite, and 890S graphite. These are selected mainly because they seem to be the only graphites with available thermal conductivity data covering a fairly wide range of temperatures. This selection, therefore, does not give a fair representation of all the graphites in common usage. Even for these few graphites, due to the lack of experimental data in low and/or high temperature regions for most of them, many sections of the recommended curves have been obtained by extensive extrapolations and are tentative and subject to modification and revision in the light of further work.

There are many other important graphites for which, unfortunately, the available thermal conductivity data are not sufficient at the present time to include them in the detailed analysis. Their thermal conductivity data and information are grouped together in the figure and table of the subsection entitled "Miscellaneous Graphites." It is hoped that, due to the current great interest in graphites, further measurements on thermal conductivity will be made over wide ranges of temperature and recommended thermal conductivity values for these graphites can be generated subsequently. It is interesting to note that in the Directory of Graphite Availability, Second Edition [498] published in 1967, there are listed 262 graphite products manufactured by 18 companies in the United States. For many of these graphites there are not available any published experimental thermal conductivity data.

[c] It is understood that most of the other pitch-bonded artificial graphites can also be loosely called Acheson graphite. Here this group is intended mainly for those early measurements in which the graphite specimens used were known only as Acheson graphite.

Acheson Graphite

Acheson graphite is generally referred to as the graphite manufactured by using the production process invented by Dr. E. G. Acheson (1856–1931) [21]. Before the second world war and especially in Europe, the commercially available artificial graphite was known only as Acheson graphite. Most of the thermal conductivity data for this group are from early measurements and are therefore of historical interest also.

There are 20 curves available. The data for specimens measured along the direction of extrusion cover the temperature range from 93 to 2000 K while those for specimens measured perpendicular to the direction of extrusion are over the range 93 to 3048 K. Most of the data were produced by Powell [1107] and Powell and Schofield [1128] for two different sets of specimens, and their data are in good agreement when taking the anisotropy of the specimens into account. Buerschaper's [220] data (curves 12 and 13) for the two principal directions near room temperature are also in agreement with their data. However, Buerschaper's data increase monotonically as the temperature decreases down to 93 K indicating that the thermal conductivity maxima are at temperatures at least below 93 K, which is considered very unlikely. Although there is no experimental information available for the locations of the thermal conductivity maxima, it is believed based on information on other graphites that the maxima of the curves would not be at temperatures lower than 250 K.

The proposed curve from 300 to 3000 K for the direction perpendicular to the axis of extrusion follows the curves of Powell and Schofield [1128] (curves 7–11), while the curve for the direction parallel to the axis of extrusion from 300 to 1000 K passes through the mean of Powell's curves [1107] (curves 14–17). From these two sections of the recommended curves so obtained, the anisotropy ratio was calculated to be 1.375 at 300 K and 1.36 at 1000 K. Extrapolating these two values to higher temperatures gave 1.349 at 1500 K, 1.339 at 2000 K, 1.328 at 2500 K, and 1.317 at 3000 K. Based upon these values for the anisotropy ratio, the curve for the direction parallel to the axis of extrusion is extrapolated from 1000 to 3000 K.

Both curves have been extensively extrapolated from 300 K down to 10 K according to the general trend of the low-temperature curves of other graphites. This is intended mainly for indicating the trend of the thermal conductivity values of this graphite at low temperatures. The values at and above room temperature are recommended values and those below room temperature are merely typical values. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

TABLE 24. Recommended thermal conductivity of Acheson graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	‖ to axis of extrusion k	⊥ to axis of extrusion k	T	‖ to axis of extrusion k	⊥ to axis of extrusion k
10	0.00606*	0.00470*	1073.2	0.644	0.488
20	0.0320*	0.0235*	1100	0.626	0.474
30	0.0791*	0.0568*	1173.2	0.576	0.436
40	0.148*	0.103*	1200	0.559	0.422
50	0.235*	0.158*	1273.2	0.516	0.389
60	0.337*	0.223*	1300	0.501	0.377
70	0.450*	0.293*	1373.2	0.462	0.348
80	0.571*	0.366*	1400	0.449	0.338
90	0.694*	0.439*	1473.2	0.412	0.312
100	0.814	0.513*	1500	0.401	0.304
123.2	1.07	0.674	1573.2	0.372	0.281
150	1.32	0.844	1600	0.361	0.274
173.2	1.48	0.966	1673.2	0.337	0.255
200	1.62	1.08	1700	0.327	0.248
223.2	1.68	1.16	1773.2	0.308	0.232
250	1.70	1.19	1800	0.296	0.226
273.2	1.69	1.21	1873.2	0.277	0.212
298.2	1.65	1.19	1900	0.269	0.207
300	1.65	1.19	1973.2	0.252	0.195
323.2	1.61	1.18	2000	0.247	0.190
350	1.55	1.14	2073.2	0.233*	0.179
373.2	1.50	1.11	2173.2	0.217*	0.166
400	1.45	1.07	2200	0.213*	0.163
473.2	1.31	0.963	2273.2	0.203*	0.155
500	1.27	0.927	2400	0.191*	0.144
573.2	1.16	0.846	2473.2	0.185*	0.139
600	1.12	0.816	2600	0.176*	0.132
673.2	1.02	0.751	2673.2	0.171*	0.129
700	0.988	0.729	2800	0.166*	0.125
773.2	0.906	0.674	2873.2	0.163*	0.123
800	0.875	0.654	3000	0.161*	0.122
873.2	0.803	0.607			
900	0.778	0.589			
973.2	0.717	0.544			
1000	0.695	0.528			

†The values at and above room temperature are recommended values for Acheson graphite, and those below room temperature are merely typical values.

*Extrapolated.

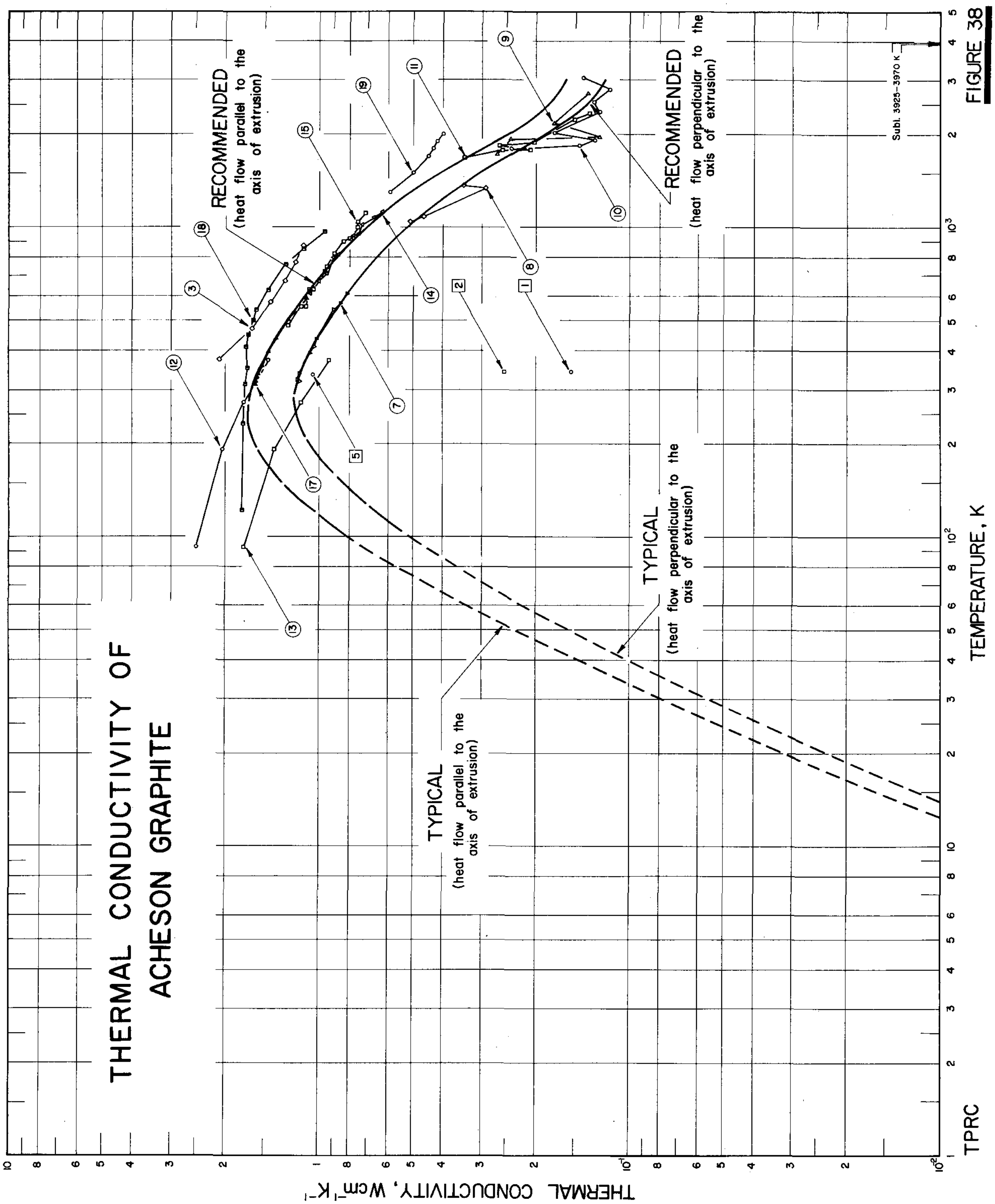

THERMAL CONDUCTIVITY OF
ACHESON GRAPHITE
RECOMMENDED
(heat flow parallel to the axis of extrusion)
RECOMMENDED
(heat flow perpendicular to the axis of extrusion)
TYPICAL
(heat flow parallel to the axis of extrusion)
TYPICAL
(heat flow perpendicular to the axis of extrusion)
Subl. 3925–3970 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 38

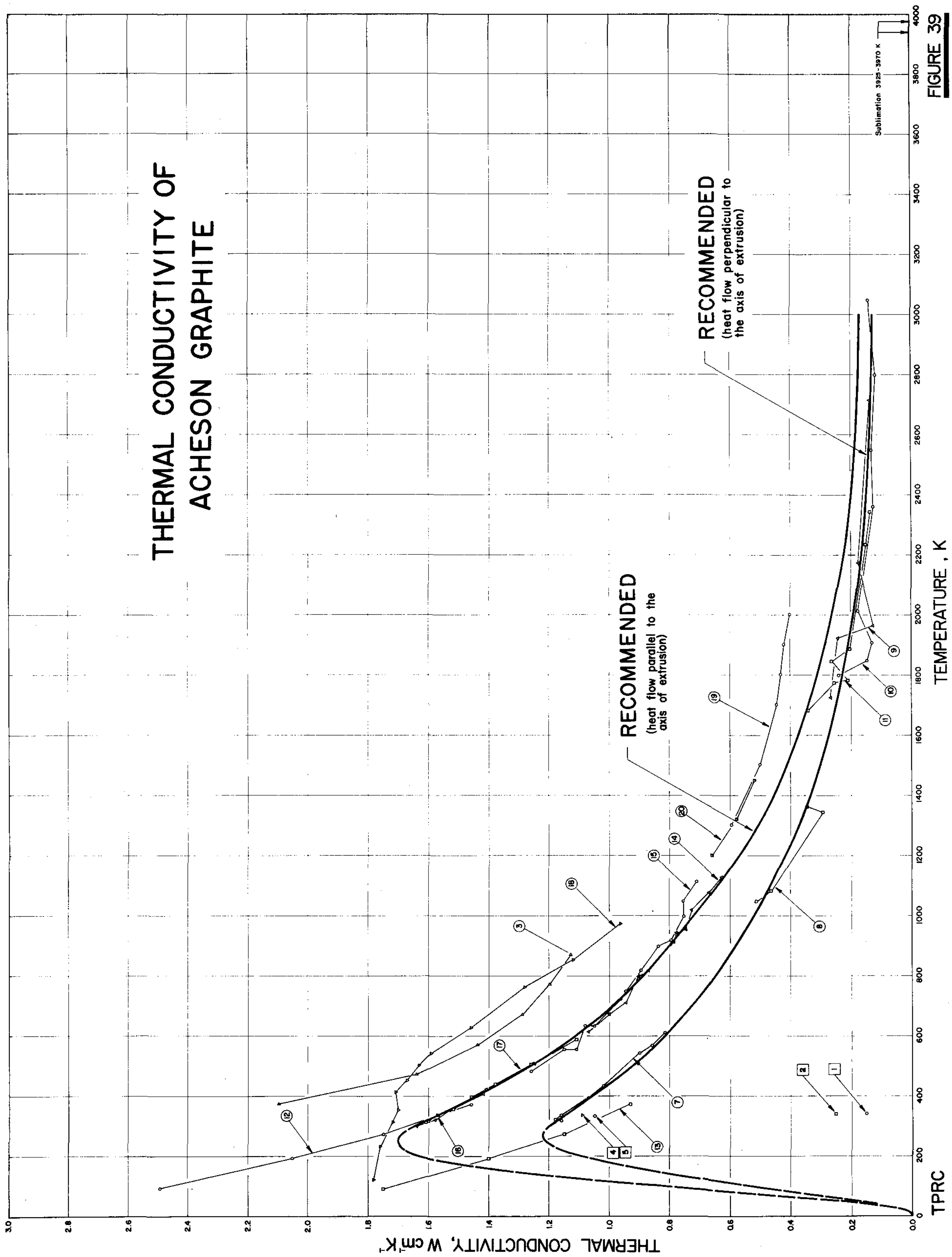

THERMAL CONDUCTIVITY OF
ACHESON GRAPHITE
RECOMMENDED
(heat flow perpendicular to the axis of extrusion)
RECOMMENDED
(heat flow parallel to the axis of extrusion)
Sublimation 3925-3970 K
TEMPERATURE , K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TPRC
FIGURE 39

TABLE 25. THERMAL CONDUCTIVITY OF ACHESON GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1524, 1525	Weeks, J. L. and Seifert, R. L.	1952	C	343.2		Density 1.7 g cm^{-3}; heat flow perpendicular to the axis of extrusion; Armco iron used as comparative material.
2	1524,	Weeks, J. L. and Seifert, R. L.	1952	C	343.2		Similar to above but heat flow parallel to the axis of extrusion.
3	588	Hansen, C. A.	1909	L	373-873		1 in. dia x 8.5 in. long.
4	1040	Noguchi, T. and Miyazaki, Y.	1956	C	336.7	1	Artificial graphite electrode 80 mm in dia and 125 mm long; apparent density 1.40 g cm^{-3}; electrical resistivity 1.23 milliohm cm; copper used as comparative material.
5	1040	Noguchi, T. and Miyazaki, Y.	1956	C	334.2	2	Similar to above but apparent density 1.399 g cm^{-3} and electrical resistivity 1.21 milliohm cm.
6*	780	Kozak, M. I.	1952	R	363-873	Acheson 2301	99 pure; powder; apparent density 0.69 g cm^{-3}; measured after repeated heating.
7	1128	Powell, R. W. and Schofield, F. H.	1939	L	318-611	1	Tubular specimen 0.3 cm I. D., 2.54 cm O. D., and 75 cm long; electrical resistivity 1.10 milliohm cm at 0 C.
8	1128	Powell, R. W. and Schofield, F. H.	1939	R	1048-1363	2	Similar to the above specimen but electrical resistivity 1.05 milliohm cm at 0 C.
9	1128	Powell, R. W. and Schofield, F. H.	1939	R	1723-2713	3	Similar to the above specimen but electrical resistivity 0.77 milliohm cm at 0 C.
10	1128	Powell, R. W. and Schofield, F. H.	1939	R	1798-3048	4	Similar to the above specimen.
11	1128	Powell, R. W. and Schofield, F. H.	1939	R	1683-2343	5	Similar to the above specimen but electrical resistivity 0.67 milliohm cm at 0 C.
12	220	Buerschaper, R. A.	1944	F	93-373		2.9 cm dia x 16 cm long; cut from a National Carbon Co. Acheson graphite electrode; heat flow parallel to the electrode axis.
13	220	Buerschaper, R. A.	1944	F	93-373		Similar to above but heat flow perpendicular to the electrode axis.
14	1107	Powell, R. W.	1937	C	613-1128		1.47 cm dia x 20 cm long; machined; electrical conductivity 1218, 1369, 1445, 1497, 1515, 1517, 1503, 1476, and 1444 ohm^{-1} cm^{-1} at 0, 100, 200, 300, 400, 500, 600, 700, and 1000 C, respectively; measured in vacuum; Armco iron used as comparative material.
15	1107	Powell, R. W.	1937	C	483-1113		Similar to above.
16	1107	Powell, R. W.	1937	L	303-423		3.85 cm dia x 38 cm long; measured in air.
17	1107	Powell, R. W.	1937	L	313-588		7.34 cm dia x 38 cm long; measured in air.
18	303	Crary, A. P.	1933	L	123-973		Two cylindrical rods 10.2 cm dia x 17.8 cm long placed in a vertical position end to end with a flat electric heater in between.
19	671	Jain, S. C. and Krishnan, K. S.	1954	E	1300-2000		Long thin rod specimen; electrical resistivity 0.7, 0.645, 0.606, 0.615, 0.640, 0.675, 0.7175, 0.765, 0.8175, and 0.840 milliohm cm at 470, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, and 2070 K, respectively; measured in vacuum.
20	671	Jain, S. C. and Krishnan, K. S.	1954	E	1200-1450		Short rod specimen.

* Not shown in figure.

AGOT Graphite

AGOT graphite is a high-purity pitch-bonded petroleum-coke-base nuclear graphite, produced by the Carbon Products Division of Union Carbide Corporation to meet the demand of nuclear industry for a graphite extremely low in boron. It is formed by extrusion into bars of 4⅜ to 16⅜ inches square cross-section and 51 inches long. The boron content is carefully controlled and averages 0.00004 percent. Its nominal bulk density is 1.70 g cm^{-3}, grain size 0.03 inch, and total ash content 0.07 percent.

There are 61 curves available for the thermal conductivity of this graphite within the temperature range of 0.3 to 2443 K. Some of the curves are for its different variations, notably AGOT-KC graphite, which is a particular kind of AGOT graphite made from Kendall Refinery coke and Chicago Barrett No. 7HO pitch [1025].

For the direction parallel to the axis of extrusion, the high-temperature data of Meyer and Koyama [948] (curves 37, 38, 39), Schweitzer and Singer [1281] (curves 25 and 26), and of National Carbon Research Laboratories [1404] (curve 54) are in reasonably good agreement, and a mean curve passing through these data links well with curve 49 of Smith and Rasor [1329, 1177, 1180] at temperatures below 320 K. The proposed curve for the direction parallel to the extrusion axis has thus been smoothly drawn through these data.

For the direction perpendicular to the axis of extrusion, only one curve (No. 1) of Tyler and Wilson [1443] over the temperature range 23 to 300 K and several single data points of Garth and Sailor [479] measured at 333 K are available. Tyler and Wilson's data at the higher temperatures, together with Smith and Rasor's data for $k_{\parallel}$ indicatè an anisotropy ratio for the order of 1.6. Furthermore, the majority of Garth and Sailor's single measurements for $k_{\parallel}$ and $k_{\perp}$ yield anisotropy ratios of from 1.5 to 1.6 at 333 K. Since it is noted that in general the anisotropy ratio of pitch-bonded graphite above room temperature decreases with increasing temperature, the values for $k_{\perp}$ from room temperature to 2473 K have been calculated from $k_{\parallel}$ by assuming the anisotropy ratio to be 1.6 at room temperature and to decrease linearly by about 6 percent at 2400 K. This decrease is about the same decrease as for anisotropy ratio of ATJ graphite from room temperature to 2400 K. The derived curve for $k_{\perp}$ has been extrapolated from room temperature down to 10 K parallel to the curve for $k_{\parallel}$.

The several much lower curves shown in figures 40 and 41 are the results of the effect of neutron irradiation on the thermal conductivity. Neutron irradiation results in the formation of vacancies which become additional phonon-scattering centers and decrease the thermal conductivity greatly.

The values at and above room temperature are recommended values and those below room temperature are merely typical values. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

TABLE 26. Recommended thermal conductivity of AGOT graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	∥ to axis of extrusion k	⊥ to axis of extrusion k	T	∥ to axis of extrusion k	⊥ to axis of extrusion k
10	0.00904	0.00515	1073.2	0.635	0.405
20	0.0531	0.0256	1100	0.618	0.394
30	0.138	0.0628	1173.2	0.573	0.366
40	0.262	0.117	1200	0.558	0.355
50	0.414	0.184	1273.2	0.516	0.330
60	0.587	0.261	1300	0.503	0.323
70	0.776	0.345	1373.2	0.470	0.303
80	0.968	0.434	1400	0.459	0.295
90	1.16	0.523	1473.2	0.431	0.277
100	1.33	0.612	1500	0.421	0.272
123.2	1.67	0.810	1573.2	0.400	0.259
150	1.98	1.02	1600	0.392	0.255
173.2	2.16	1.18	1673.2	0.375	0.245
200	2.28	1.31	1700	0.369	0.242
223.2	2.32	1.38	1773.2	0.356	0.234
250	2.30	1.41	1800	0.352	0.231
273.2	2.28	1.41	1873.2	0.341	0.224
298.2	2.21	1.38	1900	0.340	0.222
300	2.20	1.38	1973.2	0.332	0.218
323.2	2.14	1.34	2000	0.330	0.217
350	2.03	1.27	2073.2	0.324	0.214
373.2	1.95	1.22	2173.2	0.317	0.212
400	1.85	1.16	2200	0.316	0.211
473.2	1.59	0.998	2273.2	0.312	0.209
500	1.50	0.945	2400	0.304	0.204
573.2	1.31	0.820	2473.2	0.297*	0.200*
600	1.24	0.779			
673.2	1.10	0.691			
700	1.05	0.660			
773.2	0.936	0.591			
800	0.898	0.569			
873.2	0.810	0.505			
900	0.780	0.497			
973.2	0.711	0.454			
1000	0.688	0.440			

†The values at and above room temperature are recommende values for AGOT graphite, and those below room temperature ar merely typical values.

*Extrapolated.

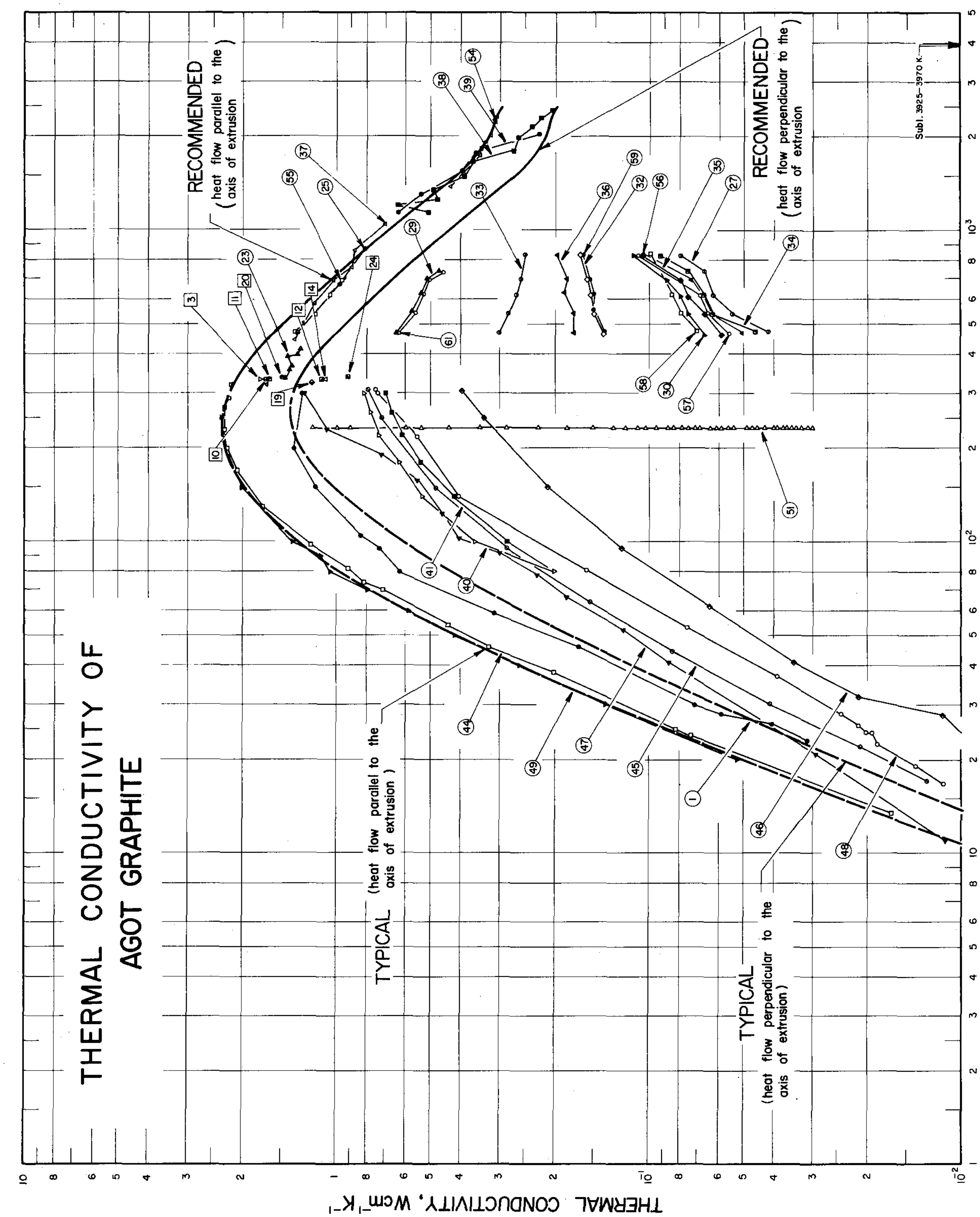

THERMAL CONDUCTIVITY OF
AGOT GRAPHITE
RECOMMENDED
(heat flow parallel to the axis of extrusion)
RECOMMENDED
(heat flow perpendicular to the axis of extrusion)
TYPICAL
(heat flow parallel to the axis of extrusion)
TYPICAL
(heat flow perpendicular to the axis of extrusion)
Subl. 3925–3970 K.
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 40

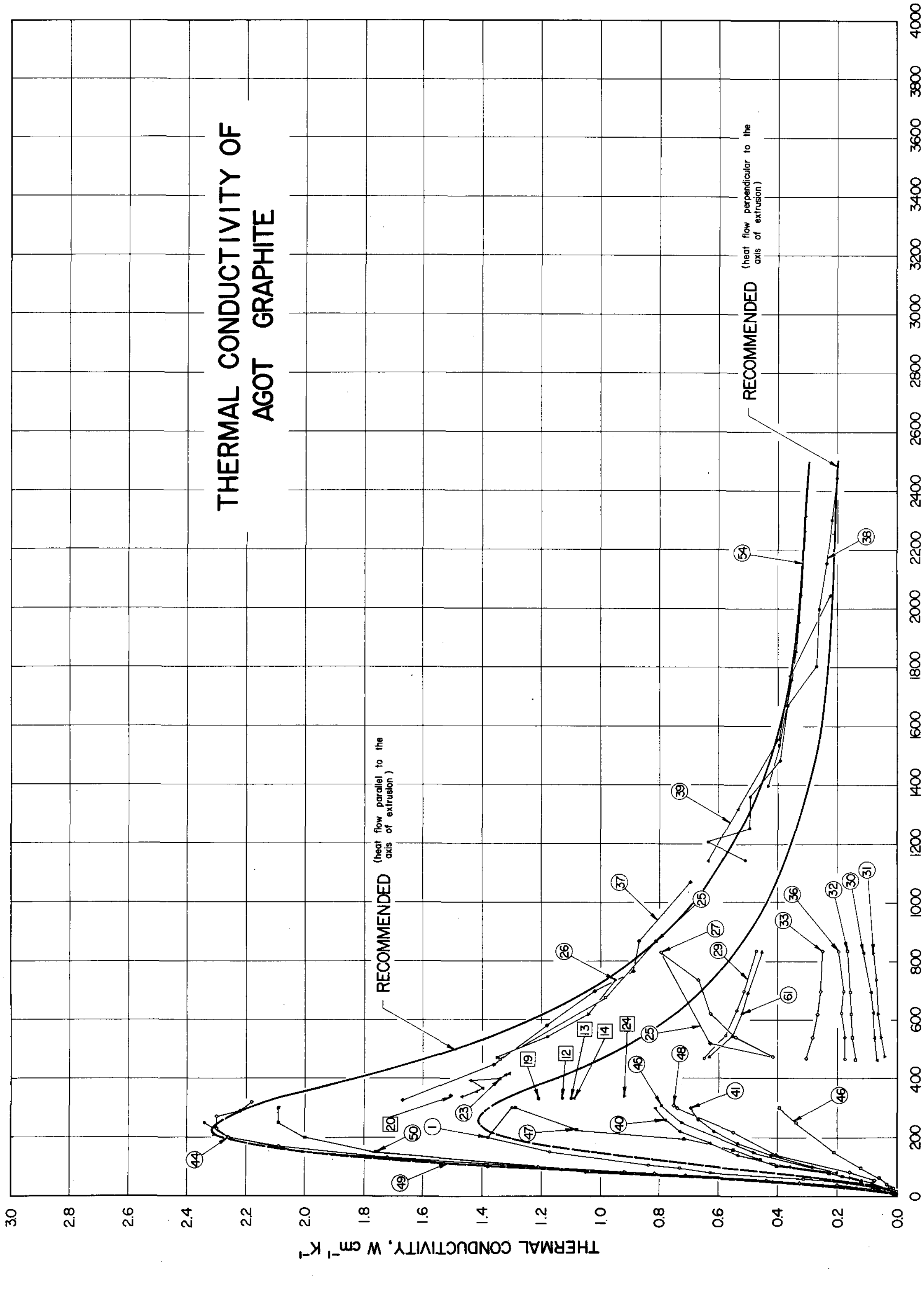

THERMAL CONDUCTIVITY OF
AGOT GRAPHITE
RECOMMENDED (heat flow parallel to the axis of extrusion)
RECOMMENDED (heat flow perpendicular to the axis of extrusion)
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE , K
TPRC

FIGURE 41

TABLE 27. THERMAL CONDUCTIVITY OF AGOT GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1443	Tyler, W. W. and Wilson, A. C.	1953	L	23-300	B	Polycrystal; from National Carbon Co.; extruded; bulk density ~1.70 g cm^{-3}; measured perpendicular to the c-axis.
2*	388	Edwards, D. O., Sarwinski, R. E., Seligmann, P., and Tough, J. T.	1968	L	0.3-2.6		Specimen cross-sectional area to length ratio A/ℓ = 19.28 cm; supplied by Union Carbide Corp, Carbon Products Div., N. Y.; heat flow parallel to the extrusion direction (there is a slight alignment of the crystallites with their c-axes perpendicular to the extrusion direction).
3	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	Cylindrical specimen 3.5 in. in dia and 4 in. long; cyinder axis parallel to the axis of extrusion.
4*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen, run No. 2.
5*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen, run No. 3.
6*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen, run No. 4.
7*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen, run No. 5.
8*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen, run No. 6.
9*	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	Measurement of the above specimen to show the "Bashing effect" by striking each end of the cylinder 10 times and 12 times around the circumference with a plastic hammer on a piece of wood on top of the cylindrical specimen. (Bashing is the hitting of the specimen hard enough to break crystallites apart but not enough to break the specimen.)
10	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen treated again with 20 blows on each end and 20 blows on the circumference.
11	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen treated again with 10 blows on each end and 20 blows around the circumference but with steel hammer with 2 steel plates at each end of the specimen.
12	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	Cylindrical specimen 3.5 in. in dia and 4 in. long; cylinder axis at right angle to the extrusion axis.
13	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen measured after striking each end 10 times and 12 times around the circumference with a plastic hammer on a piece of wood on top of the specimen.
14	479	Garth, R. C. and Sailor, V. L.	1949	L	333.2	I	The above specimen treated again with 20 blows on each end and 20 blows on the circumference with the same hammer.
15*	479	Garth, R. C. and Sailor, V. L.	1949	L	331.2	II	Cylindrical specimen 3.5 in. in dia and 4 in. long; cylinder axis parallel to the extrusion axis.
16*	479	Garth, R. C. and Sailor, V. L.	1949	L	331.2	II	The above specimen, run No. 2.
17*	479	Garth, R. C. and Sailor, V. L.	1949	L	331.2	II	The above specimen, run No. 3.
18*	479	Garth, R. C. and Sailor, V. L.	1949	L	331.2	II	The above specimen, run No. 4.
19	479	Garth, R. C. and Sailor, V. L.	1949	L	324.2	II	Cylindrical specimen 3.5 in. in dia and 4 in. long; cylinder axis at right angle to the extrusion axis.

* Not shown in figure.

TABLE 27. THERMAL CONDUCTIVITY OF AGOT GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	479	Garth, R.C. and Sailor, V.L.	1949	L	337.2	V	Similar to the above specimen but the cylinder axis parallel to the extrusion axis.
21*	479	Garth, R.C. and Sailor, V.L.	1949	L	338.2	V	Similar to the above specimen but the cylinder axis perpendicular to the extrustion axis.
22*	479	Garth, R.C. and Sailor, V.L.	1949	L	335.2	VI	Similar to the above specimen but the cylinder axis parallel to the extrusion axis.
23	479	Garth, R.C. and Sailor, V.L.	1949	L	335-415	VI	Similar to the above specimen.
24	479	Garth, R.C. and Sailor, V.L.	1949	L	339.2	VI	Similar to the above specimen but the cylinder axis perpendicular to the extrusion axis.
25	1281	Schweitzer, D. and Singer, R.	1961		446-868		Density 1.73 g cm^{-3}; grain size >0.032 in.
26	1281	Schweitzer, D. and Singer, R.	1961		473-737	AK-2	Obtained from Brookhaven pile; density 1.73 g cm^{-3}; grain size >0.032 in.
27	1281	Schweitzer, D. and Singer, R.	1961		475-829	AK-1	Similar to the above specimen; irradiated in Brooklyn National Laboratory reactor at 30-50 C by a neutron flux of 1655 megawatt days/adjacent ton.
28*	1281	Schweitzer, D. and Singer, R.	1961		474-830	JK-1	Similar to the above specimen except irradiated in Brooklyn National Laboratory reactor at 30-50 C by a neutron flux of 1685 megawatt days/adjacent ton.
29	1281	Schweitzer, D. and Singer, R.	1961		469-836	JK-1	The above specimen annealed at 1400 C for 1 hr.
30	1281	Schweitzer, D. and Singer, R.	1961		463-829	JK-2	Similar to the above specimen except annealed at 800 C for 1 hr.
31	1281	Schweitzer, D. and Singer, R.	1961		475-829	LK-1	Obtained from Brookhaven pile; density 1.73 g cm^{-3}; grain size >0.032 in.; irradiated in Brooklyn National Laboratory reactor at 30-50 C by a neutron flux of 1685 megawatt days/adjacent ton.
32	1281	Schweitzer, D. and Singer, R.	1961		465-835	LK-1	The above specimen annealed at 1000 C for 1 hr.
33	1281	Schweitzer, D. and Singer, R.	1961		469-835	LK-2	Similar to the above specimen except annealed at 1200 C for 1 hr.
34	1281	Schweitzer, D. and Singer, R.	1961		475-829	CK-1	Obtained from Brookhaven pile; density 1.73 g cm^{-3}; grain size >0.032 in.; irradiated in Brooklyn National Laboratory reactor at 30-50 C by a neutron flux of 1685 megawatt days/adjacent ton.
35	1281	Schweitzer, D. and Singer, R.	1961		464-829	CK-1	The above specimen annealed at 600 C for 1 hr.
36	1281	Schweitzer, D. and Singer, R.	1961		468-834	PK-1	Similar to the above specimen except annealed at 1100 C for 1 hr.
37	948	Meyer, R.A. and Koyama, K.	1963	C	324-1069		1 in. dia x 0.250 in. thick; supplied by National Carbon Co.; Armco iron used as comparative standard.
38	948	Meyer, R.A. and Koyama, K.	1963	→	1145-2443		1 x 0.25 x 0.05 in.; supplied by National Carbon Co.; measured in vacuum, the method consists of obtaining the steady-state temps at centers of the narrow and wide faces of specimen by optical pyrometry, specimen electrically heated, thermal conductivity calculated from measured temps, emittance of the specimen, dimensions of the specimen, and the Stefan-Boltzmann constant.
39	948	Meyer, R.A. and Koyama, K.	1963	R	1145-2044		Cylindrical specimen obtained from National Carbon Co.
40	381	Durand, R.E. and Klein, D.J.	1956	R	80-300	AGOT-CSF-MTR	Specimen size 0.02 x 0.125 x 1 in.; exposed to 6.4×10^{19} fast neutrons cm^{-2} and 5.8×10^{20} thermal neutron cm^{-2} at 698 K.

* Not shown in figure.

TABLE 27. THERMAL CONDUCTIVITY OF AGOT GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
41	381	Durand, R. E. and Klein, D. J.	1956	R	80-300	AGOT-CSF-MTR	Similar to the above specimen but exposed to 4.3 x 10^{19} fast neutrons cm^{-2} and 2.6 x 10^{20} thermal neutrons cm^{-2} at 933 K.
42*	381	Durand, R. E. and Klein, D. J.	1956	R	80-300	AGOT-CSF-MTR	Similar to the above specimen but exposed to 8.5 x 10^{19} fast neutrons cm^{-2} and 2.6 x 10^{20} thermal neutrons cm^{-2} at 908 K.
43*	381	Durand, R. E. and Klein, D. J.	1956	R	220-300	AGOT-CSF-MTR	Similar to the above specimen but exposed to 4.9 x 10^{19} fast neutrons cm^{-2} and 1.5 x 10^{20} cm^{-2} at 938 K.
44	1329, 1177, 1180	Smith, A. W. and Rasor, N. S.	1954	E	14-320	AGOT-KC	Polycrystalline; extruded petroleum coke, pitch bonded; particle size 50 μ; crystallite size 0.3 μ; specimen size 0.10 x 0.03 x 1.25 in.; density 1.65 g cm^{-3} at 25 C; thermoelectric power -0.5 μvolt K^{-1}; Hall coefficient -0.6 emu; magneto resistivity 5.4 x 10^{-10} emu; electrical resistivity 6.2 milliohm cm; total magnetic susceptibility -20.44 x 10^{-6} cgs unit; orientation factor (ρ_{max}/ρ_{min}) = 2.0; measured parallel to the axis of extrusion.
45	1180, 1329	Smith, A. W. and Rasor, N. S.	1954	E	17-308	AGOT-KC	The above specimen exposed to neutron irradiation of 12.5 MWD/T (megawatt-days per ton) at <30 C.
46	1180, 1329	Smith, A. W. and Rasor, N. S.	1954	E	17-305	AGOT-KC	The above specimen exposed to neutron irradiation of 48 MWD/T at <30 C.
47	1180, 1329	Smith, A. W. and Rasor, N. S.	1954	E	11-300	AGOT-KC	The above specimen exposed to neutron irradiation of 460 MWD/T at <30 C.
48	1180, 1329	Smith, A. W. and Rasor, N. S.	1954	E	17-308	AGOT-KC	The above specimen exposed to neutron irradiation of 1927 MWD/T at <30 C.
49	1180, 1329	Smith, A. W. and Rasor, N. S.	1956	E	20-250	AGOT-KC	The virgin specimen before bromination (experiment to show the effect of Br on thermal conductivity of graphite).
50	1180, 1329	Smith, A. W. and Rasor, N. S.	1956	E	10-300	AGOT-KC (Brom-graphite)	Brominated AGOT-KC graphite; 0.13 Br.
51	1176	Rasor, N. S.	1950	L	233.2	AGOT-KC	AGOT-KC graphite specimen 0.03 x 0.125 x 1 in.; irradiated with neutrons of 1927 MWD/T; pulse annealed for 1 min; measured under vacuum (<10^{-5} mm Hg) at constant temp of -40 C to show the effect on thermal conductivity of the specimen after being annealed (except the ends) at different temps.
52*	1176	Rasor, N. S.	1950	L	233.2	AGOT-KC	The above specimen irradiated at 212 MWD/T; both ends annealed.
53*	1176	Rasor, N. S.	1950	L	233.2	AGOT-KC	The above specimen irradiated at 1927 MWD/T with both ends annealed.
54	1404	Thielke, N. R. (compiler)	1959	E	1397-2314		Coke base graphite 0.25 in. in dia and 3.5 in. long; electrical resistivity reported as 0.636, 0.686, 0.750, 0.800, and 0.836 milliohm cm at 1090, 1371, 1659, 1918, and 2148 C, respectively; heat flow along the direction of extrusion; thermal conductivity data extracted from a smooth curve derived from the average of repeated measurements on several specimens.
55	213	Brookhaven National Lab.	1961		473-693	AGOT	No details reported.
56	213	Brookhaven National Lab.	1961		473-833	AGOT	The above specimen irradiated at ~1700 MWD/CT (central ton) over a 10-yr period.
57	213	Brookhaven National Lab.	1961		473-833	AGOT	The above specimen annealed at 600 C for 1 hr.
58	213	Brookhaven National Lab.	1961		473-833	AGOT	Similar to the above specimen but annealed at 800 C for 1 hr.

* Not shown in figure.

TABLE 27. THERMAL CONDUCTIVITY OF AGOT GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
59	213	Brookhaven National Lab.	1961		473-833	AGOT	Similar to the above specimen but annealed at 1000 C for 1 hr.
60*	213	Brookhaven National Lab.	1961		473-833	AGOT	Similar to the above specimen but annealed at 1200 C for 1 hr.
61	213	Brookhaven National Lab.	1961		473-833	AGOT	Similar to the above specimen but annealed at 1400 C for 1 hr.

* Not shown in figure.

ATJ Graphite

ATJ graphite[a] is a pitch-bonded petroleum-coke-base graphite, produced by the Carbon Products Division of Union Carbide Corporation. It is a widely known premium grade graphite with very fine grains (0.006 inch maximum) and is formed by molding into rectangular blocks, 9 × 20 × 24 inches in size, or circular bars of various diameters. Nominal room-temperature properties [1451] are: bulk density 1.73 g cm^{-3} with standard deviation 0.036 g cm^{-3} (i.e., 2.1%), electrical resistivity 11.0 × 10^{-4} Ω cm (with grain), 14.5 × 10^{-4} Ω cm (across grain), and anisotropy in electrical resistivity 1.32. Total ash content is 0.2 percent.

There are 32 sets of data available for the thermal conductivity of ATJ graphite. These include 3 sets of data for samples designated as GBH graphite which is the previous designation for the same grade of graphite. In addition to ATJ graphite, Figures 42 and 43 and Table 29 include also 7 sets of data for ATJ-S graphite, and 2 sets each for ATJ-P and ATJ-SP graphites. They are the modifications of the basic ATJ graphite. ATJ-S graphite is a density-improved version of ATJ. It has been pitch-impregnated after the first bake and before the graphitization process, and therefore it has a higher density of nominally 1.8 gm cm^{-3} and is more uniform than ATJ. Due to its higher density and greater uniformity, ATJ-S graphite is expected to have higher thermal conductivity. ATJ-P graphite is a purity-improved version of ATJ graphite and therefore has higher purity. Finally, the ATJ-SP graphite is a purity-improved version of ATJ-S graphite, and is expected to have the highest thermal conductivity. In this study, only the data for the basic ATJ graphite have been analyzed and recommended.

For the direction perpendicular to the molding pressure, the data of Lucks and Deem (curve 41) [862] are in good agreement with those of Fieldhouse, Lang, and Blau (curve 2) [432] in the narrow temperature range 650 to 800 K. Above 800 K these two sets of data diverge, and at 1200 K they differ by about 35 percent. At these higher temperatures Lucks and Deem's data (curve 41) appear to be high, which may probably be due to the uncertainty in the reference data at high temperatures in the early years for the Armco iron bar used as a comparative reference material. On the other hand, the data of Fieldhouse, et al. (curve 2) at temperatures above 1000 K are too low, since their curve (2) decreases almost linearly to values at temperatures above 1420 K lower than their other curve (1), which is for a sample measured with heat flow parallel to the molding pressure. The recommended curve from 484 to 1000 K follows curves 41 and 42, and is extended in the temperature range 1400 to 2000 K through the mean of curves 12 and 13 of workers at the Parma Research Laboratory of Union Carbide Corporation [198] and in the range 2400 to 3273 K through the mean of curve 43 of Rasor and McClelland [1178]. It is then extrapolated to 3800 K according to the general trend indicated by the data of Rasor and McClelland [1178] for 875S graphite.

[a] This graphite was previously designated as GBH graphite.

TABLE 28. Recommended thermal conductivity of ATJ graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	‖ to molding pressure k	⊥ to molding pressure k	T	‖ to molding pressure k	⊥ to molding pressure k
10	0.00396*	0.00522*	1073.2	0.465	0.607
20	0.0192*	0.0245*	1100	0.458	0.595
30	0.0457*	0.0597*	1173.2	0.437	0.566
40	0.0826*	0.109*	1200	0.430	0.556
50	0.128*	0.171*	1273.2	0.413	0.532
60	0.181*	0.241*	1300	0.407	0.524
70	0.238*	0.319*	1373.2	0.393	0.504
80	0.298*	0.400*	1400	0.389	0.497
90	0.357*	0.488*	1473.2	0.376	0.480
100	0.415	0.571	1500	0.372	0.474
123.2	0.541	0.752	1573.2	0.361	0.460
150	0.673	0.946	1600	0.358	0.455
173.2	0.771	1.08	1673.2	0.349	0.443
200	0.865	1.20	1700	0.346	0.438
223.2	0.922	1.27	1773.2	0.338	0.428
250	0.965	1.30	1800	0.336	0.424
273.2	0.984	1.31	1873.2	0.329	0.414
298.2	0.982	1.29	1900	0.327	0.411
300	0.982	1.29	1973.2	0.321	0.403
323.2	0.972	1.27	2000	0.319	0.400
350	0.952	1.24	2073.2	0.314	0.392
373.2	0.933	1.21	2173.2	0.307	0.383
400	0.907	1.18	2200	0.305	0.380
473.2	0.834	1.08	2273.2	0.301	0.374
500	0.808	1.05	2400	0.293	0.364
573.2	0.742	0.967	2473.2	0.288	0.358
600	0.718	0.938	2600	0.280	0.346
673.2	0.665	0.870	2673.2	0.275	0.340
700	0.645	0.844	2800	0.266	0.328
773.2	0.599	0.785	2873.2	0.260	0.321
800	0.583	0.763	3000	0.250	0.308
873.2	0.546	0.712	3073	0.244*	0.300*
900	0.532	0.693	3200	0.233*	0.283*
973.2	0.501	0.653	3273	0.225*	0.273*
1000	0.491	0.640	3400	0.209*	0.252*
			3600	0.170*	0.204*
			3800	0.095*	0.113*

†The values at and above room temperature are recommended values for ATJ graphite, and those below room temperature are merely typical values.

*Extrapolated.

For the direction parallel to the molding pressure the recommended curve from 600 to 2000 K lies close to curve 1 of Fieldhouse, Lang, and Blau [432] and curve 14 of workers at Parma Research Laboratory [198], and is then extrapolated to 3800 K.

The resultant curves yield anisotropy ratios of 1.314 at 300 K, 1.303 at 1000 K, 1.254 at 2000 K, and 1.189 at 3800 K, which indicates that the anisotropy ratio decreases slightly with increasing temperatures. Both curves have been extensively extrapolated from room temperature down to 10 K according to the general trend of the low-temperature curves of other graphites.

The values at and above room temperature are recommended values, and those below room temperature are merely typical values which represent typical curves serving to indicate the general trend of the thermal conductivity of this graphite at moderate and low temperatures. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

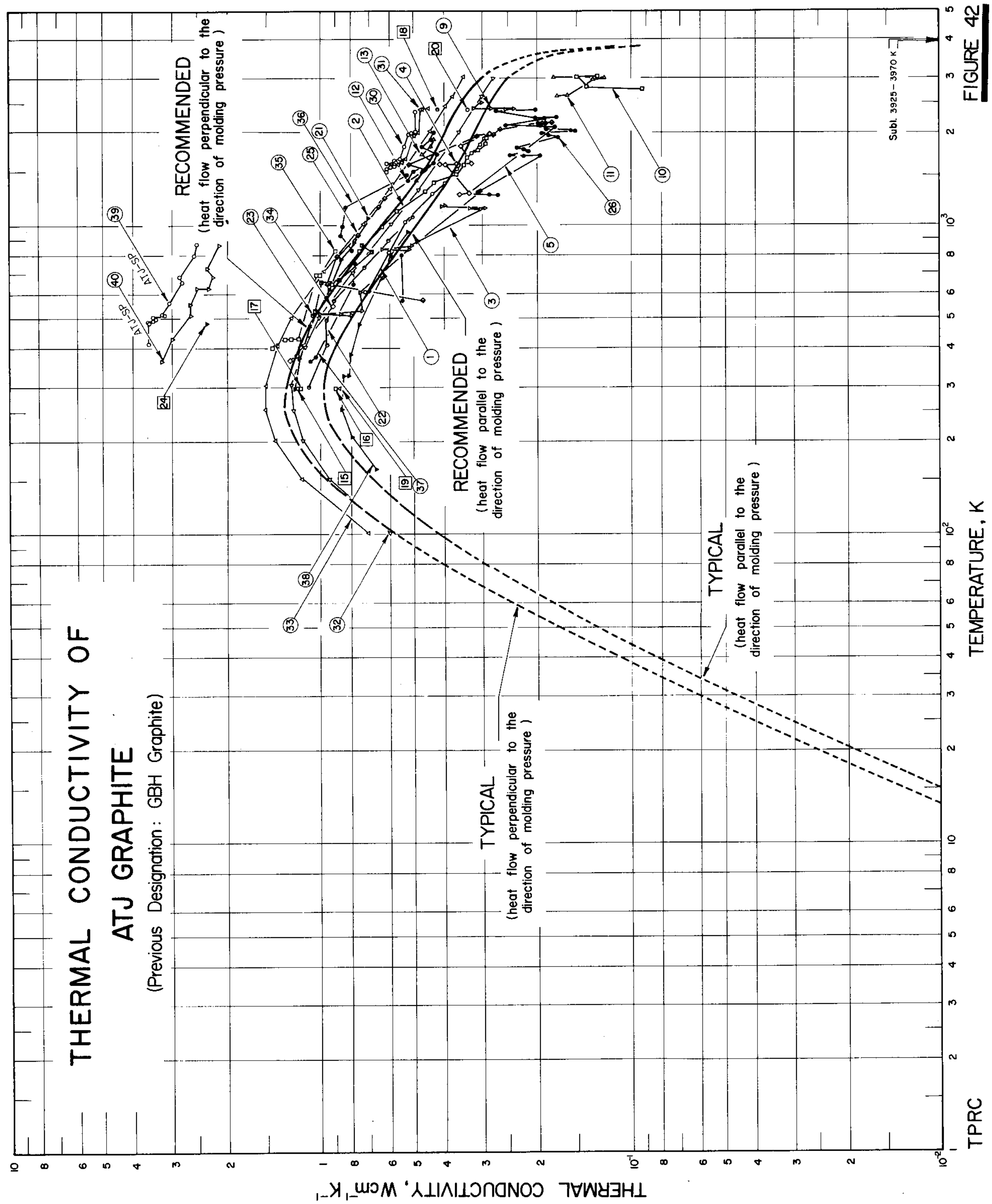

THERMAL CONDUCTIVITY OF
ATJ GRAPHITE
(Previous Designation: GBH Graphite)
RECOMMENDED
(heat flow perpendicular to the direction of molding pressure)
RECOMMENDED
(heat flow parallel to the direction of molding pressure)
TYPICAL
(heat flow perpendicular to the direction of molding pressure)
TYPICAL
(heat flow parallel to the direction of molding pressure)
ATJ-SP
ATJ-SP
Subl. 3925–3970 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 42

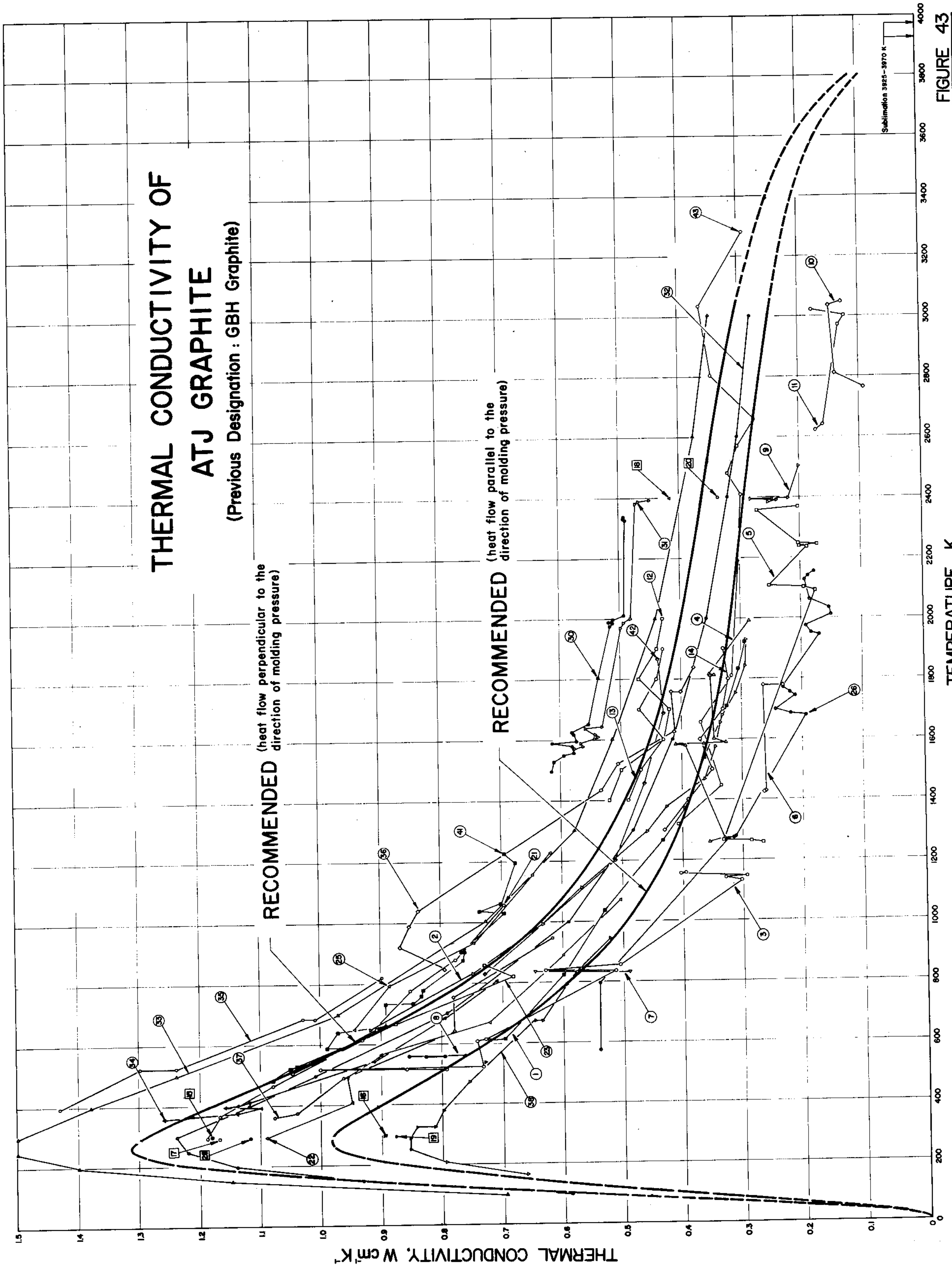

THERMAL CONDUCTIVITY OF
ATJ GRAPHITE
(Previous Designation : GBH Graphite)
RECOMMENDED (heat flow perpendicular to the direction of molding pressure)
RECOMMENDED (heat flow parallel to the direction of molding pressure)
Sublimation 3925–3970 K
TEMPERATURE , K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TPRC

FIGURE 43

TABLE 29. THERMAL CONDUCTIVITY OF ATJ GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	432	Fieldhouse, I. B., Lang, J. I., and Blau, H. H., Jr.	1960	R	610-1922		Ash content 0.2%; specimen composed of 15 disks, three of which 1 in. thick, twelve others 0.5 in. thick; each with a dia of 3±0.002 in.; maximum grain size~0.006 in.; made from blocks of ATJ graphite size 9 x 20 x 24 in.; machined perpendicular to grain orientation; siliconized.
2	432	Fieldhouse, I. B., et al.	1960	R	650-1929		Similar to the above specimen but machined parallel to grain orientation.
3	1018	Neel, D. S., Pears, C. D., and Oglesby, S., Jr.	1962	R	517-1160		Molded and fired; maximum exposure temp 2843 C; specimen 0.75 in. dia and 0.75 in. long; no deterioration observed after the experiment.
4	1018	Neel, D. S., et al.	1962	R	1261-1992		Another run of the above specimen.
5	1018	Neel, D. S., et al.	1962	R	1258-2369		Another run of the above specimen.
6	1018	Neel, D. S., et al.	1962	R	1425-1769		Another run of the above specimen.
7	1018	Neel, D. S., et al.	1962	R	832-837		Another run of the above specimen.
8	1018	Neel, D. S., et al.	1962	R	558-560		Another run of the above specimen.
9	1018	Neel, D. S., et al.	1962	R	2383-2505		Another run of the above specimen.
10	1018	Neel, D. S., et al.	1962	R	2783-3050		Another run of the above specimen.
11	1018	Neel, D. S., et al.	1962	R	2622-3022		Another run of the above specimen.
12	198	Breckenridge, R. G.	1959	E	1400-2000		Rectangular bars fabricated by molding; size 1 x 1 x 10 cm; specific gravity 1.74; measured perpendicular to the direction of molding pressure; data averaged from measurements of 4 specimens.
13	198	Breckenridge, R. G.	1959	E	1400-1900		Similar to the above specimens but data averaged from 3 other specimens.
14	198	Breckenridge, R. G.	1959	E	1300-1900		Similar to the above specimens but with specific gravity of 1.69; data averaged from 4 specimens; measured parallel to the direction of molding pressure.
15	367	Union Carbide Corp.	1965	E	298.2	ATJ	Graphite stocks size 9 x 20 x 24 in.; grain size 0.006 in.; bulk density 1.73 g cm^{-3}; electrical resistivity 1100 μohm cm; with grain orientation.
16	367	Union Carbide Corp.	1965	E	298.2	ATJ	Similar to the above but electrical resistivity 1450 μohm cm; across grain orientation.
17	231	Bushong, R. M., Zeitsch, K. J., and Higgs, P. H.	1964	L	298.2		Machined parallel to the grain orientation; measured in a high vacuum apparatus.
18	231	Bushong, R. M., et al.	1964	P	2398		The above specimen measured by transient method; in argon atm.
19	231	Bushong, R. M., et al.	1964	L	298.2		Machined perpendicular to the grain orientation; measured in a high vacuum apparatus.
20	231	Bushong, R. M., et al.	1964	P	2398		The above specimen measured by transient method; in argon atm.
21	951	Meyers, C. and Koyama, K.	1968	P	298-1060	1-A	Disk specimen 0.5 in. in dia and 0.045 in. thick; density 1.766 g cm^{-3}; heat flow perpendicular to molding direction; thermal conductivity values calculated from the measurement of thermal diffusivity (measured by xenon-flash technique), specific heat and density.

TABLE 29. THERMAL CONDUCTIVITY OF ATJ GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
22	951	Meyers, C. and Koyama, K.	1968	P	301-1074	1-E	Similar to the above specimen except heat flow parallel to molding direction.
23	800	Kummer, D. L., Rosenthal, J. J., Lum, D. W., et al.	1965	C	512-861		1 in. dia x 1 in. thick; Armco iron used as comparative material; measured with grain.
24	850	Ling-Temco-Vought, Inc.	1964	C	484.3		Obtained from National Carbon Co.; 25.85 cm^2 x 0.64 cm thick; copper used as comparative material.
25	197	Brazel, J. P. and Styhr, K. H.	1968	R	576-2053		As received; cylindrical stack specimen 5 cm in dia and 12.7 cm long composed of 3 cylinders, a 5 cm tall specimen, and 2 guard cylinders at upper and lower ends of equal height; molded; electrical resistivity 1.12 x 10^{-3} ohm cm; density 1.72 g cm^{-3}; measured in argon atm in the AB with-grain plane; temp below 1000 K measured by thermocouple while temp above 1000 K measured by optical pyrometer.
26	197	Brazel, J. P. and Styhr, K. H.	1968	R	579-2154		Molded and purified; same dimensions and measuring method as the above specimen; electrical resistivity 1.83 x 10^{-3} ohm cm; density 1.67 g cm^{-3}.
27*	239	Carroll, J. M.	1964	C	513-861		Specimen 1 in. in dia and 1 in. long; measured with grain; Armco iron used as comparative material.
28	1435	Turner, J. H. and Carter, M. B.	1964		298.2		Bulk density 1.73 g cm^{-3}; electrical resistivity 11.60 x 10^{-4} ohm cm at room temp; measured with grain.
29*	1435	Turner, J. H. and Carter, M. B.	1964		298.2		Bulk density 1.73 g cm^{-3}; electrical resistivity 14.30 x 10^{-4} ohm cm at room temp; measured across grain.
30	1396	Taylor, R. E., Davis, F. E., Powell, R. W., and Kimbrough, W. D.	1969	E	1498-2337	ATJS; Sample 1	0.125 in. dia rod specimen; obtained from Air Force Materials Laboratory; molded max particle size 0.006 in.; density ~1.8 g cm^{-3}; electrical resistivity 676, 677, 679, 681, 684, 688, 691, 694, 698, 706, 714, 757, 801, 838, and 870 μohm cm at 1006, 1030, 1055, 1081, 1121, 1159, 1197, 1230, 1255, 1309, 1360, 1637, 1924, 2148, and 2347 K, respectively; Lorenz function 29.9, 27.2, 25.0, 23.5, 22.0, 21.0, 20.1, 19.4, 18.6, and 18.0 x 10^{-8} V^2 K^{-2} at 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, and 2400 K, respectively; heat flow perpendicular to the molding direction.
31	1396	Taylor, R. E., et al.	1969	E	1572-2393	ATJS; Sample 2	Similar to above but electrical resistivity 691, 707, 723, 738, 754, 769, 786, 801, 817, 832, 846, 859, 872, 885, and 897 μohm cm at 1255, 1356, 1458, 1561, 1660, 1760, 1864, 1960, 2059, 2158, 2243, 2329, 2415, 2506, and 2589 K, respectively.
32	997	Morrison, B. H.	1970	P	100-3000	ATJS	Density 1.82 g cm^{-3} at 25 C; electrical resistivity 9.50 milliohm cm at 300 K; heat flow across grain; thermal conductivity values calculated from measured thermal diffusivity and density using the specific heat taken from Spence, G. B. (WADD-TR-61-72, Vol. XLI, 1963).
33	997	Morrison, B. H.	1970	P	100-3000	ATJS	Similar to above but electrical resistivity 7.29 milliohm cm at 300 K and heat flow with grain.
34	195	Brazel, J. P.	1969	C	361-809	ATJS	Density 1.82 g cm^{-3}; heat flow across grain; Armco iron used as comparative material; data obtained from the author.

*Not shown in figure.

TABLE 29. THERMAL CONDUCTIVITY OF ATJ GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35	195	Brazel, J. P.	1969	C	397-821	ATJS	Similar to above but heat flow with grain.
36	195	Brazel, J. P.	1969	R	828-2276	ATJS	Similar to above.
37	195	Brazel, J. P.	1969	C	363-946	ATJP	Density 1.69 g cm^{-3}; heat flow with grain; data obtained from the author.
38	195	Brazel, J. P.	1969	C	162-946	ATJP	Similar to above.
39	196	Brazel, J. P. and Kennedy, B.S.	1970	C	411-863	ATJSP	Density 1.83 g cm^{-3}; heat flow with grain; data obtained from the authors.
40	196	Brazel, J. P. and Kennedy, B.S.	1970	C	364-944	ATJSP	Density 1.84 g cm^{-3}; heat flow across grain; data obtained from the authors.
41	862	Lucks, C.F. and Deem, H.W.	1956	C	484-1227	Grade GBH	Molded graphite; from National Carbon Co; density 1.75 cm^{-3}; measured perpendicular to the direction of molding; Armco iron used as comparative material.
42	430	Fieldhouse, I.B., Hedge, J.C. and Waterman, T.E.	1956	L	829-1866	GBH	Grade GBH graphite from National Carbon Co; density 1.762 g cm^{-3}; measured with heat flow parallel to the axis of extrusion (should be axis of molding since it was molded).
43	1178	Rasor, N.S. and McClelland, J.D.	1957	R	1319-3277	GBH	Molded; very fine grained and uniform; specific gravity 1.77; anisotropy ratio 0.78; measured normal to the molding pressure, in inert gas at >150 psi pressure.

AWG Graphite

AWG graphite is a high-purity pitch-bonded petroleum-coke-base graphite, produced by the Carbon Products Division of Union Carbide Corporation. It is formed by molding into rectangular blocks, with nominal bulk density 1.75 g cm^{-3}, maximum ash content 0.08 percent (with particular attention paid to control calcium).

These are 39 curves available for the thermal conductivity of this graphite and the measurements have been made either by Smith and Rasor [1329, 1177, 1180] or by Deegan [324]. Smith and Rasor studied the effect of neutron irradiation on the thermal conductivity, while Deegan investigated the effect of proton irradiation on the thermal conductivity and the recovery of the thermal conductivity by pulse-annealing. Neutron or proton irradiation results in the formation of vacancies which become additional phonon-scattering centers and decrease the thermal conductivity. This explains the wide spread of the lower curves shown in Figure 44.

For the direction parallel to the molding pressure, the proposed curve has been drawn through the data of Smith and Rasor [1329, 1177, 1180] (curve 1), and for the perpendicular direction the curve has been drawn through the data of Rasor [1177] (curve 39). The two curves yield anisotropy ratios of 1.610 at 300 K, 1.589 at 400 K, and 1.579 at 500 K, which indicates that the anisotropy ratio decreases slightly with increasing temperatures.

The values at and above room temperature are recommended values, and those below room temperature are merely typical values which represent two typical curves serving to indicate the general trend of the thermal conductivity of this graphite at moderate and low temperatures. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

TABLE 30. Recommended thermal conductivity of AWG graphite†
(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	‖ to molding pressure k	⊥ to molding pressure k	T	‖ to molding pressure k	⊥ to molding pressure k
10	0.00397	0.00583	200	0.748	1.29
20	0.0181	0.0298	223.2	0.785	1.33
30	0.0428	0.0730	250	0.803	1.33
40	0.0783	0.133	273.2	0.807	1.32
50	0.122	0.209	298.2	0.796	1.28
60	0.168	0.296	300	0.795	1.28
70	0.212	0.389	323.2	0.778	1.24
80	0.269	0.483	350	0.754	1.20
90	0.327	0.582	373.2	0.733	1.16
100	0.375	0.677	400	0.705	1.12
123.2	0.486	0.878	473.2	0.635	1.00
150	0.604	1.08	500	0.611	0.965
173.2	0.682	1.20			

†The values at and above room temperature are recommended values for AWG graphite, and those below room temperature are merely typical values.

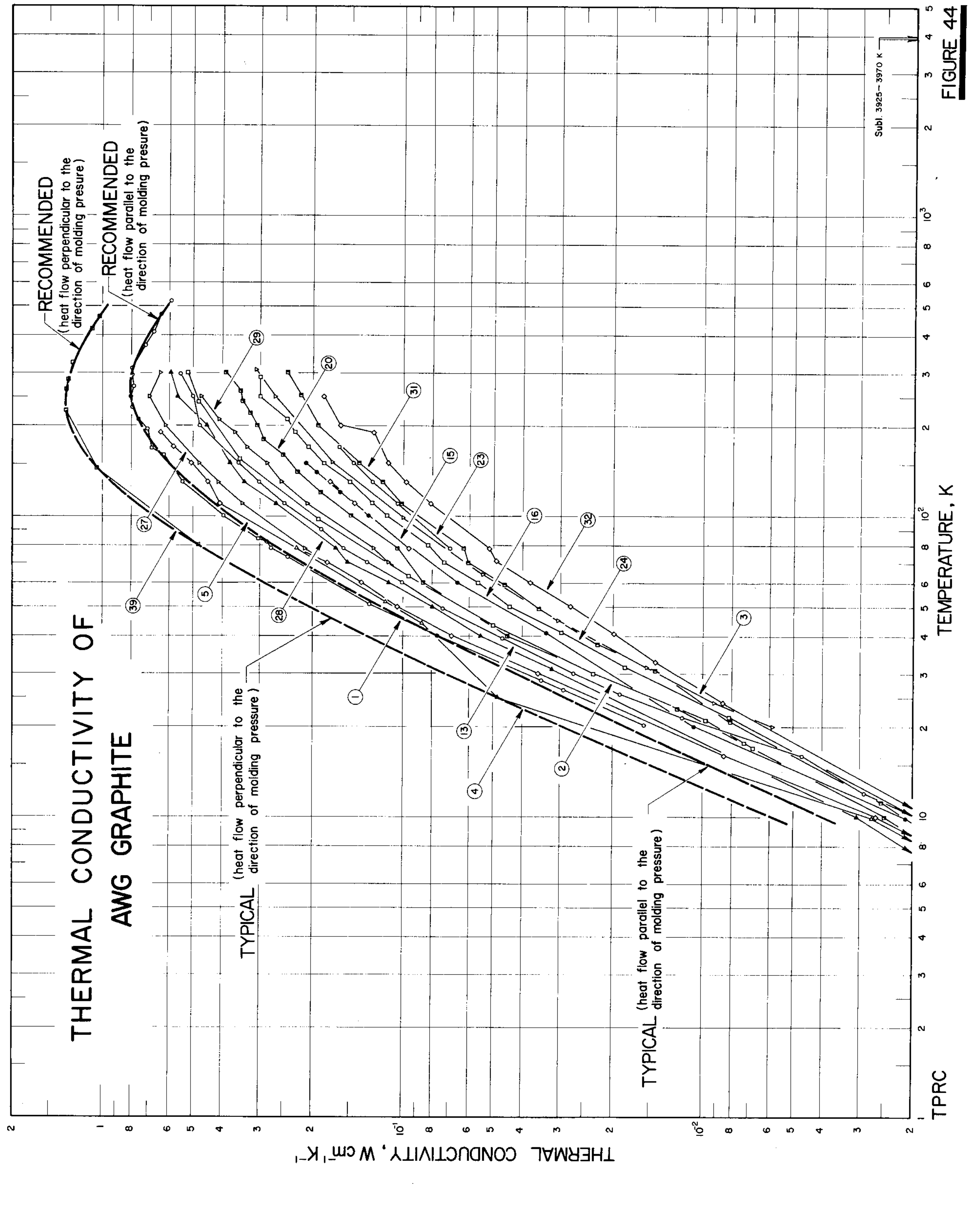

THERMAL CONDUCTIVITY OF
AWG GRAPHITE
RECOMMENDED
(heat flow perpendicular to the direction of molding presure)
RECOMMENDED
(heat flow parallel to the direction of molding presure)
TYPICAL (heat flow perpendicular to the direction of molding pressure)
TYPICAL (heat flow parallel to the direction of molding pressure)
Subl. 3925–3970 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 44

TABLE 31. THERMAL CONDUCTIVITY OF AWG GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1329, 1177, 1180	Smith, A. W. and Rasor, N. S.	1954	E	20-520		Polycrystalline; molded petroleum coke; particle size 25 μ; crystallite size 0.2 μ; density 1.75 g cm^{-3} at 25 C; thermoelectric power +2.3 μvolt K^{-1}; Hall coefficient -0.47 emu; magneto resistivity 1.9 x 10^{-10} emu; electrical resistivity 14.3 milliohm cm; total susceptibility -20.60 x 10^{-6} cgs unit; orientation factor (ρ_{max}/ρ_{min}) = 1.3; measured parallel to the direction of the molding pressure.
2	1329, 1180	Smith, A. W. and Rasor, N. S.	1954	E	17-300		The above specimen exposed to neutron bombardment of 6 MWD/T at <60 C.
3	1329, 1180	Smith, A. W. and Rasor, N. S.	1954	E	20-308		The above specimen exposed to neutron bombardment of 22.7 MWD/T at <30 C.
4	324	Deegan, G. E.	1956	E	5.6-78	C-369, No. 1	Specimen 10 mil thick cut from a block of pitch-bonded artificial graphite; electrical resistivity varied from 4.009 to 3.418 milliohm cm at 5.6 to 78 K, respectively; irradiated at 103 K by 8.6 MeV protons of 0.65 μah cm^{-2} (micro ampere hour per square centimeter); measured parallel to molding pressure.
5	324	Deegan, G. E.	1956	E	6.0-190	C-369, No. 1	The above specimen pulse-annealed for 5 min at 225 K before irradiation; electrical resistivity varied from 3.901 to 2.439 milliohm cm at 6.0 to 190 K, respectively.
6*	324	Deegan, G. E.	1956	E	78-250	C-369, No. 1	The above specimen pulse-annealed at 375 K before irradiation; electrical resistivity varied from 2.968 to 1.924 milliohm cm at 78 to 250 K, respectively.
7*	324	Deegan, G. E.	1956	E	78	C-369, No. 1	The above specimen measured at 78 K after being pulse-annealed at temps ranging from 125 to 375 K.
8*	324	Deegan, G. E.	1956	E	110	C-369, No. 1	The above specimen measured at 110 K after being pulse-annealed at 225 and 375 K.
9*	324	Deegan, G. E.	1956	E	130	C-369, No. 1	The above specimen measured at 130 K after being pulse-annealed at 225 and 375 K.
10*	324	Deegan, G. E.	1956	E	150	C-369, No. 1	The above specimen measured at 150 K after being pulse-annealed at 225 and 375 K.
11*	324	Deegan, G. E.	1956	E	170	C-369, No. 1	The above specimen measured at 170 K after being pulse-annealed at 225 and 375 K.
12*	324	Deegan, G. E.	1956	E	190	C-369, No. 1	The above specimen measured at 190 K after being pulse-annealed at 225 and 375 K.
13	324	Deegan, G. E.	1956	E	8.6-297	C-369, No. 2	Similar to the above specimen but isothermal-annealed for 2 wks at 300 K; electrical resistivity varied from 4.139 to 2.372 milliohm cm at 8.6 to 297 K, respectively; irradiated by protons of 0.31 μah cm^{-2}.
14*	324	Deegan, G. E.	1956	E	6.3-78	C-369, No. 3	Similar to the above specimen but electrical resistivity varies from 5.155 to 4.822 milliohm cm at 6.3 to 78 K, respectively; irradiated with protons at 103 K of 7.9 μah cm^{-2}.
15	324	Deegan, G. E.	1956	E	78-130	C-369, No. 3	The above specimen pulse-annealed for 5 min at 150 K; electrical resistivity varied from 4.895 to 4.736 milliohm cm at 78 to 130 K, respectively.
16	324	Deegan, G. E.	1956	E	6.0-150	C-369, No. 3	The above specimen pulse-annealed at 175 K; electrical resistivity varied from 5.155 to 4.633 milliohm cm at 6.0 to 150 K, respectively.
17*	324	Deegan, G. E.	1956	E	78-170	C-369, No. 3	The above specimen pulse-annealed at 200 K; electrical resistivity varied from 4.754 to 4.408 milliohm cm at 78 to 170 K, respectively.
18*	324	Deegan, G. E.	1956	E	6.0, 78	C-369, No. 3	The above specimen pulse-annealed at 250 K; electrical resistivity at 6.0 and 78 K being, respectively, 4.557 and 4.291 milliohm cm.

* Not shown in figure.

TABLE 31. THERMAL CONDUCTIVITY OF AWG GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
19*	324	Deegan, G. E.	1956	E	6.0, 78	C-369, No. 3	The above specimen pulse-annealed at 300 K; electrical resistivity at 6.0 and 78 K being, respectively, 4.179 and 4.30 milliohm cm.
20	324	Deegan, G. E.	1956	E	6.0-300	C-369, No. 3	The above specimen pulse-annealed at 375 K; electrical resistivity varied from 4.295 to 2.92 milliohm cm at 6.0 to 300 K, respectively.
21*	324	Deegan, G. E.	1956	E	78	C-369, No. 3	The above specimen measured at 78 K after being pulse-annealed at temps from 125 to 375 K.
22*	324	Deegan, G. E.	1956	E	5.5-78	C-369, No. 4	Similar to the above specimen but not annealed; irradiated at 103 K by protons of 12.8 μah cm^{-2}; electrical resistivity (before irradiation) varied from 5.261 to 4.943 milliohm cm at 5.5 to 78 K, respectively.
23	324	Deegan, G. E.	1956	E	78-170	C-369, No. 4	The above specimen pulse-annealed for 5 min at 200 K; electrical resistivity varied from 4.935 to 4.700 milliohm cm at 78 to 170 K, respectively.
24	324	Deegan, G. E.	1956	E	6.6-290	C-369, No. 4	The above specimen pulse-annealed at 375 K; electrical resistivity varied from 4.362 to 3.44 milliohm cm at 6.6 to 290 K, respectively.
25*	324	Deegan, G. E.	1956	E	78	C-369, No. 4	The above specimen measured at 78 K after being pulse-annealed at temps ranging from 125 to 375 K.
26*	324	Deegan, G. E.	1956	E	78	Brookhaven	Similar to the above specimen but being exposed to $\sim 10^{18}$ neutrons cm^{-2}.
27	324	Deegan, G. E.	1956	E	5.6-300	C-376, No. 1	Similar to the above specimen but irradiated at 300 K with an exposure of protons at 1.46 μah cm^{-2}; electrical resistivity varied from 3.923 to 1.964 milliohm cm at 5.6 to 300 K, respectively; not annealed.
28	324	Deegan, G. E.	1956	E	5.2-300	C-376, No. 2	Similar to the above specimen but being irradiated with an exposure of protons at 2.47 μah cm^{-2}; electrical resistivity varied from 4.083 to 2.214 milliohm cm at 5.2 to 300 K, respectively.
29	324	Deegan, G. E.	1956	E	6.2-250	C-376, No. 3	Similar to the above specimen but being irradiated with an exposure of protons at 5.8 μah cm^{-2}; electrical resistivity varied from 4.290 to 2.945 milliohm cm at 6.2 to 250 K, respectively.
30*	324	Deegan, G. E.	1956	E	6.4-250	C-376, No. 4	Similar to the above specimen but being irradiated with an exposure of 9.3 μah cm^{-2}; electrical resistivity varied from 4.350 to 3.308 milliohm cm at 6.4 to 250 K, respectively.
31	324	Deegan, G. E.	1956	E	5.6-250	C-376, No. 5	Similar to the above specimen but being irradiated with an exposure of 15.9 μah cm^{-2}; electrical resistivity varied from 4.465 to 3.567 milliohm cm at 5.6 to 250 K, respectively.
32	324	Deegan, G. E.	1956	E	5.2-250	C-376, No. 6	Similar to the above specimen but being irradiated with an exposure of 27.5 μah cm^{-2}; electrical resistivity varied from 4.653 to 3.988 milliohm cm at 5.2 to 250 K, respectively.
33*	324	Deegan, G. E.	1956	E	7.6-300	C-381, No. 1	Similar to the above specimen but being irradiated at 423 K with an exposure of 0.95 μah cm^{-2}; electrical resistivity varied from 3.568 to 1.743 milliohm cm at 7.6 to 300 K, respectively.

* Not shown in figure.

TABLE 31. THERMAL CONDUCTIVITY OF AWG GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
34*	324	Deegan, G. E.	1956	E	7.2-300	C-381, No. 2	Similar to the above specimen but being irradiated with an exposure of 3.1 μah cm^{-2}; electrical resistivity varied from 3.711 to 1.827 milliohm cm at 7.2 to 300 K, respectively.
35*	324	Deegan, G. E.	1956	E	6.8-300		Similar to the above specimen but being irradiated by protons of 4.96 μah cm^{-2}; electrical resistivity varied from 3.939 to 2.016 milliohm cm at 6.8 to 300 K, respectively.
36*	324	Deegan, G. E.	1956	E	7.6-300		Similar to the above specimen but being irradiated by protons of 11.9 μah cm^{-2}; electrical resistivity varied from 4.186 to 2.304 milliohm cm at 7.6 to 300 K, respectively.
37*	324	Deegan, G. E.	1956	E	6.8-250		Similar to the above specimen but being irradiated by protons of 19.7 μah cm^{-2}; electrical resistivity varied from 4.426 to 2.875 milliohm cm at 6.8 to 250 K, respectively.
38*	324	Deegan, G. E.	1956	E	6.4-300		Similar to the above specimen but being irradiated by protons of 30.2 μah cm^{-2}; electrical resistivity varied from 4.545 to 2.978 milliohm cm at 6.4 to 300 K, respectively.
39	1177	Rasor, N. S.	1955	E	80-460		Made from petroleum coke; molded; specimen size 0.100 x 0.020 x 1.25 in.; room temp properties: density 1.75 g cm^{-3}, thermoelectric power +2.3 μvolt K^{-1}, Hall coefficient -0.47 emu, magneto resistivity 1.9 x 10^{-10} emu, electrical resistivity 14.3 milliohm cm, total magnetic susceptibility -20.6 x 10^{-6} cgs unit, orientation factor $(\rho_{max}/\rho_{min}) = 1.0$; measured perpendicular to the direction of molding pressure.

* Not shown in figure.

Pyrolytic Graphite

Pyrolytic graphite is produced by the deposition of carbon from a gaseous hydrocarbon onto a heated surface at high temperature of the order of 2000° C. There are 197 curves available for this graphite. The general feature of the thermal conductivity of pyrolytic graphite has been briefly reviewed in the general discussion on graphite. Figure 45 shows clearly the large anisotropy in the thermal conductivity. Since the thermal conductivity of this graphite is highly sensitive to small physical and chemical variations among samples, curves for the sample measured in the same direction spread also into a very wide band. It has been noted [769] that significant variations in thermal conductivity can be encountered with pyrolytic graphites even deposited at identical temperature. This effect is ascribed to be a result of influencing factors in the manufacturing procedure other than deposition temperature.

The highest thermal conductivity curve for the direction parallel to the layer planes is that of de Combarieu [322] for a specimen deposited at 2100° C and annealed under a pressure of 200 bars for 10 to 15 minutes at 2800° C. The proposed curve follows Combarieu's data to 300 K and is then extended to higher temperatures according to the temperature dependency indicated by Taylor's [1390] (curve 51) and Pappis and Blum's [1064] (curve 26) curves. At high temperatures the proposed curve lies close to curve 48 of Johnson and Watt [686] and nearly passes through a point (curve 54) obtained by Hoch and Vardi [612]. It is interesting to note that at room temperature the thermal conductivity of highly-oriented and well-annealed pyrolytic graphite in the direction parallel to the layer planes is 4.6, 4.9, 6.2, 11.3, and 54 times higher than the thermal conductivity of silver, copper, gold, tungsten and aluminum oxide, respectively, and is only slightly lower than that of Type IIa diamond. At 2000 K it is still 2.7 and 44 times higher than that of tungsten and aluminum oxide, respectively.

For the direction perpendicular to the layer planes, the proposed curve has been drawn through the data (curve 77) of de Combarieu [323], which appear to be the only data covering from room temperature down to the low temperature region showing the thermal conductivity maximum for the perpendicular direction. This curve has been extrapolated from 300 K to 2000 K following the slope of Taylor's curve [1390] (curve 52). It is noted, here again, that the values for $k_{\perp}$ are lower than the thermal conductivity of polycrystalline aluminum oxide by 6.3 and 7.4 times at room temperature and 2000 K, respectively.

The anisotropy ratio in the thermal conductivity of pyrolytic graphite at temperatures below 1 K has been reported by Slack [1318] to be between 2 and 3. Its exact value is determined by the elastic constant and by the ellipsoidal shape of the crystallites. In the liquid-helium temperature region Klein and Holland [769] found that the ratio is close to 3, which remains the same for samples deposited at different temperatures, but rises rapidly with temperature above 20 K. For a highly-oriented and well-annealed sample, Hooker, Ubbelohde, and Young [630] found that the ratio increases to about 100 at 90 K, 196 at 150 K, 215 at 200 K, 211 at 250 K, and 210 at 300 K. Taylor [1390] also found that the anisotropy ratio for his samples is 210 at 300 K. From 300 to 900 K Taylor's data indicate a nearly constant anisotropy ratio. However, the data of de Combarieu [323] indicate a much higher anisotropy, being about 109 at 20 K, 160 at 50 K, 220 at 70 K, 309 at 100 K, and 330 from 200 to 300 K.

The proposed curves are considered as typical curves serving only to indicate the general trend of the thermal conductivity.

TABLE 32. Typical thermal conductivity of pyrolytic graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to layer planes k	⊥ to layer planes k	T	∥ to layer planes k	⊥ to layer planes k
0	0	0	500	10.8	0.0322
10	0.811	0.0116	573.2	9.36	0.0281
20	4.20	0.0397	600	8.92	0.0268
30	9.86	0.0786	673.2	7.92	0.0238
40	16.4	0.120	700	7.59	0.0229
50	23.1	0.152	773.2	6.88	0.0207
60	29.8	0.173	800	6.67	0.0201
70	36.6	0.181	873.2	6.13	0.0184
80	42.8	0.181	900	5.94	0.0178
90	47.5	0.176	973.2	5.49	0.0164
100	49.7	0.168	1000	5.34	0.0160
123.2	50.4	0.148	1073.2	5.00	0.0148
150	45.1	0.125	1100	4.88	0.0145
173.2	38.7	0.108	1173.2	4.57	0.0136
200	32.3	0.0923	1200	4.48	0.0134
223.2	28.2	0.0814	1273.2	4.22	0.0126
250	24.4	0.0711	1300	4.13	0.0124
273.2	21.3	0.0636	1373.2	3.91	0.0118
298.2	19.6	0.0573	1400	3.84	0.0116
300	19.5	0.0570	1473.2	3.64	0.0110
323.2	17.8	0.0522	1500	3.57	0.0108
350	16.2	0.0477	1573.2	3.40	0.0102
373.2	15.1	0.0442	1600	3.33	0.0100
400	13.9	0.0409	1673.2	3.18	0.00962
473.2	11.4	0.0341	1700	3.12	0.00947
			1773.2	2.97	0.00909
			1800	2.93	0.00895
			1883.2	2.80	0.00860
			1900	2.77	0.00848
			1973.2	2.66	0.00817
			2000	2.62	0.00807

†These typical values are for well-annealed pyrolytic graphite with well-oriented crystalline layer structure.

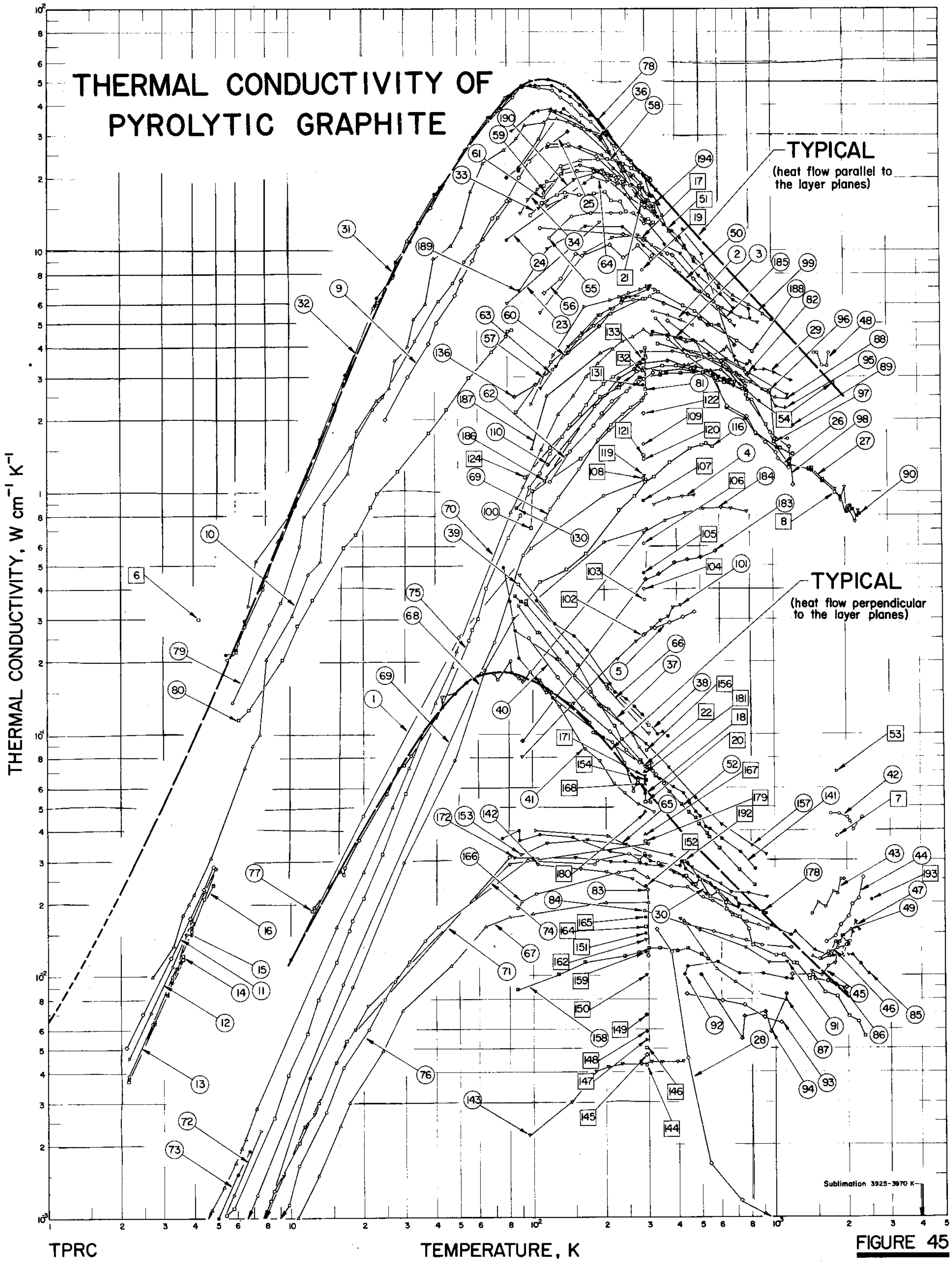

THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE
TYPICAL
(heat flow parallel to the layer planes)
TYPICAL
(heat flow perpendicular to the layer planes)
Sublimation 3925-3970 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 45

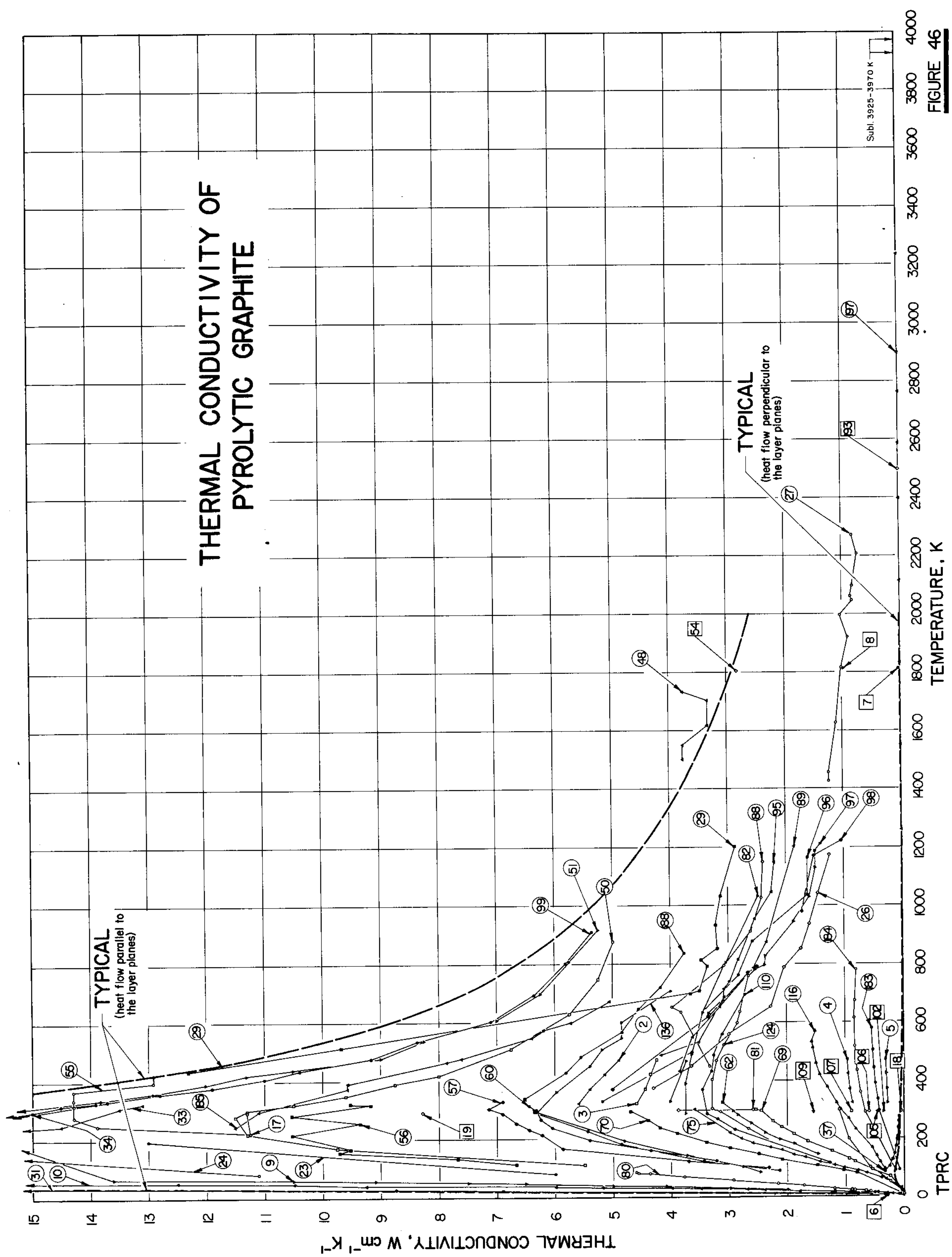

THERMAL CONDUCTIVITY OF
PYROLYTIC GRAPHITE
TYPICAL
(heat flow parallel to
the layer planes)
TYPICAL
(heat flow perpendicular to
the layer planes)
Subl. 3925–3970 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC
FIGURE 46

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1329	Smith, A.W. and Rasor, N.S.	1956	E	10-300		Obtained by pyrolytic decomposition of a hydrocarbon; no pitch bonding.
2	215	Brown, A.R.G., Watt, W., Powell, R.W., and Tye, R.P.	1956	C	323-473	deposited carbon	Also known as pyrolytic graphite; 99.75±0.2 pure with undetectable ash content; deposited from AR grade benzene at 2100 C in a vacuum of 10^{-3} cm Hg; tubular specimen 4.5 cm long, 0.95 cm O.D., and 0.75 cm I.D.; density 1.65 g cm^{-3}; electrical resistivity at 20, 50, 100, 150, and 200 C being, respectively, 245, 230, 215, 200, and 195 μohm cm; measured parallel to axis of tube and parallel to the pronounced layered structure of the specimen.
3	215	Brown, A.R.G., et al.	1956	C	323-473	deposited carbon	Similar to the above specimen but deposited at 2000 C; electrical resistivity at 20, 50, 100, 150, and 200 C being, respectively, 380, 360, 330, 305, and 290 μohm cm.
4	215	Brown, A.R.G., et al.	1956	C	323-473	deposited carbon	Similar to the above specimen but deposited at 1900 C; electrical resistivity at 20, 50, 100, 150, and 200 C being, respectively, 1.645, 1.585, 1.47, 1.37, and 1.27 milliohm cm.
5	215	Brown, A.R.G., et al.	1956	C	323-473	deposited carbon	Similar to the above specimen but deposited at 1800 C; electrical resistivity at 20, 50, 100, 150, and 200 C being, respectively, 3.23, 3.17, 3.065, 2.96, and 2.86 milliohm cm.
6	512	Goldsmid, H.J. and Lacklison, D.E.	1965	L	4.2		Rectangular block of pyrolytic graphite provided by G.E. Research Lab; reheated to to 3500 C after deposition; electrical conductivity in zero magnetic field 7.8 x 10^5 ohm^{-1} cm^{-1} at 4 K.
7	612	Hoch, M. and Vardi, J.	1962	→	1817	P-3, P-3A	Pyrolytic graphite obtained from General Electric Co; 2.3 cm dia x 0.1-0.4 cm thick; axial thermal conductivity determined by equating heat conduction to radiation loss.
8	612	Hoch, M. and Vardi, J.	1962	→	1817		k_r determined simultaneously with the above curve; heat flow parallel to layer plane.
9	190	Bowman, J.C., Krumhansl, J.A., and Meers, J.T.	1958	L	25-235	Pyrolytic graphite filament	Specimen of fibrous structures prepared by pyrolysis of methane on a hot carbon wire, measurements made under high vacuum.
10	623	Holland, M.G., Klein, C.A., and Straub, W.D.	1966	L	2.2-290		Well graphitized and highly heat treated (at 3250 C) pyrolytic graphite; measured in the layer-plane direction; in zero magnetic field.
11	623	Holland, M.G., et al.	1966	L	2.1-4.8		The above specimen measured in a magnetic field of 550 gauss applied in the c-axis direction.
12	623	Holland, M.G., et al.	1966	L	2.2-4.9		The above specimen in a field of 1015 gauss.
13	623	Holland, M.G., et al.	1966	L	2.2-4.9		The above specimen in a field of 2115 gauss.
14	623	Holland, M.G., et al.	1966	L	2.2-3.6		The above specimen in a field of 3805 gauss.
15	623	Holland, M.G., et al.	1966	L	2.2-3.9		The above specimen in a field of 8405 gauss.
16	623	Holland, M.G., et al.	1966	L	3.1-4.8		The above specimen in a field of 12600 gauss.
17	1389	Taylor, R.	1965	P	293.2		Specimen ~0.5 in. long; graphitized at 2910 C; specific heat 0.168 cal g^{-1} C^{-1} at 20 C; measured in the a-axis direction.
18	1389	Taylor, R.	1965	P	293.2		Similar to the above specimen but about 0.2 in. long; measured in the c-axis direction.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
19	1389	Taylor, R.	1965	P	293.2		Specimen ~0.5 in. long; graphitized at 2800 C; specific heat 0.168 cal g^{-1} C^{-1} at 20 C; measured in the a-axis direction.
20	1389	Taylor, R.	1965	P	293.2		Similar to the above specimen but ~0.2 in. long; measured in the c-axis direction.
21	1389	Taylor, R.	1965	P	293.2		Similar to the above specimen but ~0.5 in. long; strain annealed at 3300 C; measured in the a-axis direction.
22	1389	Taylor, R.	1965	P	293.2		Similar to the above specimen but ~0.2 in. long; measured in the c-axis direction.
23	973	Mills, J.J., Morant, R.A., and Wright, D.A.	1965	L	80,195		Specimen ~0.2 mm thick; cut from a pyrolytic graphite bar which was made at a deposition temp of 2700 C.
24	973	Mills, J.J., et al.	1965	L	80,170		Similar to the above specimen but deposition temp 2920 C.
25	973	Mills, J.J., et al.	1965	L	80,144		Similar to the above specimen but deposition temp 2980 C.
26	1064	Pappis, J. and Blum, S.L.	1961	C	375-1175		Highly regenerative pyrolytic graphite; as deposited; the pyrolytic graphite obtained by passing methane on a graphite slab in the resistance furnace at 2100 C; density 2.20 g cm^{-3}; measured parallel to the basal planes using dense sintered alumina as a comparative material.
27	1064	Pappis, J. and Blum, S.L.	1961	R	1430-2275		Similar to the above specimen but using another apparatus for higher temp range.
28	1064	Pappis, J. and Blum, S.L.	1961	R	325-1350		Similar to the above specimen but being heat treated for 3 hrs at 2900 C; measured perpendicular to the basal planes.
29	1064	Pappis, J. and Blum, S.L.	1961	C	435-1205		Similar to the above specimen but heat treated for 1 hr at 2900 C; measured parallel to the basal plane using dense sintered alumina as a comparative material.
30	1064	Pappis, J. and Blum, S.L.	1961	R	330-2340		Similar to the above specimen but without heat treatment; measured perpendicular to the basal plane.
31	322	De Combarieu, A.	1965	L	6.8-320	No. 1	Pyrolytic graphite specimen size 1 x 5 x 50 mm; the graphite deposition temp 2100 C; annealed under a pressure of 100 bars for 10-15 min at 2800 C; measured parallel to the graphite basal planes.
32	322	De Combarieu, A.	1965	L	5.5-320	No. 2	Similar to the above specimen.
33	630	Hooker, C.N., Ubbelohde, A.R., and Young, D.A.	1965	L	100-325	AB 3	Pyrolytic graphite deposited at 2150 C; annealed at 3000 C; measured parallel to the basal planes.
34	630	Hooker, C.N., et al.	1965	L	91-330	IFP 41	Similar to the above specimen but also hot pressed at 2850 C under 400 Kg cm^{-2}; measured parallel to the basal planes.
35*	630	Hooker, C.N., et al.	1965	L	91-330	IFP 56	Similar to the above specimen.
36	630	Hooker, C.N., et al.	1965	L	84-318	IFPA 57	Similar to the above specimen but hot pressed at 2850 C and annealed at 3500 C under 10 Kg cm^{-2} for 0.5 hr; measured parallel to the basal planes.
37	630	Hooker, C.N., et al.	1965	L	88-310	IFPA 57	The above specimen measured in the c-axis direction.
38	630	Hooker, C.N., et al.	1965	L	105-365	AB 4	Pyrolytic graphite deposited at 2150 C; annealed at 3250 C in induction furnace; measured in the c-axis direction.

* Not shown in figure.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
39	630	Hooker, C.N., Ubbelohde, A.R., and Young, D.A.	1965	L	88-303	AB 1	Similar to the AB 3 specimen but measured in the c-axis direction.
40	630	Hooker, C.N., et al.	1965	L	97-350	IFP 25	Similar to the IFP 41 specimen but measured in the c-axis direction.
41	630	Hooker, C.N., et al.	1965	L	107-318	IFP 25/N4	The above specimen exposed to 2 x 10^{18} fast neutron cm^{-2} at 30 C; measured in the c-axis direction.
42	686	Johnson, W. and Watt, W.	1963	R	1712-2308	A 1	Specimen 11 cm long, 1.713 cm O.D., and 1.465 cm I.D.; pyrolytic graphite deposited from hexane at 1800 C and at a total pressure of 35 cm Hg (partial pressure of hexane 7 cm Hg); the hydrogen carrier gas flows at a rate of 500 cm^3 min^{-1}; the specimen being heat treated for 2 hrs at 2800 C; density 1.71 g cm^{-3}; data obtained by the first method (direct heating of the graphite tube).
43	686	Johnson, W. and Watt, W.	1963	R	1426-1945	A 1	The above specimen measured by the third method (separate heater inserted in the tube).
44	686	Johnson, W. and Watt, W.	1963	R	1637-2313	A 2	Specimen 11 cm long, 1.728 cm O.D., and 1.39 cm I.D.; deposited from hexane at 2100 C and by a method similar to the above; heat treated for 2 hrs at 2800 C; density 2.21 g cm^{-3}; data obtained by the first method.
45	686	Johnson, W. and Watt, W.	1963	R	1420-2009	A 2	The above specimen measured by the third method.
46	686	Johnson, W. and Watt, W.	1963	R	1530-2043	B 1	Specimen 11 cm long, 1.75 cm O.D., and 1.394 cm I.D.; deposited in the same way as the above specimen; heat treated for 1.25 hrs at 2600 C; density 2.20 g cm^{-3}; data obtained by the second method (an improvement of the first method to decrease the end contact resistance of the graphite tube).
47	686	Johnson, W. and Watt, W.	1963	R	1895-2231	B 1	The above specimen measured by the third method.
48	686	Johnson, W. and Watt, W.	1963	R	1504-1736	B 1	Thermal conductivity parallel to the basal planes of the above specimen.
49	686	Johnson, W. and Watt, W.	1963	R	1422-2056	B 2	Specimen 11 cm long, 1.75 cm O.D., and 1.351 cm I.D.; deposited and heat treated in the same way as the above specimen; density 2.20 g cm^{-3}; data obtained by the third method.
50	1390	Taylor, R.	1966	P	110-880	Specimen 42	Specimen 0.5 in. long, made from as deposited pyrolytic graphite; annealed at 2900 C for 1 hr in an inert gas atm; thermal conductivity parallel to the deposition plane calculated from measurements of thermal diffusivity, a constant density of 2.20 g cm^{-3}, and the best fit specific heat data from Magnus, 1923, Schläpfer and Debrunner, 1924, Jacobs and Perks, 1934, DeSorbo and Tyler, 1953, DeSorbo, 1954, Lucks and Deem, 1956, Wagman, et al., 1945, and Rossini, et al., 1953.
51	1390	Taylor, R.	1966	P	90-920	Specimen 90	Specimen also 0.5 in. long supplied by General Electric Co. (structurally more perfect than the above specimen); annealed at 3300 C in inert gas; thermal conductivity parallel to the deposition plane calculated by using the same information as the above specimen.
52	1390	Taylor, R.	1966	P	85-830	Specimen 90	Similar to the above specimen but measured perpendicular to the deposition plane.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
53	612	Hoch, M. and Vardi, J.	1962	→	1808	P 1	Supplied by General Electric Co.; 2.540 cm dia x 0.238 cm thick; k_z determined by using the same method as that for curve No. 7.
54	612	Hoch, M. and Vardi, J.	1962	→	1808	P 1	k_r determined simultaneously with the above curve; heat flow along layer plane.
55	629	Hooker, C.N., Ubbelohde, A.R., and Young, D.A.	1963	L	122-324	A_2	Specimen approx 0.2 x 1.5 x 8 cm thickness parallel to c-axis; made from pyrolytic graphite (inner layer of sample) deposited at 2150 C from methane atm at 10 cm Hg pressure; in its "as deposited" condition; scattering length 18000 Å; heat flow perpendicular to c-axis.
56	629	Hooker, C.N., et al.	1963	L	115-324	A_1	Specimen approx 0.2 x 1.5 x 8 cm, thickness parallel to c-axis; made from pyrolytic graphite deposited at 2180 C from methane atm at 10 cm Hg pressure; in its "as deposited" condition; scattering length 12000 Å; heat flow perpendicular to c-axis.
57	629	Hooker, C.N., et al.	1963	L	100-331	A_3	Similar to the above specimen but deposited at 2000 C with scattering length 5000 Å; heat flow perpendicular to c-axis.
58	629	Hooker, C.N., et al.	1963	L	116-335	AB_1	Similar to the above specimen but deposited at 2150 C and annealed at 3000 C for 30 min; scattering length 36000 Å; heat flow perpendicular to c-axis.
59	629	Hooker, C.N., et al.	1963	L	115-327	AB_2	Similar to the above specimen except scattering length 33000 Å; heat flow perpendicular to c-axis.
60	629	Hooker, C.N., et al.	1963	L	125-316	A_2	Specimen approx 0.2 x 1.5 x 8 cm, thickness parallel to c-axis; made from pyrolytic graphite (outer layer of sample) deposited at 2150 C and at 10 cm Hg pressure; in its "as deposited" condition; scattering length 5000 Å; heat flow perpendicular to c-axis.
61	629	Hooker, C.N., et al.	1963	L	115-327	AB_2	Specimen 0.2 x 1.5 x 8 cm, thickness parallel to c-axis; made from pyrolytic graphite deposited at 2150 C from methane atm at 10 cm Hg pressure; annealed at 3000 C for 30 min; scattering length 36000 Å; measured in vacuum of $<10^{-5}$ mm Hg pressure; heat flow parallel to c-axis.
62	629	Hooker, C.N., et al.	1963	L	120-327	N_1	Specimen obtained by sealing AB_2 in an evacuated silica tube and irradiating it in a cooled (~30 C) hollow fuel element in B.E.P.O. at Harwell to an integrated fast neutron dose of about 4 x 10^{18} n.v.t.; heat flow parallel to c-axis; measured in vacuum of $<10^{-5}$ mm Hg pressure.
63	629	Hooker, C.N., et al.	1963	L	111-316	N_2	The above specimen annealed in vacuo at 240 C for 70 hrs; heat flow parallel to c-axis; measured in vacuum of $<10^{-5}$ mm Hg pressure.
64	629	Hooker, C.N., et al.	1963	L	118-331	N_3	The above specimen annealed in vacuo at 1220 C for 6 hrs; heat flow parallel to c-axis; measured in vacuum of $<10^{-5}$ mm Hg pressure.
65	629	Hooker, C.N., et al.	1963	L	104-306	A_1	Specimen 0.2 x 1.5 x 8 cm, thickness parallel to c-axis; made from pyrolytic graphite deposited at 2180 C from methane atm at 10 cm Hg pressure; in its "as deposited" condition; scattering length 12000 Å; measured in vacuum of $<10^{-5}$ mm Hg pressure; heat flow parallel to c-axis.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
66	629	Hooker, C. N., Ubbelohde, A. R., and Young, D. A.	1963	L	89-302	AB_1	Similar to the above specimen except deposited at 2150 C and annealed at 3000 C for 30 min; scattering length 36000 Å; heat flow parallel to c-axis.
67	1318	Slack, G. A.	1962	L	5.0-300	PG-O	Specimen 0.7 cm long and having a square cross sectional area of 0.17 cm^2; made from pyrolytic graphite deposited on a substrate of commercial graphite in a methane atm at 2250 C and at a total pressure of 20 mm Hg; graphite crystallites shaped like oblate ellipsoids (with rotational symmetry about the c-axis), of minor dia (parallel to c-axis) = 140 Å and major dia (perpendicular to c-axis) = 280 Å; these crystallites with an average angular tilt of 22 degrees from the c-axis formed columnar bundles of 0.1 cm in dia; density of the specimen 2.194 g cm^{-3}; electrical conductivity 1.98 ohm^{-1} cm^{-1} at 298 K; sound velocity 3.4 x 10^5 cm sec^{-1} at 9.8 megacycles sec^{-1} and at 300 K; free from any visible cracks along the [0001] planes; heat flow parallel to the c-axis.
68	1318	Slack, G. A.	1962	L	3.2-300	PG-O	Similar to the above specimen but 1.9 cm long with a square cross sectional area of 0.14 cm^2; electrical conductivity 1.85 x 10^3 ohm^{-1} cm^{-1} at 298 K; sound velocity 4.7 x 10^5 cm sec^{-1} at the same conditions as above; heat flow perpendicular to c-axis.
69	769	Klein, C. A. and Holland, M. G.	1964	L	1.8-300	RAY-17	Specimen of pyrolytic graphite in its "as-deposited" condition; manufactured by Raytheon's Adv. Mat. Dept. with a deposition temp of 1700 C; crystallite size 180 Å; density 2.13 g cm^{-3}; cut parallel to the layer plane.
70	769	Klein, C. A. and Holland, M. G.	1964	L	1.9-295	RAY-23	Similar to the above specimen but the deposition temp 2300 C; density 2.22 g cm^{-3} and crystallite size 285 Å; parallel to the layer plane.
71	769	Klein, C. A. and Holland, M. G.	1964	L	3.4-80	RAY-23	Similar to the above specimen but cut perpendicular to the layer plane.
72	769	Klein, C. A. and Holland, M. G.	1964	L	1.8-7.5	RAY-19	Similar to the above specimen but the deposition temp 1900 C; crystallite size 240 Å, and density 2.19 g cm^{-3}; cut parallel to the layer plane.
73	769	Klein, C. A. and Holland, M. G.	1964	L	2.0-6.8	RAY-21	Similar to the above specimen but the deposition temp 2100 C; crystallite size 270 Å, and density 2.20 g cm^{-3}; cut parallel to the layer plane.
74	769	Klein, C. A. and Holland, M. G.	1964	L	3.1-300	RAY-21	Similar to the above specimen but cut perpendicular to the layer plane.
75	769	Klein, C. A. and Holland, M. G.	1964	L	1.9-300	HTM	Specimen of pyrolytic graphite in its "as-deposited" condition; obtained from High Temp Mat. Inc.; deposition temp ~2100 C; density 2.19 g cm^{-3}; cut parallel to the layer plane.
76	769	Klein, C. A. and Holland, M. G.	1964	L	4.3-290	HTM	Similar to the above specimen but cut perpendicular to the layer plane.
77	323	de Combarieu, A.	1967	L	12-309		Single crystal; 10 x 10 x 4 mm; deposited at 2100 C, then annealed under a pressure of 200 bars at 2800 C for 10 to 15 min; heat flow parallel to c-axis.
78	323	de Combarieu, A.	1967	L	5.5-316		Similar to above but heat flow perpendicular to c-axis.
79	323	de Combarieu, A.	1967	L	5.9-83		Similar to above but specimen irradiated by a flux of fast neutrons of 7.4 x 10^{15} cm^{-2}.
80	323	de Combarieu, A.	1967	L	6.2-83		Similar to above but irradiation dose 4.7 x 10^{16} cm^{-2}.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
81	186	Bourdeau, R. G.	1962		298.2		From High Temperature Materials, Inc.; density 2.20-2.23 g cm^{-3}; melting point 3922 K; electrical resistivity 0.0005 ohm cm at room temp; heat flow along a-axis; preliminary result. (Measuring temp assumed 25 C).
82	186	Bourdeau, R. G.	1962		288-1033		Similar to above.
83	186	Bourdeau, R. G.	1962		298		Similar to above but heat flow along c-axis and electrical resistivity 0.55 ohm cm at room temp.
84	186	Bourdeau, R. G.	1962		290-1033		Similar to above except electrical resistivity reported as 0.60, 0.51, 0.35, 0.22, and 0.17 ohm cm at 0, 811, 1366, 1922, and 2367 K, respectively.
85	1185	Raytheon Company	1963		437-2425	F-2 PG	Deposited at 2100 C with uncontrolled delaminations; density 2.2 g cm^{-3}; electrical resistivity 0.803 and 0.169 ohm cm at 0 and 1420 C, respectively; heat flow perpendicular to the deposition plane.
86	1185	Raytheon Company	1963		1175-1987	F-2 PG	Similar to above except with controlled delaminations.
87	1185	Raytheon Company	1963		421-1113	PG	Deposited at 1900 C; heat flow perpendicular to the deposition plane.
88	1185	Raytheon Company	1963		451-1153		Deposited at 1850 C; heat flow parallel to the deposition plane.
89	1185	Raytheon Company	1963		434-1205		Deposited at 1900 C; heat flow parallel to the deposition plane.
90	1185	Raytheon Company	1963		372-2218	F-2 PG	Deposited at 2100 C; density 2.2 g cm^{-3}; electrical resistivity 479 and 250 ohm cm at 0 and 1440 C, respectively; heat flow parallel to the deposition plane.
91	1185	Raytheon Company	1963		404-1113	650	0.35 B; deposited at 2000 C; density 2.20 g cm^{-3}; electrical resistivity 6.2 and 4.11 x 10^{-2} ohm cm at room temp and 1250 C, respectively; heat flow perpendicular to the deposition plane.
92	1185	Raytheon Company	1963		423-1173	914	Similar to above except 0.75 B in specimen.
93	1185	Raytheon Company	1963		430-1063	779	1.20 B deposited at 2000 C; density 2.20 g cm^{-3}; electrical resistivity 2.05 and 1.66 x 10^{-2} ohm cm at 45 and 1150 C, respectively; heat flow perpendicular to the deposition plane.
94	1185	Raytheon Company	1963		494-1103	1009	3.5 B; deposited at 1850 C; density 2.18 g cm^{-3}; electrical resistivity 3.5 and 3.0 x 10^{-2} ohm cm at room temp and 1140 C, respectively; heat flow perpendicular to the deposition plane.
95	1185	Raytheon Company	1963		488-1150	1009	Similar to above except heat flow parallel to the deposition plane and electrical resistivity 276 and 371 μohm cm at room temp and 1140 C, respectively.
96	1185	Raytheon Company	1963		332-1168	779	1.2 B; deposited at 2000 C; density 2.20 g cm^{-3}; electrical resistivity 227 and 310 μohm cm at room temp and 1280 C, respectively; heat flow parallel to the deposition plane.
97	1185	Raytheon Company	1963		329-1213	650	0.35 B; deposited at 1850 C; density 2.20 g cm^{-3}; electrical resistivity 300 and 409 μohm cm at room temp and 1250 C, respectively; heat flow parallel to the deposition plane.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
98	1185	Raytheon Company	1963		372-1224	673 PG	Deposited at 2000 C; heat flow parallel to the deposition plane.
99	1393, 1394	Taylor, R., Kelly, B. T., and Gilchrist, K. E.	1968	P	90-1000		Obtained from General Electric Co.; ~0.02 in. in dia and 0.5 in. long; fabricated by deposition at ~2200 C; annealed at 3200 C, cut to size; heat flow parallel to the deposition plane; thermal conductivity values calculated from thermal diffusivity data measured by the heat-pulse method with density and specific heat capacity values taken from literatures.
100	1393, 1394	Taylor, R., et al.	1968	P	100-290	A	The above specimen irradiated in MTR to a dose of 0.02 x 10^{20} fast neutron cm^{-2} at 30 C.
101	1393, 1394	Taylor, R., et al.	1968	P	91-416	1A	The above specimen irradiated in MTR to a dose of 0.83 x 10^{20} fast neutron cm^{-2} at 150 C.
102	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed at 152 C for 2 hrs.
103	1393	Taylor, R., et al.	1968	P	293		The above specimen annealed again at 303 C for 2 hrs.
104	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 398 C for 2 hrs.
105	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 501 C for 2 hrs.
106	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 649 C for 2 hrs.
107	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 908 C for 2 hrs.
108	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 997 C for 2 hrs.
109	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 1097 C for 2 hrs.
110	1393, 1394	Taylor, R., et al.	1968	P	118-696	1A	The above specimen annealed again at 1200 C for 2 hrs.
111*	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 1400 C for 2 hrs.
112*	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 1600 C for 2 hrs.
113*	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 1991 C for 2 hrs.
114*	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 2397 C for 2 hrs.
115*	1393	Taylor, R., et al.	1968	P	293	1A	The above specimen annealed again at 2802 C for 2 hrs.
116	1393, 1394	Taylor, R., et al.	1968	P	96-568	2A	The above specimen irradiated again in MTR to a dose of 3.8 x 10^{20} fast neutron cm^{-2} at 300 C.
117*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed at 300 C for 2 hrs.
118*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 430 C for 2 hrs.
119	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 600 C for 2 hrs.
120	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 802 C for 2 hrs.
121	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 901 C for 2 hrs.
122	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 994 C for 2 hrs.

*Not shown in figure.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
123*	1393	Taylor, R., Kelly, B. T., and Gilchrist, K. E.	1968	P	293	2A	The above specimen annealed again at 1092 C for 2 hrs.
124	1393, 1394	Taylor, R., et al.	1968	P	95-758	2A	The above specimen annealed again at 1200 C for 2 hrs.
125*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 1395 C for 2 hrs.
126*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 1597 C for 2 hrs.
127*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 1992 C for 2 hrs.
128*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 2396 C for 2 hrs.
129*	1393	Taylor, R., et al.	1968	P	293	2A	The above specimen annealed again at 2790 C for 2 hrs.
130	1393, 1394	Taylor, R., et al.	1968	P	87-690	3A	The above specimen irradiated again in MTR to a dose of 4.85 x 10^{20} fast neutron cm^{-2} at 450 C.
131	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed at 449 C for 2 hrs.
132	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 801 C for 2 hrs.
133	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 901 C for 2 hrs.
134*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 995 C for 2 hrs.
135*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 1093 C for 2 hrs.
136	1393, 1394	Taylor, R., et al.	1968	P	86-708	3A	The above specimen annealed again at 1200 C for 2 hrs.
137*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 1397 C for 2 hrs.
138*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 1599 C for 2 hrs.
139*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 1997 C for 2 hrs.
140*	1393	Taylor, R., et al.	1968	P	293	3A	The above specimen annealed again at 2397 C for 2 hrs.
141	1393, 1394	Taylor, R., et al.	1968	P	77-833		Obtained from General Electric Co.; ~0.2 in. in dia and 0.1-0.2 in. thick; fabricated by deposition at ~2200 C; annealed at 3200 C, cut to size; heat flow perpendicular to the deposition plane; thermal conductivity values calculated from thermal diffusivity data measured by the heat-pulse method with density and specific heat capacity values taken from literatures.
142	1393, 1394	Taylor, R., et al.	1968	P	105-297	C	The above specimen irradiated in MTR to a dose of 0.02 x 10^{20} fast neutron cm^{-2} at 30 C.
143	1393, 1394	Taylor, R., et al.	1968	P	96-416	1C	The above specimen irradiated again in MTR to a dose of 0.83 x 10^{20} fast neutron cm^{-2} at 150 C.
144	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed at 154 C for 2 hrs.
145	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 300 C for 2 hrs.
146	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 399 C for 2 hrs.

* Not shown in figure.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
147	1393	Taylor, R., Kelly, B. T., and Gilchrist, K. E.	1968	P	293	1C	The above specimen annealed again at 500 C for 2 hrs.
148	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 602 C for 2 hrs.
149	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 701 C for 2 hrs.
150	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 899 C for 2 hrs.
151	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 1000 C for 2 hrs.
152	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 1094 C for 2 hrs.
153	1393, 1394	Taylor, R., et al.	1968	P	89-924	1C	The above specimen annealed again at 1200 C for 2 hrs.
154	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 1406 C for 2 hrs.
155*	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 1598 C for 2 hrs.
156	1393	Taylor, R., et al.	1968	P	293	1C	The above specimen annealed again at 2003 C for 2 hrs.
157	1393, 1394	Taylor, R., et al.	1968	P	85-925	1C	The above specimen annealed again at 2800 C for 2 hrs.
158	1393, 1394	Taylor, R., et al.	1968	P	86-530	2C	The above specimen irradiated again in MTR to a dose of 3.8×10^{20} fast neutron cm^{-2} at 300 C.
159	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed at 300 C for 2 hrs.
160*	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 452 C for 2 hrs.
161*	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 606 C for 2 hrs.
162	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 805 C for 2 hrs.
163*	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 907 C for 2 hrs.
164	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 995 C for 2 hrs.
165	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 1099 C for 2 hrs.
166	1393, 1394	Taylor, R., et al.	1968	P	88-936	2C	The above specimen annealed again at 1200 C for 2 hrs.
167	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 1410 C for 2 hrs.
168	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 1603 C for 2 hrs.
169*	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 1997 C for 2 hrs.
170*	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 2397 C for 2 hrs.
171	1393	Taylor, R., et al.	1968	P	293	2C	The above specimen annealed again at 2803 C for 2 hrs.
172	1393, 1394	Taylor, R., et al.	1968	P	84-704	3C	The above specimen irradiated again in MTR to a dose of 4.85×10^{20} fast neutron cm^{-2} at 450 C.
173*	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed at 447 C for 2 hrs.
174*	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 802 C for 2 hrs.

*Not shown in figure.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
175*	1393	Taylor, R., Kelly, B. T., and Gilchrist, K. E.	1968	P	293	3C	The above specimen annealed again at 901 C for 2 hrs.
176*	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 997 C for 2 hrs.
177*	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 1099 C for 2 hrs.
178	1393, 1394	Taylor, R., et al.	1968	P	75-920	3C	The above specimen annealed again at 1200 C for 2 hrs.
179	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 1415 C for 2 hrs.
180	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 1598 C for 2 hrs.
181	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 1997 C for 2 hrs.
182*	1393	Taylor, R., et al.	1968	P	293	3C	The above specimen annealed again at 2405 C for 2 hrs.
183	1393, 1394	Taylor, R., et al.	1968	P	93-581		Obtained from General Electric Co.; ~0.2 in. in dia and 0.5 in. long; fabricated by deposition at ~2200 C; annealed at 3200 C, cut to size; irradiated in the Dounreay Fast Reactor to a dose of 1.5 x 10^{22} n cm^{-2} at ~400 C; heat flow parallel to the deposition plane; thermal conductivity values calculated from thermal diffusivity data measured by the heat-pulse method with the density and specific heat capacity values taken from literatures.
184	1393, 1394	Taylor, R., et al.	1968	P	93-782		The above specimen annealed at 1000 C.
185	1393, 1394	Taylor, R., et al.	1968	P	110-674		The above specimen annealed at 2000, 2500, and 3000 C; no difference shown after the annealings.
186	733	Kelly, B. T. and Gilchrist, K. E.	1968	P	114-792		As deposited material obtained from High Temperature Materials, Inc.; cut to 0.2 in. cube; heat flow parallel to the deposition plane; thermal conductivity values calculated from measured thermal diffusivity and density data with specific heat capacity values taken from Taylor, R. (Brit. J. Appl. Phys., 16 (4), 509-15, 1965).
187	733	Kelly, B. T. and Gilchrist, K. E.	1968	P	101-763		Similar to above but specimen heat-treated at 2200 C.
188	733	Kelly, B. T. and Gilchrist, K. E.	1968	P	87-839		Similar to above but specimen heat-treated at 2400 C.
189	733	Kelly, B. T. and Gilchrist, K. E.	1968	P	89-701		Similar to above but specimen heat-treated at 2600 C.
190	733	Kelly, B. T. and Gilchrist, K. E.	1968	P	108-695		Similar to above but specimen heat-treated at 3000 C.
191*	840	Lepie, M. P.	1964	L	423.2		Specimen 0.05 x 0.5 x 0.6 in.; density 2.2 g cm^{-3}; heat flow along a-direction.
192	840	Lepie, M. P.	1964	L	423.2		Similar to the above specimen except heat flow along c-direction.
193	1045	Null, M. R. and Lozier, W. W.	1969	L	2500		Specimen 12.7 mm in dia and 2.80 mm thick; stress annealed; heat flow in the c-direction; thermal conductivity value calculated from the measurement of thermal diffusivity, using specific heat value of Spence, G. B. (WADD Tech. Rept. 61-72, Vol. XLI, Nov. 1963) and density 2.223 g cm^{-3}.
194	874	Maire, J., Gremion, R., Moreau, M., Rappeneau, J., Yvars, M., and Fillartre, A.	1967		296-342	Pyrocarbon	0.0060 cinder, 0.00071 V, 0.0006 Na, 0.00054 Fe, 0.00045 Cl, 0.00030 Ca, 0.0003 Mg, 0.000014 B, 0.000008 Li, 0.00000021 Sm, 0.000000072 Dy, and 0.000000012 Lu; 75 mm dia x 5 mm thick; obtained by cracking hydrocarbon at 2100 C; electrically heated to 2900 C, maintained for 30 min, pressed at 200 kg cm^{-2} in the direction perpendicular to the deposition plane (parallel to crystal c-axis), then heated at 2900 C for 15 min; density 2.26 g cm^{-3}; electrical resistivity 35-45 μohm cm at room temp; measured along a-axis.

* Not shown in figure.

TABLE 33. THERMAL CONDUCTIVITY OF PYROLYTIC GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
195*	874	Maire, J., Gremion, R., Moreau, M., Rappeneau, J., Yvars, M., and Fillartre, A.	1967		295-460	Pyrocarbon	Similar to the above specimen.
196*	874	Maire, J., et al.	1967		298.2	Pyrocarbon	Similar to the above specimen but measured along c-axis; electrical resistivity 0.24-0.50 ohm cm at room temp.
197*	253	Champetier, R. J.	1967	E	1262-3240		Specimen 11 mm in dia and 0.3 mm thick; heat flow along c-axis; measured in a vacuum of $\sim 10^{-6}$ torr.

* Not shown in figure.

875S Graphite

875S graphite* is a medium-grain (0.032 inch maximum) pitch-bonded petroleum-coke-base graphite, which is formed by extrusion into rods 20 or 24 inches in diameter and 72 inches long. It is produced by Speer Carbon Co., with a typical density of 1.67 g cm^{-3} and a typical ash content of 0.7 percent [1349]. There are six curves available for the thermal conductivity of this graphite over the temperature range from 433 to 3708 K.

For the direction perpendicular to the axis of extrusion, the data of Lucks and Deem (curve 1) [862] agree well with those (curves 6, 3, and 4) of Rasor and McClelland [1178]. Curve 6 is the result of measurements made after prolonged heating of the specimen at temperatures greater than 2480 K and thus represents the stable thermal conductivity values at high temperatures. Accordingly, the recommended curve from 433 to 3800 K follows closely the curves 1, 6, 3, and 4.

For the direction parallel to the axis of extrusion, only the data of Fieldhouse, Hedge, and Waterman (curve 2) [430] are available. If a smooth curve is drawn through their data, the resulting curve, together with the recommended curve for the direction perpendicular to the axis of extrusion just obtained above, would give anisotropy ratios of 1.64 at 800 K, 1.52 at 1400 K, and 1.49 at 1800 K. These values of the anisotropy ratio for the thermal conductivity are much greater than the anisotropy ratio of 1.19 for the electrical resistivity of this graphite as reported by Rasor and McClelland [1178]. This is inconsistent with the statement of Rasor and McClelland [1178] that these two anisotropy ratios are approximately the same. Since the data of Lucks and Deem and of Rasor and McClelland for the direction perpendicular to the axis of extrusion are in good agreement, curve 2 is suspected to be too high. This conclusion is further supported by the fact that curve 2 is so high that it approaches or even exceeds some of the curves for the same temperature and direction for pyrolytic graphite and hot-pressed graphites of much greater anisotropy. It is decided therefore that the recommended curve will not follow curve 2.

It is noted that the anisotropy ratio of pitch-bonded graphite above room temperature is generally decreasing with increase in temperature. To give a little weight to curve 2, it is assumed that the anisotropy ratio of this graphite at 3800 K is 1.19, which is the anisotropy ratio of this graphite for the electrical resistivity as reported by Rasor and McClelland [1178], and that the anisotropy ratio decreases by about 10 percent from room temperature to 3800 K. The latter assumption is based upon the anisotropy ratio of ATJ graphite which is also 1.19 at 3800 K as indicated by the derived recommended values and which decreases by about 10 percent from room temperature to 3800 K. Thus the recommended values

* This graphite was previously designated as 7087 graphite.

TABLE 34. Recommended thermal conductivity of 875S graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	∥ to axis of extrusion k	⊥ to axis of extrusion k	T	∥ to axis of extrusion k	⊥ to axis of extrusion k
10	0.00750*	0.00529*	1073.2	0.910	0.706
20	0.0411*	0.0270*	1100	0.898	0.696
30	0.105*	0.0667*	1173.2	0.868	0.673
40	0.199*	0.122*	1200	0.858	0.666
50	0.321*	0.193*	1273.2	0.833	0.646
60	0.465*	0.277*	1300	0.823	0.640
70	0.616*	0.367*	1373.2	0.800	0.623
80	0.772*	0.463*	1400	0.792	0.618
90	0.930*	0.559*	1473.2	0.773	0.603
100	1.09*	0.660*	1500	0.766	0.598
123.2	1.39*	0.880*	1573.2	0.748	0.586
150	1.66*	1.10*	1600	0.742	0.582
173.2	1.82*	1.27*	1673.2	0.725	0.570
200	1.95*	1.39*	1700	0.720	0.567
223.2	1.99*	1.46*	1773.2	0.704	0.556
250	1.99*	1.49*	1800	0.699	0.552
273.2	1.97*	1.49*	1873.2	0.685	0.542
298.2	1.92*	1.46*	1900	0.680	0.540
300	1.92*	1.46*	1973.2	0.667	0.532
323.2	1.87*	1.43*	2000	0.663	0.529
350	1.81*	1.38*	2073.2	0.652	0.522
373.2	1.75*	1.34*	2173.2	0.636	0.512
400	1.69*	1.29*	2200	0.632	0.510
473.2	1.54	1.18	2273.2	0.620	0.502
500	1.49	1.14	2400	0.601	0.490
573.2	1.38	1.04	2473.2	0.590	0.483
600	1.32	1.01	2600	0.571	0.470
673.2	1.22	0.941	2673.2	0.560	0.463
700	1.19	0.918	2800	0.540	0.448
773.2	1.11	0.861	2873.2	0.528	0.439
800	1.09	0.842	3000	0.508	0.421
873.2	1.03	0.795	3073	0.496	0.410
900	1.01	0.781	3200	0.471	0.390
973.2	0.962	0.745	3273	0.454	0.376
1000	0.946	0.734	3400	0.418	0.348
			3600	0.340	0.283
			3800	0.190*	0.160*

†The values at and above room temperature are recommended values for 875S graphite, and those below room temperature are merely typical values.

*Extrapolated.

from room temperature to 3800 K for the direction parallel to the axis of extrusion are calculated from the values for the direction perpendicular to the axis of extrusion according to the assumed values of anisotropy ratio.

Both of the recommended curves have been extensively extrapolated down to 10 K to indicate the general trend of the thermal conductivity of this graphite at moderate and low temperatures. The values at and above room temperature are recommended values and those below room temperature are merely typical values. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

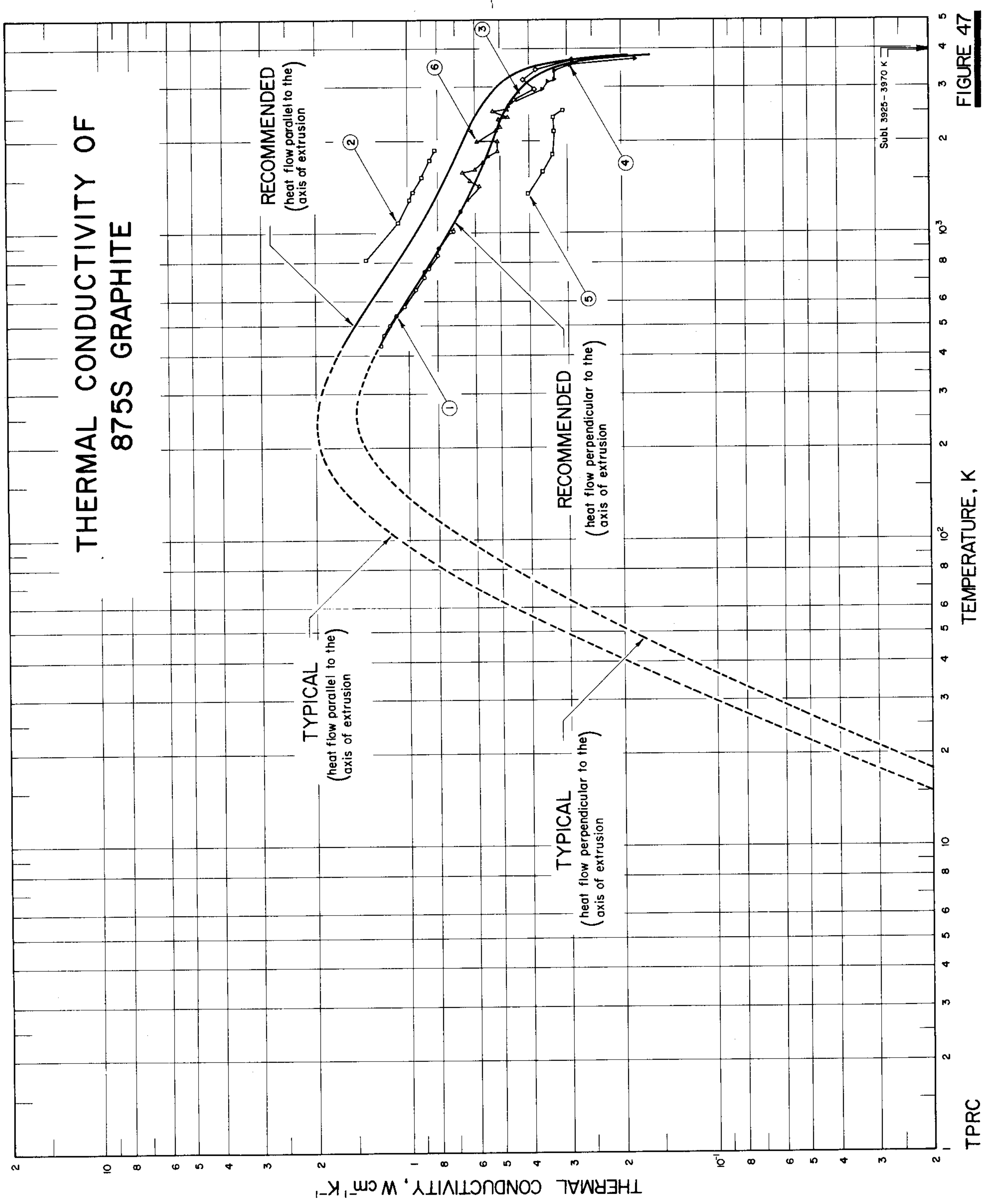

THERMAL CONDUCTIVITY OF
875S GRAPHITE
RECOMMENDED
(heat flow parallel to the axis of extrusion)
RECOMMENDED
(heat flow perpendicular to the axis of extrusion)
TYPICAL
(heat flow parallel to the axis of extrusion)
TYPICAL
(heat flow perpendicular to the axis of extrusion)
Subl. 3925–3970 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 47

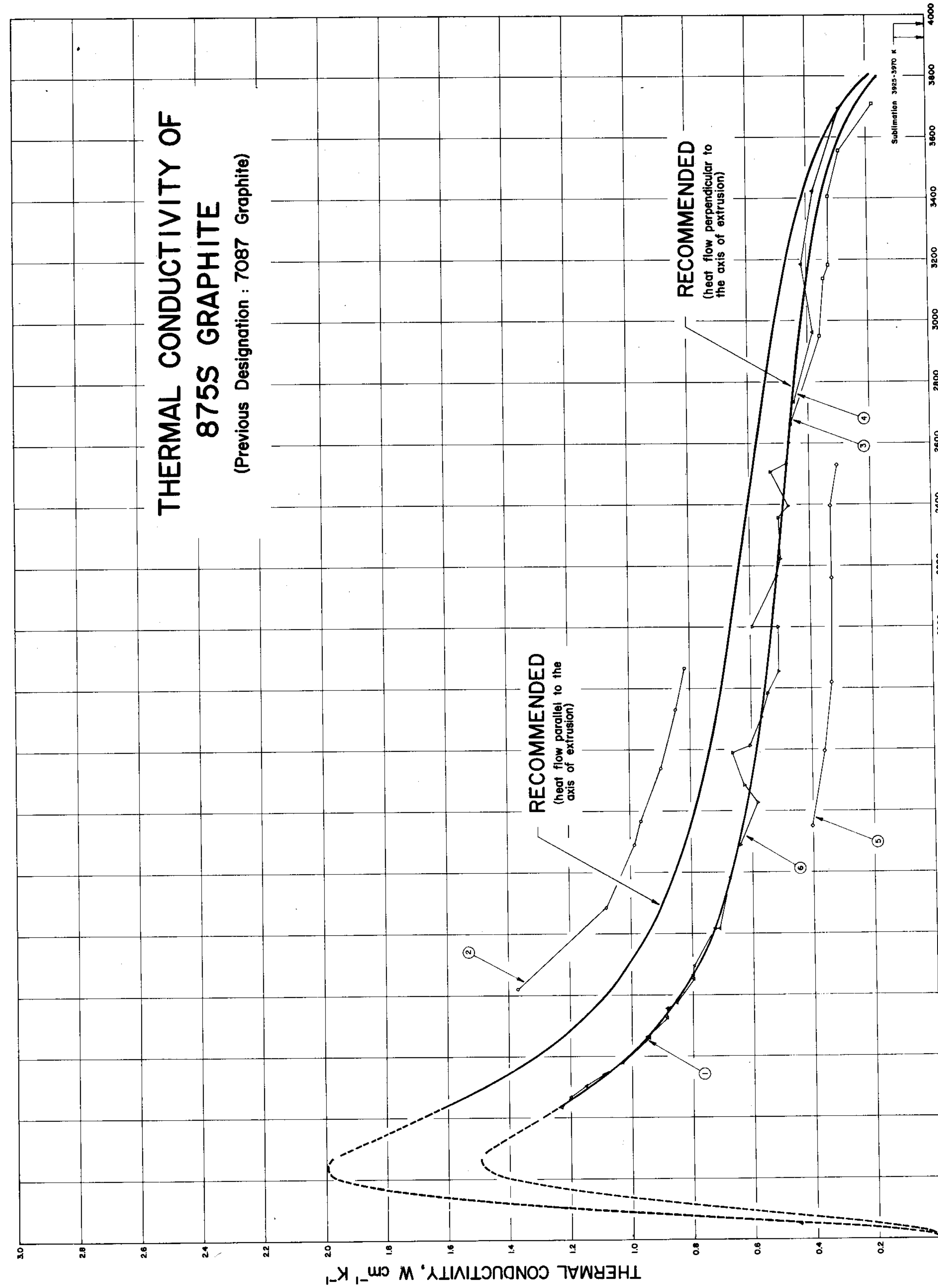

THERMAL CONDUCTIVITY OF
875S GRAPHITE
(Previous Designation : 7087 Graphite)
RECOMMENDED
(heat flow perpendicular to the axis of extrusion)
RECOMMENDED
(heat flow parallel to the axis of extrusion)
Sublimation 3925-3970 K
TEMPERATURE , K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4 2.6 2.8 3.0
1 2 3 4 5 6

FIGURE 48

TABLE 35. THERMAL CONDUCTIVITY OF 875S GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	862	Lucks, C. F. and Deem, H. W.	1956	C	433-1182		Extruded graphite; density 1.71 g cm^{-3}; measured perpendicular to the direction of extrusion; carbon used as comparative material.
2	430	Fieldhouse, I. B., Hedge, J. C., and Waterman, T. E.	1956	L	820-1865		Grade 7087 graphite from Speer Carbon Co.; density 1.698 g cm^{-3}; measured with heat flow parallel to the axis of extrusion.
3	1178	Rasor, N. S. and McClelland, J. D.	1957	R	2661-3708		Extruded; coarse grain with small voids and fissures; specific gravity 1.63; anisotropy ratio (ratio of electrical resistances measured normal and parallel to the extrusion axis) = 1.19; measured normal to the extrusion axis in inert gas at >150 psi pressure.
4	1178	Rasor, N. S. and McClelland, J. D.	1957	R	2733-3694		Rerun of the above specimen with smaller heat rate.
5	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1351-2527		The above specimen measured with heat flow radially inward.
6	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1289-2600		The above specimen measured after prolonged heating at >2200 C.

890S Graphite

890S graphite* is a fine-grain (0.008 inch maximum) pitch-bonded petroleum-coke-base graphite, which is formed by extrusion into rods 2.5 to 8 inches in diameter and 24 to 72 inches long. It is produced by Speer Carbon Company, with typical density 1.63 g cm^{-3} and typical ash content 0.08 percent [1350]. There are six curves available for the thermal conductivity of this graphite over the temperature range from 798 to 3786 K.

For the direction perpendicular to the axis of extrusion, all the three available curves are of Rasor and McClelland [1178]. A curve passing through the mean of their data from 1000 to 3800 K serves as the recommended curve.

For the direction parallel to the axis of extrusion, all the three curves, which cover the temperature range 798 to 1809 K, are of Fieldhouse, Hedge, Lang, Takada, and Waterman [427]. Of these three curves, curve 1, which is for the specimen heated only once, coincides with the curve of Rasor and McClelland. Note, however, that they are for different directions. Curve 2, which is for the specimen heated twice, is higher than curve 1 by about 20 percent, and curve 3, which is for the specimen heated three times, crosses all the curves and is higher than curve 1 by 30 percent at 800 K and lower than Rasor and McClelland's curve by 25 percent at 1800 K. Under this confusing circumstance, a small section of the recommended curve has been drawn through the middle portion of curve 3, using as a guide the general trend of the other recommended curve.

From these two sections of the recommended curves the anisotropy ratio can be calculated and is equal to 1.18 at 1000 K. By assuming that the anisotropy ratio above room temperature decreases linearly with increase in temperature and that at 3800 K it is equal to 1.08, which is the anisotropy ratio for the electrical resistivity of this graphite as reported by Rasor and McClelland [1178], the recommended values from 1000 to 3800 K are obtained by calculation based upon the recommended values already derived for the direction perpendicular to the axis of extrusion.

Both recommended curves have been excessively extrapolated from 1000 K down to 10 K to indicate the general trend of the thermal conductivity of this graphite at moderate and low temperatures. The values at and above room temperature are recommended values and those below room temperature are merely typical values. The uncertainty of the recommended values is probably of the order of ±10 to ±20 percent.

* This graphite was previously designated as 3474D graphite.

TABLE 36. Recommended thermal conductivity of 890S graphite†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	‖ to axis of extrusion k	⊥ to axis of extrusion k	T	‖ to axis of extrusion k	⊥ to axis of extrusion k
10	0.00700*	0.00542*	1073.2	0.764	0.650
20	0.0381*	0.0278*	1100	0.749	0.638
30	0.0961*	0.0687*	1173.2	0.711	0.609
40	0.182*	0.127*	1200	0.699	0.600
50	0.289*	0.200*	1273.2	0.668	0.577
60	0.419*	0.287*	1300	0.659	0.569
70	0.559*	0.379*	1373.2	0.634	0.550
80	0.702*	0.475*	1400	0.626	0.543
90	0.845*	0.574*	1473.2	0.605	0.526
100	0.984*	0.678*	1500	0.597	0.520
123.2	1.27*	0.908*	1573.2	0.579	0.504
150	1.55*	1.15*	1600	0.573	0.498
173.2	1.71*	1.31*	1673.2	0.559	0.484
200	1.83*	1.43*	1700	0.554	0.479
223.2	1.88*	1.49*	1773.2	0.541	0.468
250	1.89*	1.52*	1800	0.536	0.464
273.2	1.87*	1.51*	1873.2	0.524	0.455
298.2	1.83*	1.48*	1900	0.520	0.452
300	1.82*	1.48*	1973.2	0.508	0.443
323.2	1.77*	1.44*	2000	0.504	0.440
350	1.71*	1.40*	2073.2	0.494	0.432
373.2	1.66*	1.36*	2173.2	0.481	0.422
400	1.59*	1.32*	2200	0.477	0.419
473.2	1.43*	1.20*	2273.2	0.467	0.412
500	1.38*	1.15*	2400	0.450	0.399
573.2	1.25*	1.05*	2473.2	0.440	0.392
600	1.21*	1.01*	2600	0.422	0.377
673.2	1.11*	0.933*	2673.2	0.411	0.369
700	1.08*	0.906*	2800	0.392	0.353
773.2	0.998*	0.843*	2873.2	0.380	0.342
800	0.970*	0.821*	3000	0.358	0.320
873.2	0.902	0.768	3073	0.344	0.307
900	0.880	0.749	3200	0.313	0.282
973.2	0.828	0.703	3273	0.293	0.265
1000	0.810	0.687	3400	0.251	0.232
			3600	0.160	0.150
			3800	0.0430*	0.0400*

†The values at and above room temperature are recommended values for 890S graphite, and those below room temperature are merely typical values.

*Extrapolated.

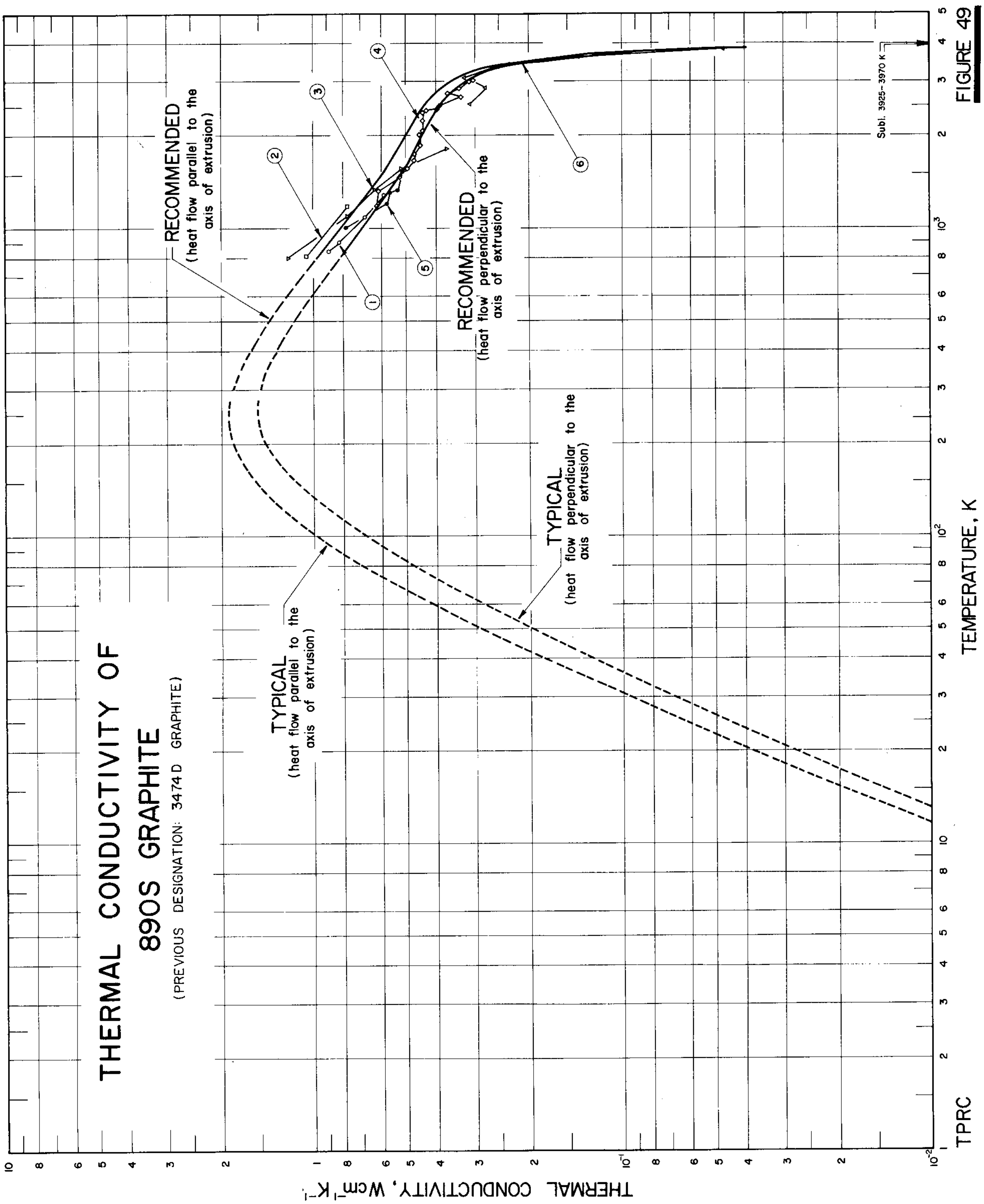

THERMAL CONDUCTIVITY OF
890S GRAPHITE
(PREVIOUS DESIGNATION: 3474 D GRAPHITE)
RECOMMENDED (heat flow parallel to the axis of extrusion)
RECOMMENDED (heat flow perpendicular to the axis of extrusion)
TYPICAL (heat flow parallel to the axis of extrusion)
TYPICAL (heat flow perpendicular to the axis of extrusion)
Subl. 3925–3970 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 49

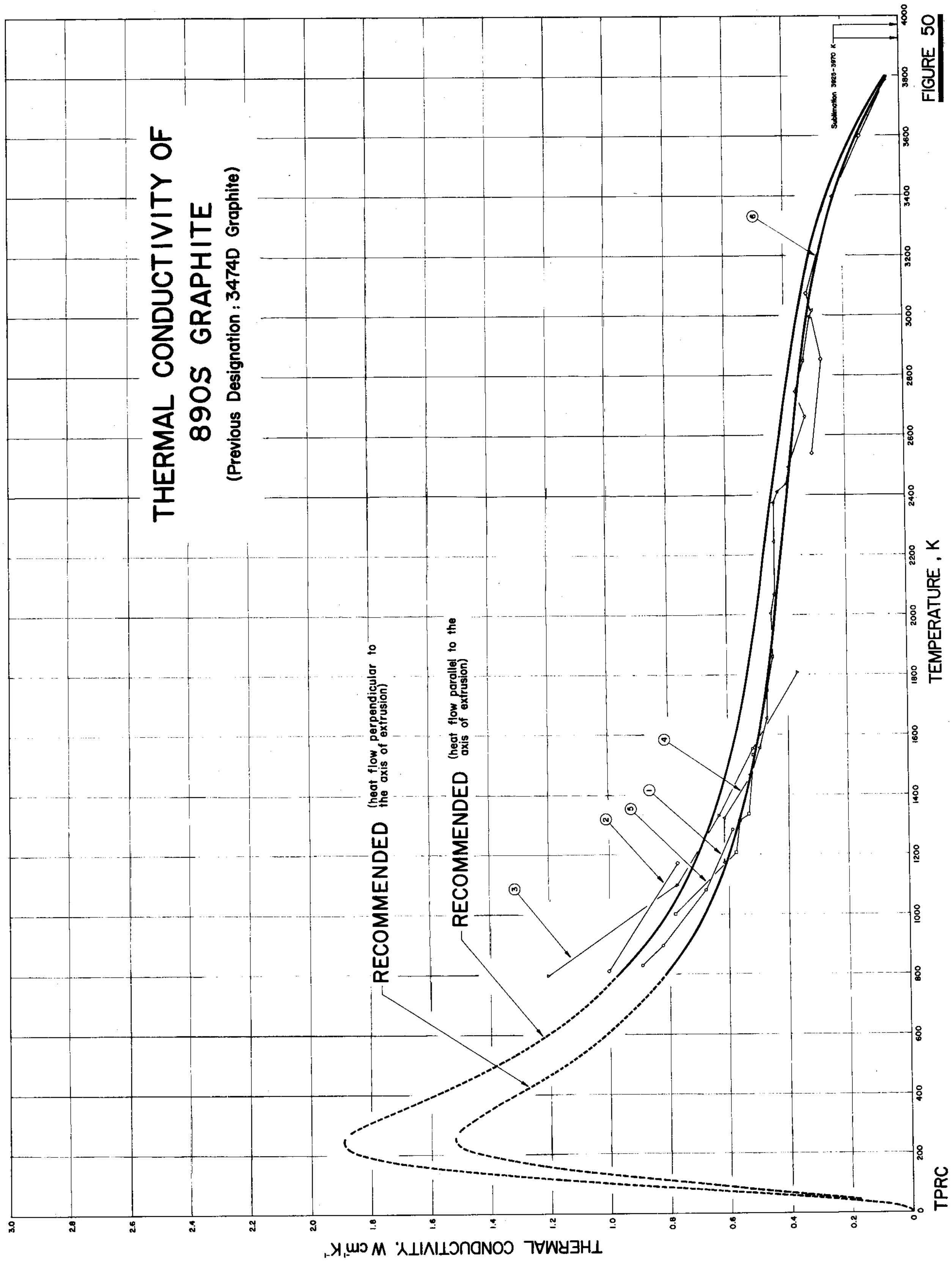

THERMAL CONDUCTIVITY OF
890S GRAPHITE
(Previous Designation: 3474D Graphite)
RECOMMENDED (heat flow perpendicular to the axis of extrusion)
RECOMMENDED (heat flow parallel to the axis of extrusion)
Sublimation 3925–3970 K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 50

TABLE 37. THERMAL CONDUCTIVITY OF 890S GRAPHITE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	427	Fieldhouse, I. B., Hedge, J. C., Lang, J. I., Takata, A. N., and Waterman, T. E.	1956	L	832-1284	1	7 in. dia x 1.5 in. thick; density 1.612 g cm^{-3}; measured with unidirectional heat flow through the disk.
2	427	Fieldhouse, I. B., et al.	1956	L	813, 1172	2	Similar to the above specimen but the specimen being heated twice.
3	427	Fieldhouse, I. B., et al.	1956	L	798-1809	3	Similar to the above specimen but the specimen being heated three times.
4	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1174-3017		Extruded; very fine grained and uniform; specific gravity 1.67; anisotropy ratio 1.08; measured with heat flow radially inward and normal to the extrusion axis; pyrometer used to measure temps; measured in inert gas at >150 psi pressure.
5	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1002-1533		The above specimen measured by using thermocouples to obtain temps.
6	1178	Rasor, N. S. and McClelland, J. D.	1957	R	2540-3786		The above specimen measured with heat flow radially outward and normal to the extrusion axis.

Miscellaneous Graphites

As pointed out in the general discussion of graphites, although there are over 1000 sets of data available for nearly 100 different grades and types of graphites, yet only for seven of them do the available thermal conductivity data cover a range of temperatures wide enough to merit special consideration. The data and information for these seven graphites have been separately presented in the tables and figures for the individual graphites in the preceding subsections. The remaining data and information for the other graphites are grouped together in table 38 and partially presented in figure 51, entitled "Thermal Conductivity of Miscellaneous Graphites."

These data have not been analyzed and no recommendations have been made. It is hoped that further measurements on the thermal conductivity of these and other graphites will cover wide ranges of temperatures so that recommended thermal conductivity values can be generated for a large number of graphites in the future.

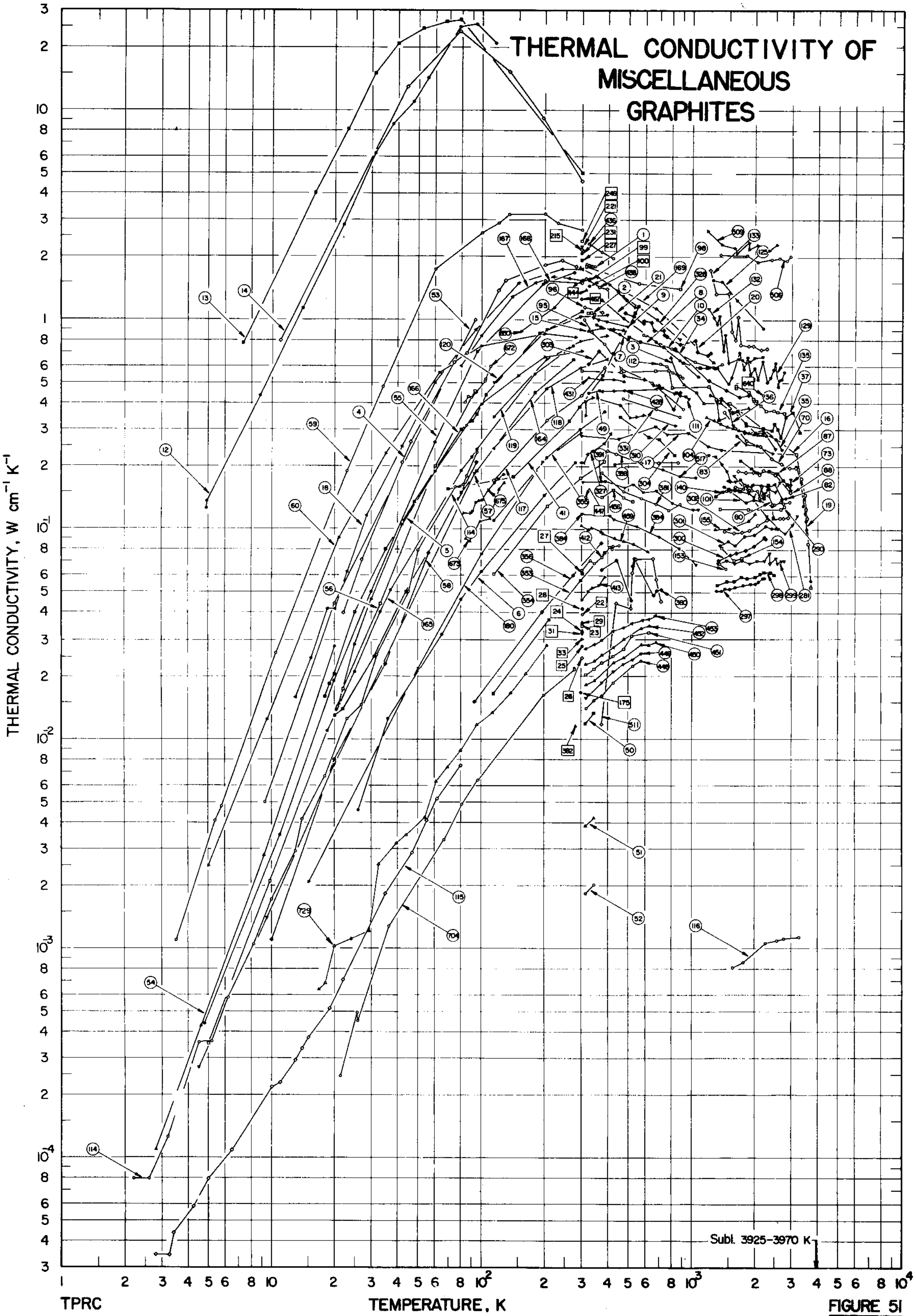

THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TEMPERATURE, K
Subl. 3925–3970 K
TPRC

FIGURE 51

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1167	Raeth, C. H.	1944	L	317-345	1583	Specimen 2.607 cm long and circular cross sectional area 5.068 cm^2; measured lengthwise.
2	1167	Raeth, C. H.	1944	L	321-344	1583	Similar to the above specimen but only 2.523 cm long and measured crosswise.
3	427	Fieldhouse, I. B., Hedge, J. C., Lang, J. L., Takada, A. N., and Waterman, T. E.	1956	L	789-1869	GBE	Specimen 7 in. in dia and 1.5 in. thick; density 1.596 g cm^{-3}; measured with unidirectional heat flow through the disk.
4	1443	Tyler, W. W. and Wilson, A. C., Jr.	1953	L	22-280	Grade CS, Sample A	Grade CS graphite (conventional coke base, pitch bonded and extruded); polycrystal; from National Carbon Co.; bulk density ~1.70 g cm^{-3}; specimen axis perpendicular to the preferred c-axis orientation.
5	1443	Tyler, W. W. and Wilson, A. C., Jr.	1953	L	21-300	Sample C	Polycrystal; natural graphite base, pitch bonded and molded; bulk density ~1.80 g cm^{-3}; specimen axis perpendicular to the preferrred c_0- axis orientation.
6	1443	Tyler, W. W. and Wilson, A. C., Jr.	1953	L	26-280	Sample D	Similar to the above specimen but pitch bonded and molded from lampblack; bulk density ~1.65 g cm^{-3}.
7	1379	Sutton, W. H.	1960	L	351-497	Grade RT-0003 (Sample 1)	Specimen cut from a RT-0003 graphite block (National Carbon Co.); density ~1.90 g cm^{-3}; heat flow perpendicular to grain orientation.
8	1379	Sutton, W. H.	1960	L	500-1294	Grade RT-0003 (Sample 2)	Similar to the above specimen.
9	1379	Sutton, W. H.	1960	L	339-495	Grade RT-0003 (Sample 3)	Similar to the above specimen but heat flow parallel to grain orientation; run No. 1.
10	1379	Sutton, W. H.	1960	L	587-1394	Grade RT-0003 (Sample 3)	Second run of the above specimen.
11*	1379	Sutton, W. H.	1960	L	612-1384	Grade RT-0003 (Sample 3)	Third run of the above specimen.
12	1328, 1329	Smith, A. W. and Rasor, N. S.	1954	C	4.9-116	Canadian Natural graphite	Large crystallite (in the order of 10^{-2} cm); very low ash content; specimen size 0.25 x 0.05 x 0.01 in.; grade AWG graphite used as comparative material.
13	1328, 1329	Smith, A. W. and Rasor, N. S.	1954	C	7.3-300	Canadian Natural graphite	Similar to the above specimen.
14	1328, 1329	Smith, A. W. and Rasor, N. S.	1954	C	11-299	Canadian Natural graphite	Similar to the above specimen.
15	215	Brown, A. R. G., Watt, W., Powell, R. W., and Tye, R. P.	1956	C	323-473	Commercial graphite	High purity; specimen (tubular) 4.5 cm long, 0.95 cm O.D., and 0.75 cm I.D.; density 1.65 g cm^{-3}; electrical resistivity at 20, 50, 100, 150, and 200 C being, respectively, 762, 760, 772, 790, and 816 μohm cm; a bar of iron of known thermal conductivity used as comparative material.
16	409	Euler, J.	1956	E	300-3710	Spektral hohle 1	Large grained artificial graphitized carbon; measured in vacuum.
17	409	Euler, J.	1956	E	300-3710	Spektral hohle 2	Fine grained artificial graphitized carbon; measured in vacuum.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	1177	Rasor, N. S.	1955	E	13-300	Natural Ceylon block	Natural Ceylon graphite; size 0.100 x 0.020 x 1.25 in.; skew orientation.
19	408	Euler, J.	1952	E	3150-3700		Manufactured graphite rod.
20	862	Lucks, C. F. and Deem, H. W.	1956	C	484-1227	Grade GBH	Molded graphite; from National Carbon Co.; density 1.75 g cm^{-3}; measured perpendicular to the direction of molding; Armco iron used as comparative material.
21	762	Kingery, W. D., Francl, J., Coble, R. L., and Vasilos, T.	1954	C	373-1073		Polycrystal; bulk density 1.55 g cm^{-3}; porosity 30.2 %; dense Al_2O_3 used as comparative material.
22	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	Korite	Manufactured from Korite petroleum asphalt (from Standard Oil Co., Indiana) and coke prepared from this asphalt; irradiated by exposing to neutrons of 150 MWD/T (megawatt-days/ ton).
23	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	Korite	The above specimen with neutron exposure of 325 MWD/T.
24	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	Korite	The above specimen with neutron exposure of 830 MWD/T.
25	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	Korite	The above specimen with neutron exposure of 1100 MWD/T.
26	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	Korite	The above specimen with neutron exposure of 4270 MWD/T.
27	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	Made from Cleves coke (Gulf Oil Co.) with standard pitch (Barrett No. 2, medium hard coal tar pitch); purified; exposed to neutrons of 500 MWD/T.
28	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 1000 MWD/T.
29	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 1500 MWD/T.
30*	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 2000 MWD/T.
31	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 2500 MWD/T.
32*	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 3000 MWD/T.
33	443	Fletcher, J. F. and Snyder, W. A.	1957		303.2	CSF	The above specimen with exposure of 3500 MWD/T.
34	430	Fieldhouse, I. B., Hedge, J. C., and Waterman, T. E.	1956	L	829-1866	GBH	Grade GBH graphite from National Carbon Co.; density 1.762 g cm^{-3}; measured with heat flow parallel to the axis of extrusion (should be axis of molding since it was molded).
35	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1220-2700	GBE	Extruded; extremely coarse grained and fragile; voids and fissures up to 0.125 in. in dia; specific gravity 1.57; anisotropy ratio 1.18; measured normal to the extrusion axis in the heating-up period, in inert gas at >150 psi pressure.
36	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1510-2507	GBE	The above specimen in the cooling-down period.
37	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1319-3277	GBH	Molded; very fine grained and uniform; specific gravity 1.77; anisotropy ratio 0.78; measured normal to the molding pressure, in inert gas at >150 psi pressure.
38*	457	Francl, J. and Kingery, W. D.	1954	C	353-1093	Grade CS	Cubic specimen 1 x 1 x 1 in.; density 1.55 g cm^{-3}; dense alumina used as comparative material.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
39*	457	Francl, J. and Kingery, W. D.	1954	C	328-1093	Grade CS	Similar to the above specimen but with cylindrical pores 0.146 cm in dia; porosity 9.8%.
40*	457	Francl, J. and Kingery, W. D.	1954	C	378-1123	Grade CS	Similar to the above specimen but the porosity 19.6%.
41	653	Icole, M.	1912	L	352-828		Specimen 18 mm in dia and 0.79 cm long.
42*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	328.7	Domestic (Japan) No. 1	Artificial graphite electrode; 80 mm dia x 125 mm long; apparent density 1.501 g cm^{-3}; electrical resistivity 0.00108 ohm cm; copper used as comparative material.
43*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	329.7	Domestic (Japan) No. 2	Similar to the above specimen but the apparent density 1.520 g cm^{-3}; electrical resistivity 0.00118 ohm cm.
44*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	326.7	Domestic (Japan) No. 3	Similar to the above specimen but the apparent density 1.533 g cm^{-3}; electrical resistivity 0.00093 ohm cm.
45*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	331.7	Domestic (Japan) No. 4	Similar to the above specimen but the apparent density 1.59 g cm^{-3}; electrical resistivity 0.00085 ohm cm.
46*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	337.2	Domestic (Japan) No. 5	Similar to the above specimen but the apparent density 1.586 g cm^{-3}; electrical resistivity 0.00094 ohm cm.
47*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	344.7	Domestic (Japan) No. 6	Similar to the above specimen but the apparent density 1.591 g cm^{-3}; electrical resistivity 0.00096 ohm cm.
48*	1040	Noguchi, T. and Miyazaki, Y.	1956	C	337.2	Domestic (Japan) No. 7	Similar to the above specimen but the apparent density 1.60 g cm^{-3}; electrical resis- 0.00099 ohm cm.
49	1397	Taylor, T. S.	1920	L	323, 363		Solid specimen 1.04 in. thick; specific gravity 1.56.
50	1397	Taylor, T. S.	1920	L	313, 343		Powder (through 20-mesh on 40-mesh) specimen 0.476 in. thick; specific gravity 0.70.
51	1397	Taylor, T. S.	1920	L	313, 343		Powder (through 40-mesh) specimen 0.476 in. thick; specific gravity 0.42.
52	1397	Taylor, T. S.	1920	L	313, 343		Powder (through 100-mesh) specimen 0.476 in. thick; specific gravity 0.48.
53	1397	Berman, R.	1952	L	9.3-93	I	Artificial graphite; made by extrusion which produced a slight anisotropy; crystal size (perpendicular to c-axis) 2000 Å; density 1.80 g cm^{-3}; electrical resistivity 1.09 and 0.6 milliohm cm at 90 and 290 K, respectively; measured parallel to the axis of extrusion.
54	138	Berman, R.	1952	L	2.8-20	I	Similar to the above specimen but the density 1.78 g cm^{-3}; electrical resistivity 1.76 and 1.09 milliohm cm at 90 and 290 K, respectively; measured perpendicular to the axis of extrusion.
55	138	Berman, R.	1952	L	4.8-275	II	Similar to the above specimen but the crystal size 1000 Å; density 1.60 g cm^{-3}; electrical resistivity at 4, 20, 90, and 290 K being, respecitvely, 2.3, 2.3, 1.7, and 1.08 milliohm cm; measured parallel to the axis of extrusion.
56	138	Berman, R.	1952	L	5-93	II	The above specimen measured perpendicular to the axis of extrusion; electrical resistivity at 4, 29, 90, and 290 K being, respectively, 3.0, 2.9, 2.2, and 1.35 milliohm cm.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
57	138	Berman, R.	1952	L	4.5-93	III	Similar to the above specimen but the crystal size 300 Å; density 1.77 g cm^{-3}; electrical resistivity at 90 and 290 K being 3.01 and 2.33 milliohm cm; measured parallel to the extrusion axis.
58	138	Berman, R.	1952	L	10-95	III	Similar to the above specimen but the density 1.76 g cm^{-3}; electrical resistivity 3.91 and 2.77 milliohm cm at 90 and 290 K respectively; measured perpendicular to the extrusion axis.
59	138	Berman, R.	1952	L	3.5-300	IV	Natural graphite; highly anisotropic; crystal size 2000 Å; density ~2.25 g cm^{-3}; electrical resistivity 1.16, 1.17, 1.21, and 0.98 milliohm cm at 4, 20, 90, and 290 K, respectively; measured perpendicular to the preferred direction of c-axis.
60	138	Berman, R.	1952	L	5.0-280	IV	The above specimen measured parallel to c-axis; electrical resistivity at 4, 20, 90, and 290 K being, respectively, 5.3, 5.4, 5.4, and 4.1 milliohm cm.
61*	138	Berman, R.	1949	L	336.2	AGHT, III	Cylindrical specimen; 3.5 in. dia x 4 in. long; cylinder axis parallel to the extrusion axis.
62*	138	Berman, R.	1949	L	336.2	AGHT, III	Similar to the above specimen but the cylinder axis at right angle to the extrusion axis.
63*	138	Berman, R.	1949	L	339.2	AGHT, III	Similar to the above specimen but the direction of cutting the specimen perpendicular to the above one.
64*	479	Garth, R.C. and Sailor, V.L.	1949	L	343.2	AGHT, IV	Similar to the above specimen but the cylinder axis parallel to the axis of extrusion.
65*	479	Garth, R.C. and Sailor, V.L.	1949	L	337.2	AGHT, IV	Similar to the above specimen but the cylinder axis perpendicular to the extrusion axis.
66*	479	Garth, R.C. and Sailor, V.L.	1949	L	344.2	AGHT, IV	Similar to the above specimen with the cylinder axis perpendicular to the extrusion axis but the direction of cutting the specimen perpendicular to that of the above specimen.
67*	479	Garth, R.C. and Sailor, V.C.	1949	L	343.2	AGHT, VII	Similar to the above specimen but the cylinder axis parallel to the extrusion axis.
68*	479	Garth, R.C. and Sailor, V.C.	1949	L	341.2	AGHT, VII	Similar to the above specimen but the cylinder axis perpendicular to the extrusion axis.
69*	479	Garth, R.C. and Sailor, V.C.	1949	L	344.2	AGHT, VII	Similar to the above specimen with the cylinder axis perpendicular to the extrusion axis but the direction of cutting of the specimen normal to the above one.
70	1008	Mrozowski, S., Andrew, J.F., Juul, N., Strauss, H.E., and Wobschall, D.C.	1961	L	1428-3148	AGSR	Graphite rod from National Carbon Co.; apparent density 1.54 g cm^{-3} (grade AGSR); heat treated to 3100 C; measured at 1 in. Hg above the atmospheric pressure.
71*	1008	Mrozowski, S., et al.	1961	L	1838.2	AGSR	The above specimen measured at a fixed temp to show the effect of pressure (approx from 0 to 60 in. Hg pressure).
72*	1008	Mrozowski, S., et al.	1961	L	2423.2	AGSR	The above specimen measured within the same pressure range but at a higher temp.
73	1008	Mrozowski, S., et al.	1961	L	2973.2	AGSR	The above specimen measured within the same pressure range but at a higher temp.
74*	1008	Mrozowski, S., et al.	1961	L	1838.2	Lab. prepared rod	Made from soft filler-soft binder mixture particles (200/270 mesh size); heat treated to 3100 C; apparent density 1.58 g cm^{-3}; measured in the same pressure range as the above specimen.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
75*	1008	Mrozowski, S., Andrew, J. F., Juul, N., Strauss, H. E., and Wobschall, D. C.	1961	L	2394.2	Lab. prepared rod	The above specimen measured in the same pressure range at a higher temp.
76*	1008	Mrozowski, S., et al.	1961	L	2913.2	Lab. prepared rod	The above specimen measured in the same pressure range at a higher temp.
77*	1008	Mrozowski, S., et al.	1961	L	1829.2	Lab. prepared rod	Made from a soft filler-soft binder mixture; coke (28/35 mesh size) used as filler; very porous; apparent density 1.25 g cm^{-3}; measured in the same pressure range as the above specimen.
78*	1008	Mrozowski, S., et al.	1961	L	2433.2	Lab. prepared rod	The above specimen measured under pressures ranging from 0 to 55.5 in. Hg.
79*	1008	Mrozowski, S., et al.	1961	L	2973.2	Lab. prepared rod	The above specimen measured under pressures ranging from 31 to 55.5 in. Hg.
80	1008	Mrozowski, S., et al.	1961	L	1473-2933	Test Rod No. 1	Material from National Carbon Co.; graphitized to 3000 C; the pressure within the test chamber kept at 1-2 in. Hg above atmospheric pressure by releasing or admitting argon at various temp levels.
81*	1008	Mrozowski, S., et al.	1961	L	1773-2523	Test Rod No. 1	Second run of the above specimen.
82	1008	Mrozowski, S., et al.	1961	L	1478-2968	Test Rod No. 1	Third run of the above specimen.
83	1008	Mrozowski, S., et al.	1961	L	1643-2433	Test Rod No. 2 (U. B. carbon)	Specimen made from 50 parts of Texas Coke (65/100 mesh as the first filler), another 50 parts of Texas Coke (200/270 mesh as the second filler), and 40 parts of M-30 coal tar pitch as the binder; extruded; graphitized to 3000 C; apparent density 1.53 g cm^{-3}; measured in argon atm at 1-2 in. Hg above the atmospheric pressure.
84*	1008	Mrozowski, S., et al.	1961	L	1513-2933	Test Rod No. 2 (U. B. carbon)	Second run of the above specimen.
85*	1008	Mrozowski, S., et al.	1961	L	1983.2	Test Rod No. 2 (U. B. carbon)	Third run of the above specimen.
86*	1008	Mrozowski, S., et al.	1961	L	1638-2448	Test Rod No. 2 (U. B. carbon)	Fourth run of the above specimen.
87	1008	Mrozowski, S., et al.	1961	L	1713-2983	Test Rod No. 3 (U. B. carbon)	Specimen made from 100 parts of 200/270 mesh size Texas Coke as filler, 50 parts of M-30 coal tar pitch as binder; extruded; heat treated to 3000 C; apparent density 1.57 g cm^{-3}; measured in argon atm at 1-2 in. Hg above the atmospheric pressure.
88	1008	Mrozowski, S., et al.	1961	L	1663-2993	Test Rod No. 3 (U. B. carbon)	Second run of the above specimen.
89*	1008	Mrozowski, S., et al.	1961	L	1783-3273	Test Rod No. 4 (U. B. carbon)	Specimen similarly prepared as the above with slight increase in density to 1.58 g cm^{-3}.
90*	1013	National Carbon Co.	1959		298.2	TS-148	Specimen made by National Carbon Co.; baked to 1425 C; typical impurities after baking 0.15 ash and 0.042 H; apparent density 1.682 g cm^{-3}; electrical resistivity 1557 μohm cm; measured with grain.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
91*	1013	National Carbon Co.	1959		298.2	TS-148	Similar to the above specimen but electrical resistivity 2594 μohm cm; measured against grain.
92*	1013	National Carbon Co.	1959		298.2	TS-160	Similar to the above specimen but with 0.13 ash after baking; apparent density 1.685 g cm^{-3}; electrical resistivity 2122 μohm cm; measured with grain.
93*	1013	National Carbon Co.	1959		298.2	TS-160	Similar to the above specimen but measured against grain; electrical resistivity 3006 μohm cm.
94*	1013	National Carbon Co.	1959		298.2	TS-160	Similar to the above specimen but baked to 2800 C; apparent density 1.785 g cm^{-3}; electrical resistivity 1842 μohm cm; measured with grain.
95	1340, 1339	Snyder, T. M. and Kamm, R. L.	1955 1942	L	308-903		Glycerine coated; specimen sandwiched between 2 copper disks; the heater being electrically operated.
96	1340	Snyder, T. M. and Kamm, R. L.	1955	L	308, 373		Similar to the above specimen but being sandwiched between 2 silver disks.
97*	1340	Snyder, T. M. and Kamm, R. L.	1955	C	323.2		Glycerine coated graphite; boiling water used as heater; brass and steel used as comparative materials.
98	1340	Snyder, T. M. and Kamm, R. L.	1955	L	313-873		Long graphite rod used as specimen; intended to eliminate errors due to uneven flow of heat into and out of the specimen.
99	1340	Snyder, T. M. and Kamm, R. L.	1955	C	323.2	Karbate 2	Commercial impregnated graphite; brass used as the comparative material.
100	1340	Snyder, T. M. and Kamm, R. L.	1955	C	323.2	Karbate 22	Similar to the above specimen.
101	1465	VanSant, J. H.	1961	R	1422-2422	Sample A	Limited impregnated graphite normal to the extrusion axis; specimen in the form of a short tube with an outer dia of about 3 in. and a wall thickness of about 0.25 in.; experiment performed in helium for temps <1540 C, for temps higher than this, argon was used instead.
102*	1465	VanSant, J. H.	1961	R	1367-2255	Sample B	Similar to the above specimen but more fully impregnated.
103*	1465	VanSant, J. H.	1961	R	1417-2255	Sample C	Similar to the above specimen.
104	567	Gumenyuk, V. S. and Lebedev, V. V.	1961	E	1173-2273		Spectrally pure; two thin rods each ~1 mm in dia used as the test specimens; annealed in high vacuum at 1700 C for 1 hr; measured in high vacuum.
105*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1193		Measured in a vacuum of 10^{-5} mm Hg; run No. 1.
106*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1185		The above specimen, run No. 2.
107*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1185		The above specimen, run No. 3.
108*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1194		The above specimen, run No. 4.
109*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1189		The above specimen, run No. 5.
110*	270	Childers, H. M. and Cerceo, J. M.	1961	P	1189		The above specimen, run No. 6.
111	98	Atomic International Div., N. American Aviation, Inc.	1960	R	653-963	LBR (grade TSP)	Nuclear graphite grade TSP from Nat. Carbon Co.; irradiated with 5 x 10^{20} neutron cm^{-2} at about 315 C.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
112	98	Atomic International Div., N. American Aviation, Inc.	1960	R	703-898	LBR (grade TSP)	The above specimen annealed in vacuum at 1000 C for 1 hr.
113*	98	Atomic International Div., N. American Aviation, Inc.	1960	R	723-898	LBR (grade TSP)	The above specimen before irradiation and not annealed.
114	1605	Zavaritskii, N. V. and Zeldovich, A.	1956	L	2.2-95	AUG-4	Resin bonded graphite; annealed to 2000 C.
115	1605	Zavaritskii, N. V. and Zeldovich, A.	1956	L	2.8-80	AUG-3	Resin bonded graphite; annealed to 1500 C.
116	718	Kasatochkin, V. I., Zamoluev, V. K., Kaverov, A. T., and Usenbaev, K.	1960	P	1573-3273	Graphitized carbon black	99.65 C, 0.27 H, 0.08 O, and 0.01 ash; particle size <1 μ; heat treated at 2500 C for 30 min (equivalent to a degree of graphitization of 0.77).
117	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Polycrystalline; made from 69.14% Kendall Coke (soft type carbon), 29.17% medium grade coal tar pitch, and 1.43% Vacwax 80 (from Socony Vacuum Oil Co.); extruded; baked for 5 days to 1100 C; density after baking, 1.49 g cm^{-3}; heat treated again to 2100 C; crystallite dia 98 Å.
118	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Similar to the above specimen but heat treated to 2200 C; crystallite dia 128 Å.
119	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Similar to the above specimen but heat treated to 2300 C; crystallite dia 184 Å.
120	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Similar to the above specimen but heat treated to 2430 C; crystallite dia 290 Å.
121*	200	Breckenridge, R. G. (Project Coordinator)	1960		1170-2450	Sample No. 1 (R-0008)	Grade R-0008 (a high quality graphite).
122*	200	Breckenridge, R. G. (Project Coordinator)	1960		1170-2600	Sample No. 2 (R-0008)	Similar to the above specimen.
123*	200	Breckenridge, R. G. (Project Coordinator)	1960		1115-2725	Sample No. 3 (R-0008)	Similar to the above specimen.
124*	612	Hoch, M. and Vardi, J.	1962	→	1260-2199	ZT type graphite; G-5, G-9	Thermal conductivity data in the z-direction (k_z) determined simultaneously with thermal conductivity in the r-direction (k_r) (see next curve) from 4 cylindrical specimens made from ZT type graphite of National Carbon Co.; density 2.00 g cm^{-3}; anisotropy ratio of electrical resistivity ρ(z-direction)/ρ(r-direction) = 2.86 at room temp; the specimens each about 2.54 cm in dia and about 0.3-0.6 cm thick; during measurement the specimens were heated in vacuum by high frequency induction; thermal conductivity determined by equating the heat conduction in specimen to the heat loss by radiation assuming the emissivity of a gray body, the analysis required 2 specimens of different thickness to solve simultaneously for k_z and k_r at a certain temp.
125	612	Hoch, M. and Vardi, J.	1962	→	1260-2199	ZT type graphite; G-5, G-9	k_r determined simultaneously with the above curve.
126*	701	Juul, N., Sato, S., and Strauss, H. E.	1963	L	1353-2303		Made from soft filler and hard binder carbon; heat treated to 2100 C for 15 min.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
127*	701	Juul, N., et al.	1963	L	1383-2583		The above specimen heat treated to 2400 C for 15 min.
128*	1088	Pike, J. N.	1963	E	1170-2340	ZT type; No. 1	Specimen 7 cm long, 1 cm wide and 1 mm thick; made by molding a selected coke-base mixture in one particular direction; impregnated and pressed at high temps; all surfaces milled, slightly sand blasted; apparent density 2.15 g cm^{-3}; measured approx parallel to the grain direction with a tilt angle of 8.1 degrees; room temp anisotropy in electrical resistivity $\approx$7.0; electrical resistivity 2.50, 2.49, 2.49, 2.47, 2.45, 2.43, 2.42, 2.40, 2.43, 2.47, and 2.51 milliohm cm at 1100, 1300, 1811, 1867, 1955, 2023, 2153, 2247, 2379, 2532, 2645, and 2785 K, respectively.
129	1088	Pike, J. N.	1963	E	1180-2760	ZT type; No. 1	Second run of the above specimen.
130*	1088	Pike, J. N.	1963	E	1180-2400	ZT type; No. 2	Similar to the above specimen but measured perpendicular to the grain direction with a tilt angle of 8.1 degrees; electrical resistivity 0.372, 0.39, 0.410, 0.425, 0.456, 0.485, 0.498, and 0.510 milliohm cm at 1100, 1320, 1500, 1665, 1964, 2274, 2428, and 2563 K, respectively.
131*	1088	Pike, J. N.	1963	E	1180-2350	ZT type; No. 2	Second run of the above specimen.
132	1088	Pike, J. N.	1963	E	1200-2180	ZT type; No. 3	Similar to the above specimen but measured parallel to the grain direction with a tilt angle of 8.1 degrees; electrical resistivity 2.50, 2.49, 2.48, 2.47, 2.44, 2.41, 2.39, 2.37, 2.36, 2.37, 2.40, and 2.42 milliohm cm at 1216, 1395, 1617, 1758, 1868, 1960, 2071, 2230, 2389, 2479, 2624, and 2726 K, respectively.
133	1088	Pike, J. N.	1963	E	1220-2280	ZT type; No. 4	Similar to the above specimen but electrical resistivity 0.416, 0.445, 0.460, 0.480, 0.501, 0.522, and 0.538 milliohm cm at 1232, 1476, 1593, 1758, 1952, 2127, and 2261 K, respectively.
134*	1088	Pike, J. N.	1963	E	1220-2630	ZT type; No. 5	Similar to the above specimen but with different dimensions of 7 x 6 x 0.1 cm; measured perpendicular to the grain direction with a tilt angle of 8.1 degrees; electrical resistivity 0.429, 0.440, 0.450, 0.463, 0.472, 0.483, 0.492, 0.500, 0.516, 0.523, 0.527, 0.531, 0.536, 0.543, and 0.560 milliohm cm at 1225, 1309, 1401, 1591, 1684, 1778, 1880, 1998, 2214, 2351, 2403, 2442, 2486, 2523, and 2609 K, respectively.
135	1498	Wagner, P., Driesner, A. R., and Kmetko, E. A.	1958	L	1623-2773	H4LM graphite	Specimen 8 in. long and 0.5 in. in dia; density 1.72 g cm^{-3}; heat flow parallel to grain; zero uranium content.
136*	1498	Wagner, P., et al.	1958	L	1593-2823	LDH graphite	Specimen 8 in. long and 0.5 in. in dia; density 1.73 g cm^{-3}; heat flow parallel to grain; uranium content 0.125 mg cm^{-3} of carbon.
137*	1498	Wagner, P., et al.	1958	L	1623-2823	CK graphite	Specimen 8 in. long and 0.5 in. in dia; density 1.71 g cm^{-3}; heat flow parallel to grain; zero uranium content.
138*	1498	Wagner, P., et al.	1958	L	1653-2823	LDC graphite	Specimen 8 in. long and 0.5 in. in dia; density 1.66 g cm^{-3}; heat flow parallel to grain; uranium content 0.250 mg cm^{-3} of carbon.
139*	198	Breckenridge, R. G.	1959	E	1300-2200	Boronated graphite	Rectangular specimen 0.1 x 1 x 10 cm (after extrusion and baking at 3273 K); cut from the portion near the parent rod center; the rod being made of a mixture of lampblack, coke, boron carbide, and pitch with a boron content of 1.3% and specific gravity of 1.79.
140	198	Breckenridge, R. G.	1959	E	1300-2465	Boronated graphite	Similar to above specimen but cut from the central portion of the parent rod.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
141	198	Breckenridge, R. G.	1959	E	1300-2200	Boronated graphite	Similar to above specimen but cut from the portion near the center of the parent rod.
142	1007	Mrozowski, S., Andrew, J. F., Juul, N., Strauss, H. E., Tsuzuku, T., and Wobschall, D. C.	1962	R	1513-2048		Extruded test rod made from a mixture of 100 parts of soft filler coke particles (200/270 mesh) and 50 parts of M-30 soft binder, baked and heat treated to 3273 K; apparent density 1.54 g cm^{-3}.
143	1007	Mrozowski, S., et al.	1962	R	1533-1933		The above specimen, run 2.
144	1007	Mrozowski, S., et al.	1962	R	1653-2393		The above specimen, run 3.
145	1007	Mrozowski, S., et al.	1962	R	1833-3268		The above specimen, run 4.
146	1007	Mrozowski, S., et al.	1962	R	1833-2743		The above specimen, run 5.
147	1007	Mrozowski, S., et al.	1962	R	1683-1963		The above specimen, run 6.
148	1007	Mrozowski, S., et al.	1962	R	1643-1703		Test rod made from 100 parts of soft coke (50 parts 65/100 mesh and 50 parts 200/270 mesh) and 35 parts of hard binder, baked and graphitized to a temp of 3273 K prior to testing; apparent density 1.65 g cm^{-3}.
149	1007	Mrozowski, S., et al.	1962	R	1643-2013		The above specimen, run 2.
150	1007	Mrozowski, S., et al.	1962	R	1753-2453		The above specimen, run 3.
151*	1007	Mrozowski, S., et al.	1962	R	1683-2093		The above specimen, run 4.
152*	1007	Mrozowski, S., et al.	1962	R	1643-2123		The above specimen, run 5.
153	1007	Mrozowski, S., et al.	1962	R	1363-1453	U. B. Graphite	Carbon rod sample extruded from a soft filler, soft binder mixture, baked to a temp of 1273 K; heat treated at 1473 K.
154	1007	Mrozowski, S., et al.	1962	R	1393-1733	U. B. Graphite	Similar to above specimen except heat treated at 1773 K.
155	1007	Mrozowski, S., et al.	1962	R	1293-2013	U. B. Graphite	Similar to above specimen except heat treated at 2073 K.
156*	1007	Mrozowski, S., et al.	1962	R	1393-2333	U. B. Graphite	Similar to above specimen except heat treated at 2373 K.
157*	1007	Mrozowski, S., et al.	1962	R	1393-2603	U. B. Graphite	Similar to above specimen except heat treated at 2673 K.
158*	1007	Mrozowski, S., et al.	1962	R	1403-2933	U. B. Graphite	Similar to above specimen except heat treated at 2773 K.
159*	1007	Mrozowski, S., et al.	1962	R	1293-3093	U. B. Carbon	Carbon rod sample extruded from a misutre of soft filler and hard binder, baked and graphitized to a temp of 3373 K.
160*	1007	Mrozowski, S., et al.	1962	R	1603-3073	U. B. Carbon	The above specimen, run 2.
161*	1007	Mrozowski, S., et al.	1962	R	1413-3103	U. B. Carbon	The above specimen, run 3.
162*	1007	Mrozowski, S., et al.	1962	R	1513-3153	U. B. Carbon	The above specimen, run 4.
163*	1007	Mrozowski, S., et al.	1962	R	1953-2953	U. B. Carbon	The above specimen, run 5.
164	190	Bowman, J. C., Krumhansl, J. A., and Meers, J. T.	1958	L	20-273	C-15	Specimen prepared from petroleum-coke base, molded with coal-tar pitch binder, baked at 2673 K, equivalent bromine residue 0.75 weight percent; measurements made under high vacuum.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
165	190	Bowman, J.C., Krumhansl, J.A., and Meers, J.T.	1958	L	18.5-273	C-15	Similar to the above specimen but baked at 2873 K and with an equivalent bromine residue of 0.5%.
166	190	Bowman, J.C., et al.	1958	L	18-300	C-15	Similar to the above specimen but baked at 3073 K and with an equivalent bromine residue of 0.25%.
167	381	Durand, R.E. and Klein, D.J.	1956	R	80-300	CSF-MTR	Virgin 10 mil sample.
168	381	Durand, R.E. and Klein, D.J.	1956	R	200,300	CSF-MTR	Virgin 20 mil sample.
169	1310	Sibley, L.B., Allen, C.M., Zielenbach, C.L., Peterson, C.L., and Goldthwaite, W.H.	1958		293-1273		Impervious graphite.
170*	367	Downey, H.A. and Micinski, E.	1948		1273,1873	EBP	Rectangular block; 24 x 20 x 6 in.; molded; baked; cut at an angle to give both against and with the grain orientation.
171*	367	Downey, H.A. and Micinski, E.	1948		1273,1873	AUC	Rod; 12 in. in dia; extruded; baked; specially cut to give an across-grain orientation.
172*	367	Downey, H.A. and Micinski, E.	1948		1273,1873	CS-312	Similar to the above specimen.
173*	367	Downey, H.A. and Micinski, E.	1948		1273,1873	C-18	Rectangular block; 24 x 20 x 6 in.; molded; baked; cut at angle to give both against and with the grain orientation.
174*	367	Downey, H.A. and Micinski, E.	1948		1273,1873	L-117	Rod; 3 in. in dia; extruded; baked; specially cut to give an across-grain orientation.
175	367	Piper, E.L.	1955		298.2	Porous-40	Molded; baked at 1000 C; specially cut to give with the grain orientation.
176*	367	Piper, E.L.	1955		298.2	Porous-60	Similar to the above specimen.
177*	367	Piper, E.L.	1955		298.2	255	Molded; baked.
178*	367	Piper, E.L.	1955		298.2	CS-112	Rod; 1.125 in. in dia; extruded; baked; specially cut to give with the grain orientation.
179*	367	Gardner, L.	1955		1355-2303	CS-312	Similar to the above specimen but the dia 12 in.
180	367	Meers, J.T.	1956		15.2-296	CEQ	Rectangular block; 6 x 5 x 3 in.; molded; baked; specially cut to give with the grain orientation.
181*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Graphite stocks 1-2.75 in. in dia; grain size 0.016 in.; bulk density 1.58 g cm^{-3}; electrical resistivity 839 μohm cm; with grain orientation.
182*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Similar to the above but electrical resistivity 1500 μohm cm; across grain orientation.
183*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Graphite stocks 3-5.75 in. in dia; grain size 0.03; bulk density 1.58 g cm^{-3}; electrical resistivity 864 μohm cm; with grain orientation.
184*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Similar to the above but electrical resistivity 1280 μohm cm; across grain orientation.
185*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Graphite stocks 6-12 in. in dia; grain size 0.06 in; bulk density 1.57 g cm^{-3}; electrical resistivity 885 μohm cm; with grain orientation.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
186*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Similar to the above but electrical resistivity 1110 μohm cm; across grain orientation.
187*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Graphite stocks 14-35 in. in dia; grain size 0.25 in.; bulk density 1.54 g cm^{-3}; electrical resistivity 965 μohm cm; with grain orientation.
188*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSR	Similar to the above but electrical resistivity 1130 μohm cm; across grain orientation.
189*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGA	Graphite stocks 35 in. in dia; grain size 0.5 in.; bulk density 1.65 g cm^{-3}; electrical resistivity 1040 μohm cm; with grain orientation.
190*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGA	Similar to the above but electrical resistivity 1090 μohm cm; across grain orientation.
191*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Graphite stocks 1-2.75 in. in dia; grain size 0.016 in.; bulk density 1.67 g cm^{-3}; electrical resistivity 799 μohm cm; with grain orientation.
192*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Similar to the above but electrical resistivity 1330 μohm cm; across grain orientation.
193*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Graphite stocks 3-5.75 in. in dia; grain size 0.03 in.; bulk density 1.69 g cm^{-3}; electrical resistivity 821 μohm cm; with grain orientation.
194*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Similar to the above but electrical resistivity 1390 μohm cm; across grain orientation.
195*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Graphite stocks 6-12 in. in dia; grain size 0.06 in.; bulk density 1.71 g cm^{-3}; electrical resistivity 820 μohm cm; with grain orientation.
196*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AGSX	Similar to the above but electrical resistivity 1010 μohm cm; across grain orientation.
197*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CS	Graphite stocks 1-2.75 in. in dia; grain size 0.016 in.; bulk density 1.68 g cm^{-3}; electrical resistivity 819 μohm cm; with grain orientation.
198*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CS	Similar to the above but electrical resistivity 1310 μohm cm; across grain orientation.
199*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CS	Graphite stocks 3-18 in. in dia; grain size 0.03 in.; bulk density 1.72 g cm^{-3}; electrical resistivity 860 μohm cm; with grain orientation.
200*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CS	Similar to the above but electrical resistivity 1100 μohm cm; across grain orientation.
201*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	ATL	Graphite stocks 20-24 in. in dia; grain size 0.03 in.; bulk density 1.70 g cm^{-3}; electrical resistivity 890 μohm cm; with grain orientation.
202*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	ATL	Similar to the above but electrical resistivity 1070 μohm cm; across grain orientation.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
203*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	ATL	Graphite stocks 30-50 in. in dia; grain size 0.03 in.; bulk density 1.78 g cm^{-3}; electrical resistivity 1130 μohm cm; with grain orientation.
204*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	ATL	Similar to the above but electrical resistivity 1180 μohm cm; across grain orientation.
205*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AUC	Graphite stocks 1-8 in. in dia; grain size 0.016 in.; bulk density 1.68 g cm^{-3}; electrical resistivity 790 μohm cm; with grain orientation.
206*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AUC	Similar to the above but electrical resistivity 1230 μohm cm; across grain orientation.
207*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AUC	Graphite stocks 9-18 in. in dia; grain size 0.03 in.; bulk density 1.69 g cm^{-3}; electrical resistivity 767 μohm cm; with grain orientation.
208*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	AUC	Similar to the above but electrical resistivity 978 μohm cm; across grain orientation.
209*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CEQ	Graphite stock size 6 x 5 x 2.875 in.; grain size 0.008 in.; bulk density 1.55 g cm^{-3}; electrical resistivity 5029 μohm cm; with grain orientation.
210*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CDA	Graphite stock size 6 x 5 x 2.6875 in.; grain size 0.006 in.; bulk density 1.62 g cm^{-3}; electrical resistivity 1072 μohm cm; with grain orientation.
211*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CDA	Similar to the above but electrical resistivity 1640 μohm cm; across grain orientation.
212*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CDG	Graphite stocks size 12 x 12 x 0.25 to 12 x 12 x 1 in.; grain size 0.016 in.; bulk density 1.36 g cm^{-3}; electrical resistivity 1351 μohm cm; with grain orientation.
213*	367	Industrial Graphite Eng. Handbook, National Carbon Co.	1962		298.2	CDG	Similar to the above but the sizes 15 x 18 x 0.25 to 15 x 18 x 2 in.; bulk density 1.40 g cm^{-3}; electrical resistivity 1522 μohm cm.
214*	367	Barratt, T.	1914		290, 373	Pencil lead graphite	Cylindrical rod; 0.183 cm in dia, 10.4 cm long; specific gravity 2.11; specimen made from a "Kohinor" pencil lead grade 6H.
215	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.940 g cm^{-3}; electrical resistivity 6.97 x 10^{-4} ohm cm; with grain.
216*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.940 g cm^{-3}; electrical resistivity 21.87 x 10^{-4} ohm cm; across grain.
217*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.924 g cm^{-3}; electrical resistivity 7.24 x 10^{-4} ohm cm; with grain.
218*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.924 g cm^{-3}; electrical resistivity 21.90 x 10^{-4} ohm cm; across grain.
219*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.953 g cm^{-3}; electrical resistivity 6.91 x 10^{-4} ohm cm; with grain.
220*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.953 g cm^{-3}; electrical resistivity 23.18 x 10^{-4} ohm cm; across grain.
221	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.942 g cm^{-3}; electrical resistivity 6.70 x 10^{-4} ohm cm; with grain.
222*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.942 g cm^{-3}; electrical resistivity 18.95 x 10^{-4} ohm cm; across grain.
223*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.955 g cm^{-3}; electrical resistivity 6.87 x 10^{-4} ohm cm; with grain.
224*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.955 g cm^{-3}; electrical resistivity 22.04 x 10^{-4} ohm cm; across grain.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
225*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.923 g cm^{-3}; electrical resistivity 7.07 x 10^{-4} ohm cm; with grain.
226*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.923 g cm^{-3}; electrical resistivity 22.67 x 10^{-4} ohm cm; across grain.
227	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.932 g cm^{-3}; electrical resistivity 7.43 x 10^{-4} ohm cm; with grain.
228*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.932 g cm^{-3}; electrical resistivity 16.09 x 10^{-4} ohm cm; across grain.
229*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.92 g cm^{-3}; electrical resistivity 7.76 x 10^{-4} ohm cm; with grain.
230*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.92 g cm^{-3}; electrical resistivity 16.45 x 10^{-4} ohm cm; across grain.
231	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.93 g cm^{-3}; electrical resistivity 7.54 x 10^{-4} ohm cm; with grain.
232*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.93 g cm^{-3}; electrical resistivity 15.84 x 10^{-4} ohm cm; across grain.
233*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.95 g cm^{-3}; electrical resistivity 6.66 x 10^{-4} ohm cm; with grain.
234*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.95 g cm^{-3}; electrical resistivity 15.82 x 10^{-4} ohm cm; across grain.
235*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.94 g cm^{-3}; electrical resistivity 7.42 x 10^{-4} ohm cm; with grain.
236*	377	Dull, R. B.	1964	L	298.2	ZTA	Bulk density 1.94 g cm^{-3}; electrical resistivity 16.18 x 10^{-4} ohm cm; across grain.
237*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.98 g cm^{-3}; electrical resistivity 6.68 x 10^{-4} ohm cm; with grain.
238*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.98 g cm^{-3}; electrical resistivity 19.74 x 10^{-4} ohm cm; across grain.
239*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.97 g cm^{-3}; electrical resistivity 6.96 x 10^{-4} ohm cm; with grain.
240*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.97 g cm^{-3}; electrical resistivity 17.81 x 10^{-4} ohm cm; across grain.
241*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.99 g cm^{-3}; electrical resistivity 6.43 x 10^{-4} ohm cm; with grain.
242*	377	Dull, R. B.	1964	L	298.2	ZTB	Bulk density 1.99 g cm^{-3}; electrical resistivity 21.13 x 10^{-4} ohm cm; across grain.
243*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.93 g cm^{-3}; electrical resistivity 6.97 x 10^{-4} ohm cm; with grain.
244*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.93 g cm^{-3}; electrical resistivity 11.97 x 10^{-4} ohm cm; across grain.
245*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.92 g cm^{-3}; electrical resistivity 7.15 x 10^{-4} ohm cm; with grain.
246*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.92 g cm^{-3}; electrical resistivity 11.00 x 10^{-4} ohm cm; across grain.
247*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.94 g cm^{-3}; electrical resistivity 6.90 x 10^{-4} ohm cm; with grain.
248*	377	Dull, R. B.	1964	L	298.2	ZTC	Bulk density 1.94 g cm^{-3}; electrical resistivity 13.21 x 10^{-4} ohm cm; across grain.
249	377	Dull, R. B.	1964	L	298.2	ZTD	Bulk density 2.01 g cm^{-3}; electrical resistivity 5.41 x 10^{-4} ohm cm; with grain.
250*	377	Dull, R. B.	1964	L	298.2	ZTD	Bulk density 2.01 g cm^{-3}; electrical resistivity 7.88 x 10^{-4} ohm cm; across grain.
251*	377	Dull, R. B.	1964	L	298.2	ZTE	Bulk density 1.96 g cm^{-3}; electrical resistivity 8.94 x 10^{-4} ohm cm; with grain.
252*	377	Dull, R. B.	1964	L	298.2	ZTE	Bulk density 1.96 g cm^{-3}; electrical resistivity 20.40 x 10^{-4} ohm cm; across grain.
253*	377	Dull, R. B.	1964	L	298.2	ZTF	Bulk density 1.99 g cm^{-3}; electrical resistivity 7.31 x 10^{-4} ohm cm; with grain.
254*	377	Dull, R. B.	1964	L	298.2	ZTF	Bulk density 1.99 g cm^{-3}; electrical resistivity 20.50 x 10^{-4} ohm cm; across grain.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
255*	377	Dull, R. B.	1964	L	298.2	ZTF	Bulk density 1.99 g cm^{-3}; electrical resistivity 7.24 x 10^{-4} ohm cm; with grain.
256*	377	Dull, R. B.	1964	L	298.2	ZTF	Bulk density 1.99 g cm^{-3}; electrical resistivity 21.48 x 10^{-4} ohm cm; across grain.
257*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.84 g cm^{-3}; electrical resistivity 12.21 x 10^{-4} ohm cm; with grain.
258*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.84 g cm^{-3}; electrical resistivity 15.73 x 10^{-4} ohm cm; across grain.
259*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.825 g cm^{-3}; electrical resistivity 12.25 x 10^{-4} ohm cm; with grain.
260*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.825 g cm^{-3}; electrical resistivity 16.87 x 10^{-4} ohm cm; across grain.
261*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.842 g cm^{-3}; electrical resistivity 12.34 x 10^{-4} ohm cm; with grain.
262*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.842 g cm^{-3}; electrical resistivity 15.20 x 10^{-4} ohm cm; across grain.
263*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.844 g cm^{-3}; electrical resistivity 12.06 x 10^{-4} ohm cm; with grain.
264*	377	Dull, R. B.	1964	L	298.2	RVA	Bulk density 1.844 g cm^{-3}; electrical resistivity 15.65 x 10^{-4} ohm cm; across grain.
265*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.84 g cm^{-3}; electrical resistivity 13.08 x 10^{-4} ohm cm; with grain.
266*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.84 g cm^{-3}; electrical resistivity 16.41 x 10^{-4} ohm cm; across grain.
267*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.84 g cm^{-3}; electrical resistivity 12.71 x 10^{-4} ohm cm; with grain.
268*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.84 g cm^{-3}; electrical resistivity 16.03 x 10^{-4} ohm cm; across grain.
269*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.85 g cm^{-3}; electrical resistivity 13.13 x 10^{-4} ohm cm; with grain.
270*	377	Dull, R. B.	1964	L	298.2	RVC	Bulk density 1.85 g cm^{-3}; electrical resistivity 16.75 x 10^{-4} ohm cm; across grain.
271*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 12.62 x 10^{-4} ohm cm; with grain.
272*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 21.64 x 10^{-4} ohm cm; across grain.
273*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 12.52 x 10^{-4} ohm cm; with grain.
274*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 21.72 x 10^{-4} ohm cm; across grain.
275*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 12.72 x 10^{-4} ohm cm; with grain.
276*	377	Dull, R. B.	1964	L	298.2	RVD	Bulk density 1.87 g cm^{-3}; electrical resistivity 21.54 x 10^{-4} ohm cm; across grain.
277*	377	Dull, R. B.	1964	L	298.2	CFW	Bulk density 1.90 g cm^{-3}; electrical resistivity 11.98 x 10^{-4} ohm cm; with grain.
278*	377	Dull, R. B.	1964	L	298.2	CFW	Bulk density 1.90 g cm^{-3}; electrical resistivity 12.60 x 10^{-4} ohm cm; across grain.
279*	377	Dull, R. B.	1964	L	298.2	CFZ	Bulk density 1.91 g cm^{-3}; electrical resistivity 12.77 x 10^{-4} ohm cm; with grain.
280*	377	Dull, R. B.	1964	L	298.2	CFZ	Bulk density 1.91 g cm^{-3}; electrical resistivity 16.08 x 10^{-4} ohm cm; across grain.
281	1009	Mrozowski, S., Andrew, J. F., Repetski, J., Strauss, H. E., and Wobschall, D. C.	1958	R	1593–3198		Specimen 0.5 in. in dia, 8 in. long; prepared by mixing 100 parts (by weight) of raw Texas coke (calcined for 4 hrs at 1200 C in a baking furnace, crushed and ground) and 40 parts of Medium No. 30 coal tar pitch (supplied by Barrett Co.) for 15 min at 160 C and also 3 parts of extrusion oil (VacWax 80 of Socony Vacuum Co.) mixed again at 150 C for 5 hrs; extruded and baked at 1000 C; graphitized in nitrogen atm at 3100 C for 10 mins.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
282*	1009	Mrozowski, S., Andrew, J. F., Repetski, J., Strauss, H. E., and Wobschall, D. C.	1958	R	2189-3033		Similar to the above but using Texas coke of 200/270 mesh as raw material and extruded at 8200 psi.
283*	1009	Mrozowski, S., et al.	1958	R	1906-3200		Similar to the above but using Texas coke of 100/150 mesh as raw material and extruded at 6100 psi.
284*	1009	Mrozowski, S., et al.	1958	R	2078-3134		Similar to the above but using Texas coke of 28/35 mesh as raw material and extruded at 4100 psi.
285*	1009	Mrozowski, S., et al.	1958	R	2068-2815		The above specimen measured in high vacuum chamber.
286*	1005	Mrozowski, S., Andrew, J. F., Juul, N., Okada, I., Strauss, H. E., and Wobschall, D. C.	1960	R	1403-3273	Graphitized carbon rod	Specimen 1.57 in. in dia; made from 100 parts of filler (50 parts of 100/150 mesh and 50 parts of <270 mesh phenol formaldehyde) and 43 parts binder; extruded at 11500 psi; graphitized to 3100 C.
287*	1005	Mrozowski, S., et al.	1960	R	1418-3188	Graphitized carbon rod	Specimen made from 100 parts of calcined Texas coke (28/35 mesh), 44 parts of coal tar pitch; extruded and baked to 1200 C; density after baking 1.25 g cm^{-3}; graphitized to 3100 C; measured in argon atm at 1-2 in. Hg above atmospheric pressure.
288*	1005	Mrozowski, S., et al.	1960	R	1503-3073	Graphitized carbon rod	Specimen 1.36 in. in dia; made from 100 parts of filler (50 parts of 65/100 mesh and 50 parts of 200/270 mesh Texas coke) and 40 parts of M-30 coal tar pitch as binder; extruded at 7000 psi; graphitized to 3100 C.
289*	1005	Mrozowski, S., et al.	1960	R	1363-3183	Graphitized carbon rod	Specimen 1.61 in. in dia made from 100 parts of filler, (50 parts of 65/100 mesh and 50 part 200/270 mesh) and 35 parts of phenol benzaldehyde as binder; extruded at 5300 psi; graphitized to 3100 C.
290	1005	Mrozowski, S., et al.	1960	R	1373-2773	Graphitized carbon rod	Specimen 1.24 in. in dia; made from 100 parts of filler (50 parts of 100/150 mesh and 50 parts of <270 mesh phenol formaldehyde) and 48 parts of M-30 coal tar pitch as binder; extruded at 2300 psi; graphitized to 3100 C.
291*	1006	Mrozowski, S., Andrew, J. F., Juul, N., Sato, S., Strauss, H. E., and Tsuzuku, T.	1963	R	1343-2313		Prepared by mixing 50 parts 65/100 mesh and 50 parts <200 mesh soft filler (soft Texas coke), and 40 parts soft binder (M-30 pitch); extruded to 0.5 in. dia; baked for 4 days to 1000 C; density after baking 1.55 g cm^{-3}; heat treated at 2100 C for 10 min; measured in an argon atm (pressure approx 1 atm).
292*	1006	Mrozowski, S., et al.	1963	R	1303-2603		The above specimen heat treated at 2400 C for 10 min.
293*	1006	Mrozowski, S., et al.	1963	R	1303-2948		The above specimen heat treated at 2800 C for 10 min.
294*	1006	Mrozowski, S., et al.	1963	R	1353-2303		Prepared by mixing 50 parts 65/100 mesh and 50 parts 200/270 mesh soft filler (soft Texas coke) and 35 parts hard binder (phenol benzaldehyde); extruded to 0.5 in. dia; baked for 4 days to 1000 C; density after baking 1.56 g cm^{-3}; heat treated at 2100 C for 10 min; measured in an argon atm (pressure approx 1 atm).
295*	1006	Mrozowski, S., et al.	1963	R	1383-2583		The above specimen heated at 2400 C for 10 min.
296*	1006	Mrozowski, S., et al.	1963	R	1373-2973		The above specimen heated at 2800 C for 10 min.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
297	1006	Mrozowski, S., Andrew, J. F., Juul, N., Sato, S., Strauss, H. E., and Tsuzuku, T.	1963	R	1318-2233		Prepared by mixing 50 parts 100/150 mesh and 50 parts <270 mesh hard filler (phenol formaldehyde), and 48 parts soft binder (M-30 pitch); extruded to 0.5 in. dia; baked for 4 days to 1000 C; density after baking 1.14 g cm^{-3}; heat treated at 2100 C for 10 min; measured in an argon atm (pressure approx 1 atm).
298	1006	Mrozowski, S., et al.	1963	R	1323-2473		The above specimen heat treated at 2400 C for 10 min.
299	1006	Mrozowski, S., et al.	1963	R	1333-2763		The above specimen heat treated at 2800 C for 10 min.
300	1006	Mrozowski, S., et al.	1963	R	1343-2263		Prepared by mixing 50 parts 100/150 mesh and 50 parts <270 mesh hard filler (phenol formaldehyde), and 43 parts hard binder (phenol benzaldehyde); extruded to 0.5 in. dia; baked for 4 days to 1000 C; density after baking 1.22 g cm^{-3}; heat treated at 2100 C for 10 min; measured in an argon atm (pressure approx 1 atm).
301	1006	Mrozowski, S., et al.	1963	R	1368-2523		The above specimen heat treated at 2400 C for 10 min.
302	1006	Mrozowski, S., et al.	1963	R	1438-2893		The above specimen heat treated at 2800 C for 10 min.
303	895	Mason, I. B. and Knibbs, R. H.	1962	C	323-873	EY 9	Specimen made from Morgan Crucible Co. graphite; cut parallel to the direction of extrusion; density 1.64 g cm^{-3}; electrical resistivity reported as 1.93, 1.71, 1.53, 1.40, and 1.30 milliohm cm at 88, 205, 320, 420, and 545 C, respectively; Armco iron used as the comparative material.
304	895	Mason, I. B. and Knibbs, R. H.	1962	C	313-828	EY 9	Similar to the above specimen but cut perpendicular to the direction of extrusion; electrical resistivity reported as 2.87, 2.58, 2.21, and 2.05 milliohm cm at 70, 185, 350, and 425 C, respectively.
305*	895	Mason, I. B. and Knibbs, R. H.	1962	C	321-916	HX 10	Specimen made from material of Harwell Graphite Plant; cut parallel to the direction of extrusion; density 1.87 g cm^{-3}; electrical resistivity at 83, 195, 360, and 450 C being, respectively, 1.50, 1.30, 1.10, and 1.02 milliohm cm.
306*	895	Mason, I. B. and Knibbs, R. H.	1962	C	321-838	British Reactor Grade A	Specimen cut parallel to the direction of extrusion; density 1.73 g cm^{-3}; electrical resistivity at 100, 200, 300, 400, and 450 C being, respectively, 0.60, 0.53, 0.48, 0.45, and 0.44 milliohm cm.
307*	895	Mason, I. B. and Knibbs, R. H.	1962	C	321-846	British Reactor Grade A	Similar to the above specimen but cut perpendicular to the direction of extrusion; electrical resistivity at 100, 200, and 300 C being, respectively, 1.03, 0.90, and 0.82 milliohm cm.
308*	895	Mason, I. B. and Knibbs, R. H.	1962	C	318-816	British Reactor Grade A	Similar to the above specimen but cut parallel to the direction of extrusion.
309*	895	Mason, I. B. and Knibbs, R. H.	1962	C	318-823	British Reactor Grade A	Similar to the above specimen but cut perpendicular to the direction of extrusion.
310	895	Mason, I. B. and Knibbs, R. H.	1962	C	313-831	British Reactor Grade Carbon	British Reactor Grade carbon stock graphitized to 2100 C; not impregnated; cut parallel to the direction of extrusion; density 1.62 g cm^{-3}; electrical resistivity at 100, 200, 300, 400, and 500 C being, respectively, 3.10, 2.87, 2.67, 2.49, and 2.33 milliohm cm.
311*	895	Mason, I. B. and Knibbs, R. H.	1962	C	313-798	British Reactor Grade Carbon	Similar to the above specimen but graphitized to 2300 C; density 1.68 g cm^{-3}; electrical resistivity at 100, 200, 300, 400, and 500 C being, respecitvely, 2.35, 2.08, 1.85, 1.64, and 1.46 milliohm cm.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
312*	895	Mason, I. B. and Knibbs, R. H.	1962	C	313-753	British Reactor Grade Carbon	Similar to the above specimen but graphitized to 2600 C; density 1.62 g cm^{-3}; electrical resistivity at 100, 200, 300, 400, and 500 C being, respectively, 1.17, 1.02, 0.92, 0.85, and 0.80 milliohm cm.
313*	895	Mason, I. B. and Knibbs, R. H.	1962	C	303-901	British Reactor Grade Carbon	Similar to the above specimen but graphitized to 2820 C; density 1.65 g cm^{-3}; electrical resistivity at 100, 200, 300, 400, 500, 600, and 700 C being, respectively, 0.78, 0.71, 0.67, 0.65, 0.64, 0.65, and 0.67 milliohm cm.
314*	1140	Powell, R.W., Tye, R. P., and Metcalf, S.C.	1965		323.2	EY 9	Grade EY 9 graphite from Morgan Crucible Co.; electrical resistivity 1.71 milliohm cm at room temp.
315*	1140	Powell, R.W., et al.	1965		323.2	EY 9	Similar to the above specimen but electrical resistivity 1.86 milliohm cm at room temp.
316*	1140	Powell, R.W., et al.	1965		323.2	EY 9	Similar to the above specimen but electrical resistivity 1.89 milliohm cm at room temp.
317*	184	Bortz, S.A. and Connors, C. L.	1966		364-2239	JTA; 7-F-12	Measured in the with-the-grain direction.
318*	1533	Wheeler, M. J.	1965	P	1575-2400	EY 9A	Density 1.76 g cm^{-3} data calculated from measurements of thermal diffusivity; specific heat data from "Nuclear Graphite" by Nightingale, R. E., Yoshikawa, H. H., and Losty, H. H. W., 1962.
319*	1533	Wheeler, M. J.	1965	P	1320-2380	Moderator graphite	Density 1.71 g cm^{-3}; data calculated from measurements of thermal diffusivity and specific heat data from the same source as above.
320*	173	Bocquet, M. and Micaud, G.	1964	E	295-511	ZTA	Prepared from coke L, supplied by Péchiney Co., by extruding into a 10 mm dia bar; the graphite was impregnated once with tar; measured along the a-axis.
321*	173	Bocquet, M. and Micaud, G.	1964	E	298-536	ZTA	Similar to the above specimen; measured along the c-axis.
322*	173	Bocquet, M. and Micaud, G.	1964	E	306-714	ZTA	Similar to the above specimen; the dia was a bit smaller and measured along the a-axis.
323*	173	Bocquet, M. and Micaud, G.	1964	E	321-721	ZTA	Similar to the above specimen; measured along the c-axis.
324*	173	Bocquet, M. and Micaud, G.	1964	E	302-598	ZTA	Prepared from coke L, supplied by Péchiney Co., by extruding into 10 mm dia bar; the graphite was impregnated once with tar; measured along the c-axis.
325*	173	Bocquet, M. and Micaud, G.	1964	E	307-605	ZTA	Similar to the above specimen except neutron-irradiated at 350 C.
326*	173	Bocquet, M. and Micaud, G.	1964	E	311-506	ZTA	Similar to the above specimen except neutron-irradiated at 250 C.
327	173	Bocquet, M. and Micaud, G.	1964	E	393-411	ZTA	Similar to the above specimen except neutron-irradiated at 150 C.
328	1281	Schweitzer, D. and Singer, R.	1961		469-873	MH4LM	Density 1.90 g cm^{-3}; grain size >0.032 in.
329*	1281	Schweitzer, D. and Singer, R.	1961		471-875	MH4LM	Similar to the above specimen except irradiated in Material Testing Reactor at 475 C by a neutron flux of 3.5×10^{19} nvt with energy >0.1 MeV.
330	1281	Schweitzer, D. and Singer, R.	1961		471-874	ATL-82-1	Grain size 0.016 to 0.03 in.
331*	1281	Schweitzer, D. and Singer, R.	1961		471-873	ATL-82-2	Similar to the above specimen; irradiated in Hanford reactor at 360 to 420 C by a neutron flux of 3.2×10^{20} nvt with energy >0.1 MeV.
332*	1281	Schweitzer, D. and Singer, R.	1961		472-874	ATL-82-3	Similar to the above specimen except irradiated in Material Testing Reactor at 475 C by a neutron flux of 3.6×10^{19} nvt with energy >0.1 MeV.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
333	*1281	Schweitzer, D. and Singer, R.	1961		468-868	R0025-1	Obtained from National Carbon Co.; grain size <0.016 in.
334	*1281	Schweitzer, D. and Singer, R.	1961		468-869	R0025-2	Similar to the above specimen.
335	*1281	Schweitzer, D. and Singer, R.	1961		472-867	R0025-3	Similar to the above specimen; irradiated at Testing Reactor at 360 to 420 C by a neutron flux of 3.6 x 10^{19} nvt with energy >0.1 MeV.
336	*1281	Schweitzer, D. and Singer, R.	1961		471-865	R0025-3A	The above specimen annealed at 925 C for 16 hrs.
337	* 612	Hoch, M. and Vardi, J.	1962	→	1671	ZT type graphite; G 3A	Thermal conductivity data in the z-direction (k_z) determined simultaneously with thermal conductivity in the r-direction (k_r, see next curve) from 4 cylindrical specimens made from ZT type graphite of National Carbon Co.; density 1.980 g cm^{-3}; anisotropy ratio of electrical resistivity ρ(z-direction)/ρ(r-direction) = 2.50 at room temp; the specimens each about 2.537 cm dia x 1.126 cm thick being heated in vacuum by high frequency induction; thermal conductivity determined by equating the heat conduction in specimen to the heat loss by radiation assuming the emissivity of a grey body; the analysis required 2 specimens of different thickness to solve simultaneously for k_z and k_r at a certain temp.
338	* 612	Hoch, M. and Vardi, J.	1962	→	1671	ZT type graphite; G 3A	k_r determined simultaneously with the above curve.
339	* 612	Hoch, M. and Vardi, J.	1962	→	1671	ZT type graphite; G 7	Similar to the above specimens except with size 2.539 cm dia x 0.287 cm thick and density 1.978 g cm^{-3}; k_z was measured.
340	* 612	Hoch, M. and Vardi, J.	1962	→	1671	ZT type graphite; G 7	k_r determined simultaneously with the above curve.
341	*1140	Powell, R.W., Tye, R.P., and Metcalf, S.C.	1965		673-1173	EY 9 graphite	Obtained from Morgan Crucible Co.; electrical resistivity 1790-1850 μohm cm at room temp; data reported were mean values.
342	* 361	Digesu, F.L. and Pears, C.D.	1965	R	1367-3311	CFZ grade	99.74 C, <0.6 H, 0.19 ash, 0.07 CaO, 0.02 Al_2O_3, 0.04 total sulfur, and <0.01 sulfide sulfur; specimens 1 in. long, 1 in. O.D. and 0.25 in. I.D.; supplied by Union Carbide Co.; heat flow measured parallel to cylindrical axis; with grain; bulk density (mean value) 1.899 g cm^{-3}; thermal conductivity data calculated from the mean values of 9 specimens (standard deviation 0.0946, 0.0609, 0.0786, 0.0963, and 0.111 at 1366.5, 2199.8, 2755.4, 3033.2, and 3310.9 K, respectively).
343	* 361	Digesu, F.L. and Pears, C.D.	1965	R	1367-3311	CFZ grade	Similar to the above specimens except bulk density (mean value) 1.908 g cm^{-3}; standard deviation 0.0891, 0.129, 0.0986, 0.0968, and 0.0544 at 1366.5, 2199.8, 2755.4, 3033.2, and 3310.9 K, respectively.
344	* 361	Digesu, F.L. and Pears, C.D.	1965	R	1367-3311	CFZ grade	Similar to the above specimens except specimen orientation across grain; bulk density (mean value) 1.896 g cm^{-3}; standard deviation 0.0661, 0.0749, 0.0711, 0.0606, and 0.0526 at 1366.5, 2199.8, 2755.4, 3033.2, and 3310.9 K, respectively.
345	* 361	Digesu, F.L. and Pears, C.D.	1965	R	1367-3311	CFZ grade	Similar to the above specimens except bulk density (mean value) 1.906 g cm^{-3}; standard deviation 0.0535, 0.0362, 0.0799, 0.0862, and 0.0539 at 1366.5, 2199.8, 2755.4, 3033.2, and 3310.9 K, respectively.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
346*	361	Digesu, F. L. and Pears, C. D.	1965	C	338.7	CFZ grade	99.74 C, <0.6 H, 0.19 ash, 0.07 CaO, 0.02 Al_2O_3, 0.04 total sulfur and <0.01 sulfide sulfur; specimens 1 in. in dia and 1 in. long; supplied by Union Carbide Co.; with grain; bulk density (mean value) 1.903 g cm^{-3}; thermal conductivity data from the mean values of 10 specimens (standard deviation 0.0937 at 338.7 K); Armco iron used as comparative material.
347*	361	Digesu, F. L. and Pears, C. D.	1965	C	338.7	CFZ grade	Similar to the above specimens except bulk density (mean value) 1.907 g cm^{-3}; standard deviation 0.108 at 338.7 K.
348*	361	Digesu, F. L. and Pears, C. D.	1965	C	338.7	CFZ grade	Similar to the above specimens except bulk density (mean value) 1.881 g cm^{-3}; standard deviation 0.0317 at 338.7 K.
349*	361	Digesu, F. L. and Pears, C. D.	1965	C	338.7	CFZ grade	Similar to the above specimens except bulk density (mean value) 1.907 g cm^{-3}; standard deviation 0.0288 at 338.7 K.
350*	719	Kaspar, J.	1967		1088-3030	Supertemp Pyrolytic graphite	Annealed; electrical conductivity 9.54, 7.73, 6.40, 5.42, 4.72, 4.19, 3.71, and 3.28 x 10^3 ohm^{-1} cm^{-1} at 1088, 1365, 1643, 1920, 2198, 2475, 2753, and 3030 K, respectively.
351*	184	Bortz, S. A. and Connors, C. L.	1966		372-2205	JTA; 14-G-1	Measured with the grain.
352*	184	Bortz, S. A. and Connors, C. L.	1966		354-2222	JTA; 14-G-1	Measured across the grain.
353	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Polycrystalline; prepared from a mix consisted of 100 parts of Kendall coke, 42 parts of medium grade coal tar pitch and 2 part of Socony Vacuum Oil. Co. Vacwax 80, the coke calcined to 1100 C, crushed into powder, passed 2 times through a small Raymond mill, then the mix made and extruded through a 0.5 in. die, cut into 6 in. long rods; the rods baked for 5 days to reach the top temp of 1100 C, subsequently heat treated at 1200 C for about 5 min; density 1.49 g cm^{-3}; crystallite dia 37 Å.
354	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Similar to the above specimen except heat treated at 1750 C and the crystallite dia 61.5 Å.
355	675	Jamieson, C. P. and Mrozowski, S.	1956	L	115-385		Similar to the above specimen except heat treated at 1950 C and the crystallite dia 79 Å.
356	220	Buerschaper, R. A.	1944	F	93-373		Cut from a carbon electrode; supplied by National Carbon Co.; 2.9 cm dia x 3.2 cm long.
357*	237	Carnegie, I. T.	1961	R	1128-1410	AUC	No details reported.
358*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	CA	Prepared by hot-pressing extruded graphite; grain size 0.015 in.; bulk density 1.68 g cm^{-3}; electrical resistivity 819 μohm cm at room temp; measured with grain.
359*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	CA	Similar to the above specimen but electrical resistivity 1310 μohm cm at room temp; measured across grain.
360*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	CB	Prepared by hot-pressing extruded graphite; grain size 0.030 in.; bulk density 1.72 g cm^{-3}; electrical resistivity 860 μohm cm at room temp; measured with grain.
361*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	CB	Similar to the above specimen but electrical resistivity 1100 μohm cm at room temp; measured across grain.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
362*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTA	Prepared by hot-pressing process; bulk density 1.94 g cm^{-3}; electrical resistivity 7.0 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
363*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTA	Similar to the above specimen except electrical resistivity 22.0 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
364*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTB	Fabricated from impregnated ATJ graphite by severe hot-pressing process; bulk density 2.01 g cm^{-3}; electrical resistivity 6.60 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
365*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTB	Similar to the above specimen except electrical resistivity 21.62 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
366*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade CFW	Fabricated from impregnated ATL graphite by hot-pressing process; bulk density 1.89 g cm^{-3}; electrical resistivity 11.79 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
367*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade CFW	Similar to the above specimen except electrical resistivity 12.48 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
368*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade RVA	Pressure-cured; bulk density 1.84 g cm^{-3}; total mercury porosity ~10%; electrical resistivity 12.13 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
369*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade RVA	Similar to the above specimen except electrical resistivity 15.62 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
370*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTE	Obtained by hot-pressing of pressure-cured RVA graphite (as a base stock); bulk density 1.96 g cm^{-3}; electrical resistivity 8.95 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
371*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTE	Similar to the above specimen except electrical resistivity 20.40 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
372*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTF	Obtained by hot-pressing of the pressure-cured stock at higher pressures and temps; bulk density 2.00 g cm^{-3}; electrical resistivity 7.40 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
373*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade ZTF	Similar to the above specimen except electrical resistivity 20.06 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
374*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade CFZ	Obtained by impregnating RVA graphite; hot-pressed; bulk density 1.90 g cm^{-3}; porosity <5%; electrical resistivity 12.03 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
375*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade CFZ	Similar to the above specimen except electrical resistivity 14.44 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
376*	1435	Turner, J. H. and Carter, M. B.	1964		298.2	Grade RVD	Prepared by pressure-curing process; bulk density 1.87 g cm^{-3}; electrical resistivity 12.62 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
377*	1435	Turner, J.H. and Carter, M.B.	1964		298.2	Grade RVD	Similar to the above specimen except electrical resistivity 21.64 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
378*	1435	Turner, J.H. and Carter, M.B.	1964		298.2	Grade RVC	Pressure-curved graphite having spherical particles in the blend; bulk density 1.85 g cm^{-3}; electrical resistivity 13.08 x 10^{-4} ohm cm at room temp; heat flow measured in with-grain direction.
379*	1435	Turner, J.H. and Carter, M.B.	1964		298.2	Grade RVC	Similar to the above specimen except electrical resistivity 16.40 x 10^{-4} ohm cm at room temp; heat flow measured in across-grain direction.
380*	588	Hansen, C.A.	1909	L	373-713		Ordinary carbon supplied by National Carbon Co.; made from petroleum coke.
381	588	Hansen, C.A.	1909	L	373-873		The results of the above specimen recalculated by Richards, J.W.
382	246	Cellier, L.	1898	P	280.0		0.485 cm dia x 1.675 cm long; density 1.698 g cm^{-3}; thermal conductivity calculated from measured thermal diffusivity and specific heat capacity.
383*	655	IIT Research Inst.	1966		364-993	JTA; 7-F-12	Measured with grain.
384	951	Meyers, C. and Koyama, K.	1968	P	300-1039	H205 grade; 1-A	Disk specimen 0.5 in. in dia and 0.045 in. thick; density 1.755 g cm^{-3}; heat flow parallel to molding pressure; thermal conductivity value calculated from the measurement of thermal diffusivity (measured by xeon flash technique), specific heat and density.
385*	951	Meyers, C. and Koyama, K.	1968	P	298-1048	H205 grade; 1-B	Similar to the above except heat flow perpendicular to molding pressure.
386*	951	Meyers, C. and Koyama, K.	1968	P	388-1045	TS-574 grade	Disk specimen 0.5 in. in dia and 0.045 in. thick; heat flow parallel to x-direction.
387*	951	Meyers, C. and Koyama, K.	1968	P	388-1045	TS-574 grade	Similar to the above except heat flow parallel to y-direction. (This paper indicated as z-direction, could be typing error.)
388	951	Meyers, C. and Koyama, K.	1968	P	396-853	TS-574 grade	Similar to the above except heat flow parallel to z-direction (this paper indicated as y-direction, could be typing error).
389*	951	Meyers, C. and Koyama, K.	1968	P	304-1103	TS-835 grade	Disk specimen 0.5 in. in dia and 0.045 in. thick; heat flow parallel to x-direction; thermal conductivity value calculated from the measurement of thermal diffusivity (measured by xeon flash technique), specific heat and density (based on 81% graphite, 19% MoS_2 and density = 1.885 g cm^{-3}).
390*	951	Meyers, C. and Koyama, K.	1968	P	405-1084	TS-835 grade	Similar to the above specimen except heat flow parallel to y-direction.
391	951	Meyers, C. and Koyama, K.	1968	P	304-1086	TS-835 grade	Similar to the above specimen except heat flow parallel to z-direction.
392*	1018, 1017	Neel, D.S. and Pears, C.D.	1962	R	550-1311	CS grade	1 in. dia x 1 in. long.
393*	1018, 1017	Neel, D.S. and Pears, C.D.	1962	R	511-2517	CS grade	1 in. dia x 1 in. long; heat soaked.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
394*	238	Carpenter, F., Engle, G., Goeddel, W., Godsin, W., Pentelandolfo, J., Pyle, R., and Shoffner, J.	1961	C	2273	GP-38 grade	98 pure; powder specimen 1 in. in dia and 2 in. long; manufactured by National Carbon Co.; particle size <20 μ; prepared by hot pressing techniques; density 1.90-1.95 g cm^{-3}; electrical resistivity 3.5 x 10^{-3} ohm cm; a graphite of known thermal conductivity used as a reference.
395*	501	Godfrey, T. G., Moore, J. P., and McElroy, D. L.	1964	R	324-1183	CGB grade	Obtained from Union Carbide Corp; 2.125 in. O. D., 0.375 in. I. D., and 1 in. thick; machined; density 1.824 g cm^{-3}; electrical resistivity 1232, 1132, 1045, 993.2, 962.7, 945.4, 937.3, 936.5, 941.5, 948.8, and 960.8 μohm cm at 23, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 C, respectively; measured perpendicular to the extrusion axis.
396*	501	Godfrey, T. G., et al.	1964	L	307,348	CGB grade	Cut from the same bar as the above specimen; 1.00 in. dia x 0.8 in. thick; measured perpendicular to the extrusion axis.
397*	501	Godfrey, T. G., et al.	1964	L	307-348	CGB grade	Similar to above but measured parallel to the extrusion axis.
398*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 1	0.5 in. dia x 5 in. long; measured with grain; reported value averaged over measurements made on five specimens cut from various parts of 103 in. dia billet.
399*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 1	The above specimens measured across grain.
400*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 2	Similar to above but measured with grain.
401*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 2	The above specimens measured across grain.
402*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 3	Similar to above but measured with grain.
403*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 3	The above specimens measured across grain.
404*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 4	Similar to above but measured with grain.
405*	1449	Union Carbide Corp.	1964	L	298.2	CFW grade; 4	The above specimens measured across grain.
406*	108	Baker, D. E.	1964	P	299-764	TSX	1 to 2 cm in dia and 1.5 to 2 mm thick; graphitized at 3000 C; density 1.71 g cm^{-3}; measured perpendicular to the direction of extrusion; thermal conductivity values calculated from measured thermal diffusivity with specific heat capacity data taken from Rossini, F. D., et al. ("Selected Values of Physical and Thermodynamic Properties of Hydrocarbons and Related Compounds Comprising the Tables of the American Petroleum Institute Research Project 44," Carnegie Press, Pittsburgh, 1953).
407*	108	Baker, D. E.	1964	P	300-783	TSX	The above specimen irradiated by 1.2 x 10^{21} nvt (E>0.18 MeV) at 650±10 C in Engineering Test Reactor; measured perpendicular to the direction of extrusion.
408*	108	Baker, D. E.	1964	P	298-745	TSCBF	1 to 2 cm in dia and 1.5 to 2 mm thick; graphitized at 2450 C; density 1.65 g cm^{-3}; measured perpendicular to the direction of extrusion; same measuring method as above.
409*	108	Baker, D. E.	1964	P	300-809	TSCBF	The above specimen irradiated by 1.0 x 10^{21} nvt (E>0.18 MeV) at 650±10 C in Engineering Test Reactor; measured perpendicular to the direction of extrusion.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
410*	108	Baker, D. E.	1964	P	298-807	CSF	1 to 2 cm in dia and 1.5 to 2 mm thick; graphitized at 2800 C; density 1.66 g cm^{-3}; measured perpendicular to the direction of extrusion; same measuring method as above.
411*	108	Baker, D. E.	1964	P	299-810	CSF	The above specimen irradiated by 1.2 x 10^{21} nvt (E >0.18 MeV) at 650±10 C in Engineering Test Reactor; measured perpendicular to the direction of extrusion.
412	108	Baker, D. E.	1964	P	300-451	CSF	Similar to above but irradiated by 1.86 x 10^{20} nvt (E >0.18 MeV) at 75 C in Engineering Test Reactor; measured perpendicular to the direction of extrusion.
413	108	Baker, D. E.	1964	P	300-384	CSF	The above specimen annealed at 240 C for 2 hrs; measured perpendicular to the direction of extrusion.
414*	1175	Rappeneau, J., Bocquet, M., Micaud, G., and Fillatre, A.	1964	L	302-598		Rod specimen.
415*	1175	Rappeneau, J., et al.	1964	L	293-410		Rod specimen irradiated by a dose 3 x 10^{20} n cm^{-2} at 170 C.
416*	1175	Rappeneau, J., et al.	1964	L	311-501		Rod specimen irradiated by a dose 3 x 10^{20} n cm^{-2} at 250 C.
417*	1175	Rappeneau, J., et al.	1964	L	307-601		Rod specimen irradiated by a dose 3 x 10^{20} n cm^{-2} at 350 C.
418*	1161	Pustovalov, V. V.	1961	R	1277-2404	Electrode graphite	Disk specimen; measured in a vacuum of 1 x 10^{-4} mm Hg.
419*	1450	Union Carbide Corp.	1964		298.2	CFW grade	Average bulk density 1.861 g cm^{-3}; measured with grain; reported value averaged over measurements made on 6 specimens cut from billet No. 1.
420*	1450	Union Carbide Corp.	1964		298.2	CFW grade	Average bulk density 1.869 g cm^{-3}; measured across grain; reported value averaged over measurements made on 4 specimens cut from billet No. 1.
421*	1450	Union Carbide Corp.	1964		298.2	CFW grade	Average bulk density 1.860 g cm^{-3}; measured with grain; reported value averaged over measurements made on 30 specimens cut from billet No. 2.
422*	1450	Union Carbide Corp.	1964		298.2	CFW grade	The above specimens measured across grain.
423*	1450	Union Carbide Corp.	1964		2196-3270	CFW grade; 1	Average bulk density 1.883 g cm^{-3}; preliminary result.
424*	1450	Union Carbide Corp.	1964		2212-3286	CFW grade; 2	Similar to above.
425*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-1273	LMD 1	Graphitized R grade petroleum coke with 12% resin; 0.8 cm cross-section and 10 cm long; obtained from Royal Aircraft Establishment, Farnborough; prepared by adding a small amount of kerosene, poured into a bar mold, hot-pressed at 180 C under 6 psi, removed from mold, heated at 250 C for 24 hrs, again heated at 940 C in nitrogen to carbonize the resin, carbon-deposition-treated at 840 C using benzene at 50 C as the source, finally heat-treated at 1700 C; density 1.73 g cm^{-3}; electrical resistivity 2297, 2290, 2235, 2205, 2165, 2030, 1930, 1860, and 1830 μohm cm at 20, 50, 100, 150, 200, 400, 600, 800, and 900 C, respectively.
426*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-423	LMD 3	Similar to above but electrical resistivity 2490, 2435, 2385, and 2340 μohm cm at 20, 50, 100, and 105 C, respectively.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
427*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	HMD 1	Same materials and fabrication method as above but compact pressure 250 psi; density 1.85 g cm^{-3}; electrical resistivity 1453, 1445, 1405, 1375, and 1340 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
428	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-1273	HMD 4	Similar to above but electrical resistivity 1427, 1380, 1345, 1315, 1285, 1205, 1155, 1125, and 1120 μohm cm at 20, 50, 100, 150, 200, 400, 600, 800, and 900 C, respectively.
429*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	R 250	Same materials and fabrication method as above but without heat-treatment at 1700 C; density 1.87 g cm^{-3}; electrical resistivity 1084, 1055, 1035, 1010, and 985 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
430*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	R 250A	Similar to above but with heat treatment at 1700 C; density 1.65 g cm^{-3} and electrical resistivity 1395, 1355, 1320, 1295, and 1275 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
431	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	R 250B	Similar to above but density 1.74 g cm^{-3} and electrical resistivity 1281, 1220, 1190, 1165, and 1140 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
432*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	R 250C	Similar to above but density 1.83 g cm^{-3} and electrical resistivity 1325, 1230, 1195, 1170, and 1150 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
433*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-473	R 500	Same materials and fabrication method as above but compact pressure 500 psi; density 1.83 g cm^{-3}; electrical resistivity 960, 958, 935, 915, and 895 μohm cm at 20, 50, 100, 150, and 200 C, respectively.
434*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-423	R 1000	Same materials and fabrication method as above but compact pressure 1000 psi; density 1.83 g cm^{-3}; electrical resistivity 864, 850, 835, and 820 μohm cm at 20, 50, 100, and 150 C, respectively.
435*	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-423	G 500	Natural graphite containing 12.4% resin; same fabrication method as above but compact pressure 500 psi; density 1.76 g cm^{-3}; electrical resistivity 506, 496, 486, and 476 μohm cm at 20, 50, 100, and 150 C, respectively.
436	1440	Tye, R. P. and Woodman, M. J.	1966	L	323-423	G 1000	Same materials and fabrication method as above but compact pressure 1000 psi; density 1.82 g cm^{-3}; electrical resistivity 445, 441, 429, and 417 μohm cm at 20, 50, 100, and 150 C, respectively.
437*	1003	Mottershead, D. and James, A.	1966	E	313-676	PGA grade; A1	0.25 in. dia x 3 in. long; cut, machined; heat flow parallel to extrusion.
438*	1003	Mottershead, D. and James, A.	1966	E	413-493	PGA grade; A2	Similar to above.
439*	1003	Mottershead, D. and James, A.	1966	E	313.2	PGA grade; A3	Similar to above.
440*	1003	Mottershead, D. and James, A.	1966	E	314-476	PGA grade; A3	The above specimen irradiated at 450 C by a fast-neutron dose of 2.53 x 10^{20} n cm^{-2}.
441*	1003	Mottershead, D. and James, A.	1966	E	313.2	PGA grade; A4	Similar to above but specimen not irradiated.
442*	1003	Mottershead, D. and James, A.	1966	E	314-590	PGA grade; A4	The above specimen irradiated at 350 C by a fast-neutron dose of 8.62 x 10^{20} n cm^{-2}.
443*	1003	Mottershead, D. and James, A.	1966	E	313-709	PGA grade; B1	0.25 in. dia x 3 in. long; cut, machined; heat flow perpendicular to extrusion.
444	1003	Mottershead, D. and James, A.	1966	E	313.2	PGA grade; B2	Similar to above.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
445*	1003	Mottershead, D. and James, A.	1966	E	311-509	PGA grade; B2	The above specimen irradiated at 250 C by a fast-neutron dose of 12.46 x 10^{20} n cm^{-2}.
446*	1003	Mottershead, D. and James, A.	1966	E	313.2	PGA grade; B3	Similar to above but specimen not irradiated.
447	1003	Mottershead, D. and James, A.	1966	E	313.2	PGA grade; B3	The above specimen irradiated at 150 C by a fast-neutron dose of 7.74 x 10^{20} n cm^{-2}.
448	1003	Mottershead, D. and James, A.	1966	E	314-573	PGA grade; B3	The above specimen annealed at 380 C.
449	1003	Mottershead, D. and James, A.	1966	E	314-572	PGA grade; B3	The above specimen again annealed at 550 C.
450	1003	Mottershead, D. and James, A.	1966	E	314-673	PGA grade; B3	The above specimen again annealed at 740 C.
451	1003	Mottershead, D. and James, A.	1966	E	313-623	PGA grade; B3	The above specimen again annealed at 1100 C.
452	1003	Mottershead, D. and James, A.	1966	E	313-672	PGA grade; B3	The above specimen again annealed at 1200 C.
453	1003	Mottershead, D. and James, A.	1966	E	313-669	PGA grade; B3	The above specimen again annealed at 1300 C.
454*	1003	Mottershead, D. and James, A.	1966	E	313-674	PGA grade; B3	The above specimen again annealed at 1400 C.
455*	1003	Mottershead, D. and James, A.	1966	E	314-623	PGA grade; B3	The above specimen again annealed at 1500 C.
456	1495	Wagner, P. and Dauelsberg, L. B.	1966	P	373-523	ZTA grade	Obtained from Carbon Products Co.; derived from the hot-working of ATJ graphite; bulk density 1.90-1.95 g cm^{-3}; heat flow perpendicular to the applied force; thermal conductivity values calculated from measured thermal diffusivity data.
457*	1495	Wagner, P. and Dauelsberg, L. B.	1966	C	597-1078	ZTA grade	Similar to the above specimen but measured by a comparative apparatus.
458*	1495	Wagner, P. and Dauelsberg, L. B.	1966	R	1643-2859	ZTA grade	Similar to the above specimen but measured by a radial heat-flow apparatus.
459	1495	Wagner, P. and Dauelsberg, L. B.	1966	P	298-647	ZTA grade	Obtained from Carbon Products Co.; derived from the hot-working of ATJ graphite; bulk density 1.90-1.95 g cm^{-3}; heat flow parallel to the applied force; thermal conductivity values calculated from measured thermal diffusivity data.
460*	1495	Wagner, P. and Dauelsberg, L. B.	1966	C	573-942	ZTA grade	Similar to above but measured by a comparative apparatus.
461*	806	Lafyatis, P.C., Waters, C.W., and Dull, R.B.	1965	L	298.2	RVA; 6	0.5 in. dia x 5 in. long; bulk density 1.80 g cm^{-3}; electrical resistivity 1263 μohm cm at room temp; measured with grain.
462*	806	Lafyatis, P.C., et al.	1965	L	298.2	RVA; 6	Similar to the above specimen but measured across grain; electrical resistivity 1743 μohm cm at room temp.
463*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	RVA; 6	Cut from the same billet as the above specimen; 100 x 2 x 2 mm; electrical resistivity 1052, 1102, and 1151 μohm cm at 1000, 1500, and 2000 C, respectively; measured with grain by the rectangular bar method.
464*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	RVA; 6	Similar to above but measured across grain; electrical resistivity 1419, 1448, and 1479 μohm cm at 1000, 1500, and 2000 C, respectively.
465*	806	Lafyatis, P.C., et al.	1965	P	2573-2773	RVA; 6	Cut from the same billet as the above specimen; electrical resistivity 1246 and 1341 μohm cm at 2500 and 2700 C, respectively; measured with grain by the arc image furnace method; thermal conductivity values calculated from the cooling rate of the specimen, specific heat capacity and density.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
466*	806	Lafyatis, P.C., Waters, C.W., and Dull, R.B.	1965	P	2573, 2773	RVA; 6	Similar to above but measured across grain; electrical resistivity 1560 and 1618 μohm cm at 2500 and 2700 C, respectively.
467	806	Lafyatis, P.C., et al.	1965	L	298.2	RVA; 7	0.5 in. dia x 5 in. long; bulk density 1.80 g cm^{-3}; electrical resistivity 1230 μohm cm at room temp; measured with grain.
468*	806	Lafyatis, P.C., et al.	1965	L	298.2	RVA; 7	Similar to the above specimen but measured across grain; electrical resistivity 1670 μohm cm at room temp.
469*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	RVA; 7	Cut from the same billet as the above specimen; 100 x 2 x 2 mm; electrical resistivity 1073, 1117, and 1165 μohm cm at 1000, 1500, and 2000 C, respectively; measured with grain by the rectangular bar method.
470*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	RVA; 7	Similar to above but measured across grain; electrical resistivity 1405, 1429, and 1451 μohm cm at 1000, 1500, and 2000 C, respectively.
471*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	RVA; 7	Cut from the same billet as the above specimen; electrical resistivity 1316 and 1357 μohm cm at 2500 and 2700 C, respectively; measured with grain by the arc image furnace method; thermal conductivity values calculated from the cooling rate of the specimen, specific heat capacity, and density.
472*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	RVA; 7	Similar to above but measured across grain; electrical resistivity 1557 and 1648 μohm cm at 2500 and 2700 C, respectively.
473*	806	Lafyatis, P.C., et al.	1965	L	298.2	CFZ; 3	0.5 in. dia x 5 in. long; bulk density 1.88 g cm^{-3}; electrical resistivity 1152 μohm cm at room temp; measured with grain.
474*	806	Lafyatis, P.C., et al.	1965	L	298.2	CFZ; 3	Similar to the above specimen but measured across grain; electrical resistivity 1552 μohm cm at room temp.
475*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	CFZ; 3	Cut from the same billet as the above specimen; 100 x 2 x 2 mm; electrical resistivity 1024, 1076, and 1131 μohm cm at 1000, 1500, and 2000 C, respectively; measured with grain by the rectangular bar method.
476*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	CFZ; 3	Similar to above but measured across grain; electrical resistivity 1377, 1414, and 1444 μohm cm at 1000, 1500, and 2000 C, respectively.
477*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	CFZ; 3	Cut from the same billet as the above specimen; electrical resistivity 1246 and 1386 μohm cm at 2500 and 2700 C, respectively; measured with grain by the arc image furnace method; thermal conductivity values calculated from the cooling rate of the specimen, specific heat capacity, and density.
478*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	CFZ; 3	Similar to above but measured across grain; electrical resistivity 1552 and 1646 μohm cm at 2500 and 2700 C, respectively.
479*	806	Lafyatis, P.C., et al.	1965	L	298.2	CFZ; 4	0.5 in. x 5 in. long; bulk density 1.87 g cm^{-3}; electrical resistivity 1146 μohm cm at room temp; measured with grain.
480*	806	Lafyatis, P.C., et al.	1965	L	298.2	CFZ; 4	Similar to above but measured across grain; electrical resistivity 1549 μohm cm at room temp.

*Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
481*	806	Lafyatis, P.C., Waters, C.W., and Dull, R.B.	1965	E	1273-2273	CFZ; 4	Cut from the same billet as the above specimen; 100 x 2 x 2 mm; electrical resistivity 948, 1039, and 1101 μohm cm at 1000, 1500, and 2000 C, respectively; measured with grain by the rectangular bar method.
482*	806	Lafyatis, P.C., et al.	1965	E	1273-2273	CFZ; 4	Similar to above but measured across grain; electrical resistivity 1323, 1360, and 1392 μohm cm at 1000, 1500, and 2000 C, respectively.
483*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	CFZ; 4	Cut from the same billet as the above specimen; electrical resistivity 1172 and 1248 μohm cm at 2500 and 2700 C, respectively; measured with grain by the arc image furnace method; thermal conductivity values calculated from the cooling rate of the specimen, specific heat capacity, and density.
484*	806	Lafyatis, P.C., et al.	1965	P	2773, 2973	CFZ; 4	Similar to above but measured across grain; electrical resistivity 1480 and 1545 μohm cm at 2500 and 2700 C, respectively.
485*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Prepared by National Carbon Co. from lampblack filler and pitch binder; 0.426 in. dia x 4 in. long; heat-treated at 3000 C; density 1.61 g cm^{-3}; electrical resistivity 4.1 milliohm cm at room temp.
486*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to the above specimen but irradiated at 650 C by a neutron dose of 353 MWD/At; electrical resistivity 4.41 milliohm cm.
487*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to above but irradiated at 650 C by a neutron dose of 634 MWD/At; electrical resistivity 4.45 milliohm cm.
488*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to above but irradiated at 650 C by a neutron dose of 1273 MWD/At; electrical resistivity 4.44 milliohm cm.
489*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to above but irradiated at 650 C by a neutron dose of 1674 MWD/At; electrical resistivity 4.51 milliohm cm.
490*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to above but irradiated at 650 C by a neutron dose of 1977 MWD/At; electrical resistivity 4.49 milliohm cm.
491*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to above but irradiated at 650 C by a neutron dose of 2200 MWD/At; electrical resistivity 4.49 milliohm cm.
492*	1588	Yoshikawa, H.H.	1964		298.2	L-30	Similar to abuve but irradiated at 650 C by a neutron dose of 2597 MWD/At; electrical resistivity 4.50 milliohm cm.
493*	998, 999	Moser, J.B. and Kruger, O.L.	1964	P	298.2		Density 1.73 g cm^{-3} at room temp; thermal conductivity value calculated from measured thermal diffusivity and specific heat capacity.
494*	197	Brazel, J.P. and Styhr, K.H.	1968	R		POCO AXM grade	Unpurified; cylindrical stack specimen 5 cm in dia and 12.7 cm long composed of 3 cylinders, a 5 cm tall specimen and 2 guard cylinders (upper and lower) of equal height sufficient to total 12.7 cm; molded; electrical resistivity 1.69 x 10^{-3} ohm cm; density 1.73 g cm^{-3}; measured in argon atm in the AB with-grain plane; temp below 1500 K measured by thermocouples while temp above 1500 K measured by optical pyrometer.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
495*	1369	Störmer, R.	1934	E	290.2	Electrographite; I	0.5 cm in dia and 3 to 4 cm long; obtained from Siemens-Plania-Werke; electrical resistivity 0.7477 milliohm cm.
496*	1369	Störmer, R.	1934	E	290.2	Electrographite; II	Similar to above but electrical resistivity 5.97 milliohm cm.
497*	1370	Strauss, H. E.	1963	E	1301-3081	SF-HB graphite	0.5 in. dia cylindrical specimen prepared from a mixture of soft filler and hard binder, extruded, baked to 1200 C, then graphitized to 3000 C; electrical resistivity 1.019, 1.161, 1.183, 1.199, 1.214, 1.230, 1.239, 1.245, and 1.257 milliohm cm at 1063, 1625, 1720, 1829, 1989, 2177, 2349, 2534, and 2904 C, respectively.
498*	1370	Strauss, H. E.	1963	E	1596-2562	SF-HB graphite	The above specimen, 2nd run.
499*	1370	Strauss, H. E.	1963	E	1417-3101	SF-HB graphite	The above specimen, 3rd run.
500*	1370	Strauss, H. E.	1963	E	1515-3143	SF-HB graphite	The above specimen, 4th run.
501*	1370	Strauss, H. E.	1963	E	1953-3076	SF-HB graphite	The above specimen, 5th run.
502*	1370	Strauss, H. E.	1963	E	1392-2334		0.5 in. dia cylindrical specimen prepared from a mixture of soft filler and soft binder, extruded, baked to 1000 C; heat-treated at 1200, 1500, 1800, and 2100 C, successively; electrical resistivity 2.05, 1.90, and 1.72 milliohm cm at 1048, 1551, and 2054 C, respectively.
503*	1370	Strauss, H. E.	1963	E	1398-2603		The above specimen again heat-treated at 2400 C; electrical resistivity 1.29, 1.36, 1.42, and 1.46 milliohm cm at 1011, 1516, 2023, and 2313 C, respectively.
504*	1370	Strauss, H. E.	1963	E	1412-2938		The above specimen again heat-treated at 2800 C; electrical resistivity 1.06, 1.23, 1.34, and 1.41 milliohm cm at 1011, 1774, 2290, and 2627 C, respectively.
505*	1370	Strauss, H. E.	1963	R	1306-2002		Commercial graphite.
506	700	Juul, N. H.	1962	E	1364-2940	US graphite R	Prepared from Texas coke and M-30 coal tar pitch; density 1.55 g cm^{-3}; heat flow perpendicular to the axis of extrusion.
507*	700	Juul, N. H.	1962	E	1073-2571	W	Supplied by Graphite Specialties Co.; prepared from Thermax type filler; density 1.86 g cm^{-3}; measured perpendicular to the extrusion axis.
508*	700	Juul, N. H.	1962	E	1158-2640	US graphite Z	Prepared from phenol formaldehyde and phenol benzaldehyde; density 1.32 g cm^{-3}; measured perpendicular to the extrusion axis.
509	700	Juul, N. H.	1962	E	1181-2528	US graphite G	Prepared from Texas coke and M-30 coal tar pitch; density 1.55 g cm^{-3}; measured perpendicular to the extrusion axis.
510*	700	Juul, N. H.	1962	E	1199-3042	US graphite A	Similar to above but density 1.33 g cm^{-3}.
511	588	Hansen, C. A.	1909	L	373-713		The results of Hansen, C. A. (see curve No. 358) recalculated by Richards, J. W.
512*	1578	Worth, K.	1963	E	1321-2287	GLI-S1	Supplied by Great Lakes Carbon Corp.
513*	1578	Worth, K.	1963	E	1630-2395	GLI-C3	Supplied by Great Lakes Carbon Corp.
514*	1578	Worth, K.	1963	E	1261-2276	NCI-C2	Supplied by National Carbon Co.
515*	1578	Worth, K.	1963	E	1186-2295	NCI-S2	Supplied by National Carbon Co.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
516*	951	Meyers, C. and Koyama, K.	1968	P	301-1035	CBN grade; 1-C	Disk specimen 0.5 in. in dia and 0.045 in. thick; density 1.706 g cm^{-3}; heat flow perpendicular to molding pressure; thermal conductivity value calculated from the measurement of thermal diffusivity (measured by xeon flash technique), specific heat and density.
517	951	Meyers, C. and Koyama, K.	1968	P	300-1038	CBN grade; 1-C	Similar to the above specimen except heat flow parallel to molding pressure.
518*	951	Weeks, C.C. and Nakata, M. M. (Arthur D. Little, Inc.)	1969	R	1294-2215	RVD; F-2	Specimen 1.3 cm I.D., 5 cm O.D. and 2.54 cm long.
519*	1521	Weeks, C.C. and Nakata, M. M. (Arthur D. Little, Inc.)	1969	R	1270-2226	RVD; G-2	Similar to the above.
520*	1521	Weeks, C.C. and Nakata, M. M. (Arthur D. Little, Inc.)	1969	R	1255-2286	AXM-5Q1	Similar to the above.
521*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	549-1058	RVD grade; sample AA-2 No. 1	Specimen 1 in. in dia and 1 in. long; supplied by Arthur D. Little, Inc.; density 1.887 g cm^{-3}; measured in the with-grain direction; Armco iron used as comparative material.
522*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	511-1097	RVD grade; sample AA-2 No. 2	Similar to the above except specimen 0.9990 in. long; density 1.878 g cm^{-3}; run 1.
523*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	1085-1252	RVD grade; sample AA-2	The above specimen, run 2.
524*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	526-983	RVD grade; sample BB-2	Similar to the above except specimen 1 in. long; density 1.889 g cm^{-3}.
525*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1397-2488	RVD grade; specimen FF-3	Specimen 0.250 in. I.D., 1.500 in. O.D., and 1.875 in. long; supplied by Arthur D. Little, Inc.; density 1.907 g cm^{-3}; measured in the with-grain direction; run 1.
526*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	2441-2721	RVD grade; specimen FF-3	The above specimen run No. 2.
527*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1187-1864	RVD grade; specimen GG-3	Similar to the above specimen except density 1.871 g cm^{-3}; run No. 1.
528*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	2226-3074	RVD grade; specimen GG-3	The above specimen run No. 2.
529*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1309-2994	RVD grade; specimen HH-3	Similar to the above specimen except density 1.875 g cm^{-3}; run No. 1.
530*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	549-1086	RVD grade; specimen A-3	Specimen 1 in. in dia and 0.9991 in. long; supplied by Arthur D. Little, Inc; density 1.869 g cm^{-3}; measured in the across-grain direction; Armco iron used as comparative material.
531*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	532-1287	AXM-5QI; sample 11A	Specimen 1 in. in dia and 1 in. long; supplied by Arthur D. Little, Inc; density 1.761 g cm^{-3}; measured in vacuum.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
532*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	516-993	AXM-5QI; sample 13-B	Similar to the above except specimen 0.9980 in. long; density 1.764 g cm^{-3}.
533*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	843-1112	AXM-5QI; sample 8A	Similar to the above except specimen 0.9981 in. long; density 1.769 g cm^{-3}; not measured in vacuum.
534*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	533-1269	AXM-5QI; sample 19C	Similar to the above specimen except density 1.75 g cm^{-3}; measured in vacuum.
535*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	522-1172	AXM-5QI; sample 9A	Similar to the above except specimen 1 in. long; density 1.768 g cm^{-3}; not measured in vacuum; run No. 1.
536*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	537-776	AXM-5QI; sample 9A	The above specimen run No. 2.
537*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	C	544-1186	AXM-5QI; sample 9-B	Similar to the above specimen except density 1.762 g cm^{-3}; run No. 1.
538*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1805-3010	AXM-5QI; specimen 2AR	Specimen 0.25 in. I.D., 1.500 in. O.D., and 1.875 in. long; supplied by Arthur D. Little, Inc; density 1.758 g cm^{-3}.
539*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1288-3044	AXM-5QI; specimen 2CR	Similar to the above specimen except density 1.771 g cm^{-3}.
540*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1693-2461	AXM-5QI; specimen 1AR	Similar to the above specimen except density 1.754 g cm^{-3}.
541*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1762-3038	AXM-5QI; specimen 1CR	Similar to the above specimen except density 1.755 g cm^{-3}.
542*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1189-2516	AXM-5QI; specimen 1ER	Similar to the above specimen except density 1.757 g cm^{-3}; run No. 1.
543*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	2495-3014	AXM-5QI; specimen 1ER	The above specimen run No. 2.
544*	1346	Southern Research Institute (Arthur D. Little, Inc.)	1969	R	1692-3048	AXM-5QI; specimen 9C	Similar to the above except density 1.773 g cm^{-3}.
545*	1045	Null, M.R. and Lozier, W.W.	1969	P	1600	CEP grade; block D	Specimen 12.7 mm in dia and 7.76 mm thick; electrical resistivity 4.4 milliohm cm at room temp; measured in the across-grain direction; thermal conductivity value calculated from the measurement of thermal diffusivity, using specific heat data of Spence, G.B., WADD Tech. Rept. 61-72, Vol. XLI, Nov. 1963, and density 1.614 g cm^{-3} at room temp.
546*	1045	Null, M.R. and Lozier, W.W.	1969	P	2000	CEP grade; block D.	Similar to the above except specimen 7.61 mm thick.
547*	1045	Null, M.R. and Lozier, W.W.	1969	P	2200	CEP grade; block D	Similar to the above except specimen 7.90 mm thick; density 1.618 g cm^{-3} at room temp.
548*	1045	Null, M.R. and Lozier, W.W.	1969	P	2500	CEP grade; block D	Similar to the above.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
549*	1045	Null, M.R. and Lozier, W.W.	1969	P	2800	CEP grade; block D	Similar to the above.
550*	1045	Null, M.R. and Lozier, W.W.	1969	P	1600	CEP grade; block D	Specimen 12.7 mm in dia and 7.78 mm thick; electrical resistivity 5.2 milliohm cm at room temp; measured in the with-grain direction; thermal conductivity value calculated from the same method as the above except using density 1.621 g cm^{-3} at room temp.
551*	1045	Null, M.R. and Lozier, W.W.	1969	P	2000	CEP grade; block D	Similar to the above except specimen 7.64 mm thick.
552*	1045	Null, M.R. and Lozier, W.W.	1969	P	2200	CEP grade; block D	Similar to the above except specimen 7.84 mm thick.
553*	1045	Null, M.R. and Lozier, W.W.	1969	P	2500	CEP grade; block D	Similar to the above except specimen 7.91 mm thick.
554*	1045	Null, M.R. and Lozier, W.W.	1969	P	2800	CEP grade; block D	Similar to the above except specimen 7.84 mm thick.
555*	996, 995	Morrison, B.H.	1969	P	1048-2873	AAQ grade	Polyfurfuryl alcohol bonded material, has been graphitized at 2800 C; electrical resistivity (parallel to the extrusion direction) of 11.60 μohm cm; density 1.901 g cm^{-3}; thermal conductivity values calculated from the measurements of thermal diffusivity, density, and using specific heat data of Spence, G. B., WADD-TR-61-72, Vol. XLI, July 1963; reported values obtained from smooth curve.
556*	978	Moeller, C.E. and Wilson, D.R.	1960	R	558-1644	CS-312	2.875 O.D. x 0.875 in. I.D. x 5.5 in. long; obtained from National Carbon Co.; heat flow perpendicular to the extrusion axis.
557*	638	Howard, R.A. and Piper, E.L.	1964	L	298.2	RVC grade	0.5 in. dia x 5 in. long; prepared by pressure curing; bulk density 1.81 g cm^{-3}; electrical resistivity 1260 μohm cm; heat flow with the grain.
558*	638	Howard, R.A. and Piper, E.L.	1964	L	298.2	RVC grade	Similar to the above specimen but heat flow across the grain; electrical resistivity 1420 μohm cm.
559*	1458	Van de Velde, J., Ockfen, H., and Noels, T.	1968	C	298.2	French nuclear graphite; A	One bitumin impregnation; bulk density 1.68 g cm^{-3}; heat flow with grain; copper used as comparative material.
560*	1458	Van de Velde, J., et al.	1968	C	298.2	French nuclear graphite; A	Similar to above but measured with heat flow against grain.
561*	1458	Van de Velde, J., et al.	1968	C	298.2	French nuclear graphite; A	Similar to above; specimen irradiated by a neutron flux 1.12 x 10^{20} n cm^{-2} in CO_2 atm at 309 C; heat flow with grain.
562*	1458	Van de Velde, J., et al.	1968	C	298.2	German nuclear graphite; B	Bulk density 1.67 g cm^{-3}; heat flow with grain; copper used as comparative material.
563*	1458	Van de Velde, J., et al.	1968	C	298.2	German nuclear graphite; B	Similar to above but heat flow against grain.
564*	1458	Van de Velde, J., et al.	1968	C	298.2	German nuclear graphite; B	Similar to above; specimen irradiated by a neutron flux of 1.12 x 10^{20} n cm^{-2} in CO_2 atm at 307 C; heat flow with grain.
565*	1458	Van de Velde, J., et al.	1968	C	298.2	British PGA; C	Bulk density 1.69 g cm^{-3}; heat flow with grain; copper used as comparative material.
566*	1458	Van de Velde, J., et al.	1968	C	298.2	British PGA; C	Similar to above but heat flow against grain.
567*	1458	Van de Velde, J., et al.	1968	C	298.2	British PGA; C	Similar to above; specimen irradiated by a neutron flux 1.12 x 10^{20} n cm^{-2} in CO_2 atm at 319 C; heat flow with grain.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
568*	1458	Van de Velde, J., Ockfen, H., and Noels, T.	1968	C	298.2	British PG-isotropic type; D	Bulk density 1.77 g cm^{-3}; heat flow with grain; copper used as comparative material.
569*	1458	Van de Velde, J., et al.	1968	C	298.2	British PG-isotropic type; D	Similar to above but heat flow against grain.
570*	1458	Van de Velde, J., et al.	1968	C	298.2	British PG-isotropic type; D	Similar to above; specimen irradiated by a neutron flux 1.12 x 10^{20} n cm^{-2} in CO_2 atm at 249 C; heat flow with grain.
571*	493	Giuliani, S.	1967	C	363-729	CL3780; 21	1.2 to 1.3 cm in dia and 1.8 to 2.5 cm long; molded; density 1.622 g cm^{-3}; Armco iron used as comparative material; heat flow parallel to the molding direction.
572*	493	Giuliani, S.	1967	C	373-733	CL3780; 22	Similar to above but density 1.645 g cm^{-3} and heat flow perpendicular to the direction of molding.
573*	493	Giuliani, S.	1967	C	364-734	CL3780; 49	Similar to above but density 1.617 g cm^{-3} and heat flow parallel to the molding direction.
574*	493	Giuliani, S.	1967	C	381-710	CL3780; CR49	Similar to above but specimen irradiated by a thermal neutron flux of 1.50 x 10^{20} n cm^{-2} at 450 C for 622 hrs.
575*	493	Giuliani, S.	1967	C	370-753	CL3780; 50	Similar to the above specimen but not irradiated; density 1.637 g cm^{-3}; heat flow perpendicular to the molding direction.
576*	493	Giuliani, S.	1967	C	385-708	CL3780; CR50	Similar to above but specimen irradiated by a thermal neutron flux of 1.75 x 10^{20} n cm^{-2} at 450 C for 622 hrs.
577*	493	Giuliani, S.	1967	C	384-753	CL3780; ARR2	1.2 to 1.3 cm in dia and 1.8 to 2.5 cm long; molded; irradiated by a thermal neutron flux of 1.85 x 10^{20} n cm^{-2} at 440 C for 662 hrs; Armco iron used as comparative material; heat flow parallel to the molding direction.
578*	493	Giuliani, S.	1967	C	372-712	CL3780; ARR5	Similar to above but specimen irradiated by a thermal neutron flux of 1.72 x 10^{20} n cn^{-2} and heat flow perpendicular to the molding direction.
579*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade; specimen T-31A	Specimen 0.5 x 0.5 x 5 in.; cut from 103 in. dia billet No. 1; bulk density 1.862 g cm^{-3}; measured with grain.
580*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade; specimen T-31A	The above specimen measured in the across-grain direction; bulk density 1.855 g cm^{-3}.
581*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade; specimen T-32B	Similar to the above specimen except bulk density 1.872 g cm^{-3}; measured with grain.
582*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade; specimen T-32B	The above specimen measured in the across-grain direction; bulk density 1.867 g cm^{-3}.
583*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade;	Similar to the above specimen except bulk density 1.859 g cm^{-3}; measured with grain.
584*	376, 378	Dull, R.B. and Lafyatis, P.G.	1964	L	298.2	CFW grade; specimen T-33C	The above specimen measured in the across-grain direction; bulk density 1.855 g cm^{-3}.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
585*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-34A	Similar to the above specimen except bulk density 1.866 g cm^{-3}; measured with grain.
586*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-34A	The above specimen measured in the across-grain direction; bulk density 1.855 g cm^{-3}.
587*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-35B	Similar to the above specimen except bulk density 1.854 g cm^{-3}; measured with grain.
588*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-35B	The above specimen measured in the across-grain direction; bulk density 1.858 g cm^{-3}.
589*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-36C	Similar to the above specimen except bulk density 1.854 g cm^{-3}; measured with grain.
590*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-36C	The above specimen measured in the across-grain direction; bulk density 1.856 g cm^{-3}.
591*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-37A	Similar to the above specimen except bulk density 1.872 g cm^{-3}; measured with grain.
592*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-37A	The above specimen measured in the across-grain direction; bulk density 1.871 g cm^{-3}.
593*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-38B	Similar to the above specimen except bulk density 1.860 g cm^{-3}; measured with grain.
594*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-38B	The above specimen measured in the across-grain direction; bulk density 1.868 g cm^{-3}.
595*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-39C	Similar to the above specimen except bulk density 1.862 g cm^{-3}; measured with grain.
596*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-39C	The above specimen measured in the across-grain direction; bulk density 1.855 g cm^{-3}.
597*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-40A	Similar to the above specimen except bulk density 1.882 g cm^{-3}; measured with grain.
598*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-40A	The above specimen measured in the across-grain direction; bulk density 1.880 g cm^{-3}.
599*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-41B	Similar to the above specimen except bulk density 1.870 g cm^{-3}; measured with grain.
600*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-41B	The above specimen measured in the across-grain direction; bulk density 1.876 g cm^{-3}.
601*	376, 378	Dull, R. B. and Lafyatis, P. G	1964	L	298.2	CFW grade; specimen T-42C	Similar to the above specimen except bulk density 1.842 g cm^{-3}; measured with grain.
602*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-42C	The above specimen measured in the across-grain direction; bulk density 1.853 g cm^{-3}.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
603*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-43A	Similar to the above specimen except bulk density 1.873 g cm^{-3}; measured with grain.
604*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-43A	The above specimen measured in the across-grain direction; bulk density 1.863 g cm^{-3}.
605*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-44B	Similar to the above specimen except bulk density 1.859 g cm^{-3}; measured with grain.
606*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-44B	The above specimen measured in the across-grain direction; bulk density 1.862 g cm^{-3}.
607*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-45C	Similar to the above specimen except measured with grain.
608*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen T-45C	The above specimen measured in the across-grain direction; bulk density 1.858 g cm^{-3}.
609*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-31A	Similar to the above specimen except bulk density 1.856 g cm^{-3}; measured with grain.
610*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-31A	The above specimen measured in the across-grain direction; bulk density 1.872 g cm^{-3}.
611*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-32B	Similar to the above specimen except bulk density 1.841 g cm^{-3}; measured with grain.
612*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-32B	The above specimen measured in the across-grain direction; bulk density 1.864 g cm^{-3}.
613*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-33C	Similar to the above specimen except bulk density 1.866 g cm^{-3}; measured with grain.
614*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-33C	The above specimen measured in the across-grain direction; bulk density 1.855 g cm^{-3}.
615*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-34A	Similar to the above specimen except bulk density 1.872 g cm^{-3}; measured with grain.
616*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-34A	The above specimen measured in the across-grain direction; bulk density 1.871 g cm^{-3}.
617*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-35B	Similar to the above specimen except bulk density 1.869 g cm^{-3}; measured with grain.
618*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-35B	The above specimen measured in the across-grain direction; bulk density 1.863 g cm^{-3}.
619*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-36C	Similar to the above specimen except bulk density 1.871 g cm^{-3}; measured with grain.
620*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-36C	The above specimen measured in the across-grain direction; bulk density 1.868 g cm^{-3}.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
621*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-37A	Similar to the above specimen except bulk density 1.871 g cm^{-3}; measured with grain.
622*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-37A	The above specimen measured in the across-grain direction; bulk density 1.862 g cm^{-3}.
623*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-38B	Similar to the above specimen except bulk density 1.870 g cm^{-3}; measured with grain.
624*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-38B	The above specimen measured in the across-grain direction; bulk density 1.868 g cm^{-3}.
625*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-39C	Similar to the above specimen except bulk density 1.854 g cm^{-3}; measured with grain.
626*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-39C	The above specimen measured in the across-grain direction; bulk density 1.862 g cm^{-3}.
627*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-40A	Similar to the above specimen except bulk density 1.854 g cm^{-3}; measured with grain.
628*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-40A	The above specimen measured in the across-grain direction; bulk density 1.859 g cm^{-3}.
629*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-41B	Similar to the above specimen except bulk density 1.866 g cm^{-3}; measured with grain.
630*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-41B	The above specimen measured in the across-grain direction; bulk density 1.867 g cm^{-3}.
631*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-42C	Similar to the above specimen except measured with grain.
632*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-42C	The above specimen measured in the across-grain direction; bulk density 1.871 g cm^{-3}.
633*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-43A	Similar to the above specimen except bulk density 1.863 g cm^{-3}; measured with grain.
634*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-43A	The above specimen measured in the across-grain direction; bulk density 1.865 g cm^{-3}.
635*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-44B	Similar to the above specimen except bulk density 1.867 g cm^{-3}; measured with grain.
636*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-44B	The above specimen measured in the across-grain direction; bulk density 1.865 g cm^{-3}.
637*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-45C	Similar to the above specimen except bulk density 1.857 g cm^{-3}; measured with grain.
638*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	298.2	CFW grade; specimen B-45C	The above specimen measured in the across-grain direction; bulk density 1.863 g cm^{-3}.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
639*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	L	1145-1963	CFW grade; specimen B-31C	Similar to the above except density 1.855 g cm^{-3}.
640	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	P	2200	CFW grade; specimen No. 1	Specimen 0.127 cm thick, cut with thickness across-grain from contract specimen T-58B; thermal conductivity values calculated from the measurement of thermal diffusivity (measured in the across-grain direction), using specific heat data of 0.5 cal g^{-1} K^{-1} and bulk density of 1.85 g cm^{-3}.
641*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	P	2200	CFW grade; specimen No. 2	Similar to the above specimen.
642*	376, 378	Dull, R. B. and Lafyatis, P. G.	1964	P	2200	CFW grade; specimen No. 3	Similar to the above except specimen 0.130 cm thick.
643*	1556	White, J. L. and Koyama, K.	1968	P	298.2	HW	Prepared by hot-working the mixture of 80 graphitized petroleum coke and 20 binder pitch; bulk density 2.30 g cm^{-3}; porosity <1%; heat flow parallel to the direction of hot-working; thermal conductivity values calculated from measured thermal diffusivity and density using literature specific heat capacity data; measured at various strain in hot-working ranging from 0 to -0.528%.
644*	1556	White, J. L. and Koyama, K.	1968	P	298.2	HW	Similar to above but heat flow perpendicular to the direction of hot-working; measured at various strain in hot-working ranging from 0 to -0.526%.
645*	1556	White, J. L. and Koyama, K.	1968	P	298.2	HWLC-Zr	1.8 Zr; prepared by hot-working with a dispersed liquid carbide phase the mixture of 80 graphitized petroleum coke and 20 binder pitch; bulk density 2.30 g cm^{-3}; porosity <1%; heat flow parallel to the direction of hot-working; same measuring method as above; measured at various strain in hot-working ranging from 0 to -0.595%.
646*	1556	White, J. L. and Koyama, K.	1968	P	298.2	HWLC-Zr	Similar to above but heat flow perpendicular to the direction of hot-working; measured at various strain in hot-working ranging from 0 to -0.596%.
647*	950	Meyers, C.	1968	P	298-1094	UCC grade TS-814; sample No. 2-6 (outer)	<0.010 Fe and 0.0120 ash; specimen 0.5 in. in dia and 0.045 in. thick; density ~1.81 g cm^{-3}; specimen axis taken perpendicular to the log-axis at near edge location; thermal conductivity values calculated from thermal diffusivity measurements (by xenon flash technique) using specific heat data of Rossini, F. D., et al., Carnegie Press, Pittsburgh, 1953.
648*	950	Meyers, C.	1968	P	295-1053	UCC grade TS-814; sample No. 2-1 (inner)	Similar to the above specimen except density 1.78 g cm^{-3}; specimen axis taken perpendicular to the log-axis at near centerline location.
649*	950	Meyers, C.	1968	P	292-1074	UCC grade TS-814; (center)	Similar to the above specimen except density 1.81 g cm^{-3}; specimen axis taken parallel to the log-axis at near centerline location.
650	1496	Wagner, P. and Dauelsberg, L. B.	1968	P	155-547	Grade SX-5	Specimen 1.25 cm in dia and 15 cm long; fine-grained extruded specimen supplied by Speer Carbon Co.; maximum particle size 0.081 cm; heat flow measured parallel to the direction of extrusion (X); thermal conductivity values calculated from thermal diffusivity measurements (used flash transient technique), specific heat data and density.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
651*	1496	Wagner, P. and Dauelsberg, L. B.	1968	P	460-895	Grade SX-5	The above specimen measured by steady-state linear heat flow comparison method, and molybdenum used as comparative material.
652*	1496	Wagner, P. and Dauelsberg, L. B.	1968	R	1250-2704	Grade SX-5	The above specimen measured by radial heat flow method.
653*	1496	Wagner, P. and Dauelsberg, L. B.	1968	P	155-816	Grade SX-5	Similar to the above specimen except heat flow measured perpendicular to the direction of extrusion (Z); thermal conductivity values calculated from thermal diffusivity measurements (used flash transient technique), specific heat data and density.
654*	1496	Wagner, P. and Dauelsberg, L. B.	1968	C	466-965	Grade SX-5	The above specimen measured by steady-state linear heat flow comparison method, and molybdenum used as comparative material.
655*	1496	Wagner, P. and Dauelsberg, L. B.	1968	R	1173-2702	Grade SX-5	The above specimen measured by radial heat flow method.
656*	394	Engle, G. B. and Koyama, K.	1968	E	1473	S-780	Specimen 0.25 x 0.8 x 0.05 in.; apparent density 1.89 g cm^{-3}; electrical resistivity 7.00 x 10^{-4} ohm cm; measured in the direction normal to the longitudinal axis of the parent log.
657*	394	Engle, G. B. and Koyama, K.	1968	E	1473	TS-711 (T)	Similar to the above specimen.
658*	394	Engle, G. B. and Koyama, K.	1968	E	1473	H-207-85	Similar to the above specimen except apparent density 1.84 g cm^{-3}.
659*	394	Engle, G. B. and Koyama, K.	1968	E	1473	TS-711 (N)	Similar to the above specimen except apparent density 1.88 g cm^{-3}; electrical resistivity 12.75 x 10^{-4} ohm cm.
660*	394	Engle, G. B. and Koyama, K.	1968	E	1473	CHN	Similar to the above specimen except apparent density 1.85 g cm^{-3}; electrical resistivity 9.00 x 10^{-4} ohm cm.
661*	394	Engle, G. B. and Koyama, K.	1968	E	1473	NC-8	Similar to the above specimen except apparent density 1.72 g cm^{-3}; electrical resistivity 7.05 x 10^{-4} ohm cm.
662*	394	Engle, G. B. and Koyama, K.	1968	E	1473	H-315-A	Similar to the above specimen except apparent density 1.85 g cm^{-3}; electrical resistivity 7.50 x 10^{-4} ohm cm.
663*	394	Engle, G. B. and Koyama, K.	1968	E	1473	H-319	Similar to the above specimen except apparent density 1.80 g cm^{-3}; electrical resistivity 8.90 x 10^{-4} ohm cm.
664*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 49B-2	Composed of 80 ground pyrolytic graphite and 20 thermax carbon black (Thermatomic Carbon Co.) as filler and 40 Varcum as binder, hot-molded at 2000 psi pressure and 900 C; graphitized bulk density 1.703 g cm^{-3}; electrical resistivity 1913 μohm cm; heat flow measured with grain; measuring temp assumed at room temp.
665*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 49B-2	Similar to the above specimen except electrical resistivity 11017 μohm cm; heat flow measured across-grain.
666*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50B-1	Composed of 80 natural graphite flakes (Southwestern graphite Co. grade 1651) and 20 thermax carbon black (Thermatomic Carbon Co.) as filler and 20 pitch as binder; hot-molded at 1500 psi pressure and 900 C; graphitized bulk density 1.648 g cm^{-3}; electrical resistivity 877 μohm cm; heat flow measured with-grain; measuring temp assumed at room temp.
667*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50B-1	Similar to the above specimen except electrical resistivity 5387 μohm cm; heat flow measured across-grain.

* Not shown in figure.

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
668*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50D-1	Composed of 100 natural graphite flakes (Southwestern graphite Co. grade 1651) as filler and 30 Varcum as binder; hot-molded at 1000 psi pressure and 900 C; graphitized bulk density 1.673 g cm^{-3}; electrical resistivity 986 μohm cm; heat flow measured with-grain; measuring temp assumed at room temp.
669*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50D-1	Similar to the above specimen except electrical resistivity 3368 μohm cm; heat flow measured across-grain.
670*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50I-1	Composed of 80 ground pyrolytic graphite and 20 needle coke flour (Carbon Products Div., Union Carbide Corp) as filler and 30 pitch as binder; hot-molded at 1000 psi pressure and 870 C; graphitized bulk density 1.649 g cm^{-3}; electrical resistivity 1530 μohm cm; heat flow measured with-grain; measuring temp assumed at room temp.
671*	1335	Smith, M. G.	1968		298.2	Anisotropic graphite; 50I-1	Similar to the above specimen except electrical resistivity 18730 μohm cm; heat flow measured across-grain.
672	899, 900	Masuyama, T.	1966	L	83-111	Low permeability graphite	Composed of reactor graphite and hard carbon; specimen 5 mm I. D., 10 mm O. D., and 100 mm long; baked at 800 C; density ~1.83 g cm^{-3}.
673	899, 900	Masuyama, T.	1966	L	83-128	Low permeability graphite	The above specimen irradiated in the fuel aperture of a graphate-moderated reactor at Brookhaven National Laboratory at the average temp of 140 C and at the irradiation dose of 94.2 MWD = 3.4 x 10^{19} nvt (thermal neutron) = 6.6 x 10^{18} nvt (fast neutron E >0.6 MeV).
674*	899, 900	Masuyama, T.	1966	L	87-139	Low permeability graphite	The above specimen measured after annealed 1 hr at 400 C.
675	899, 900	Masuyama, T.	1966	L	82-129	Low permeability graphite	The above specimen measured after annealed 1 hr at 800 C.
676*	1608	Zeigarnik, V. A., Peletskii, V. E., and Tarabanov, A. S.	1968		731-1435	Graphite RV; 1	Obtained by pressing (300-320 kg cm^{-2} pressure) into die; annealed at 1000 C; graphitization at 2300 C; large grained, non-homogeneous material; apparent density 1.56 g cm^{-3}; porosity 27%.
677*	1608	Zeigarnik, V. A., et al.	1968		769-1160	Graphite RV; 2	Similar to the above.
678*	1608	Zeigarnik, V. A., et al.	1968		714-1152	Graphite RV; 3	Similar to the above.
679*	1608	Zeigarnik, V. A., et al.	1968		692-976	Graphite RV; 4	Similar to the above.
680*	1608	Zeigarnik, V. A., et al.	1968		991-1184	Graphite RV; 5	Similar to the above.
681*	1608	Zeigarnik, V. A., et al.	1968		1279-1642	Graphite RV; 6	Similar to the above.
682*	1608	Zeigarnik, V. A., et al.	1968		715-1131	Graphite N; 1	Similar to the above except specimen small grained, very homogeneous; effective pore dia = 11 μ; apparent density 1.82 g cm^{-3}; porosity 16%.
683*	1608	Zeigarnik, V. A., et al.	1968		618-1013	Graphite N; 2	Similar to the above.
684*	1608	Zeigarnik, V. A., et al.	1968		671-1055	Graphite N; 3	Similar to the above.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
685*	1608	Zeigarnik, V.A., Peletskii, V.E., and Tarabanov, A.S.	1968		995-1630	Graphite N;4	Similar to the above.
686*	212	Briggs, R.B.	1964	R	324-671	Grade CGB	Specimen consists of a 9 in. tall stack of 2 in. O.D., 0.375 in. I.D., and 1 in. thick disk; bulk density 1.824 g cm^{-3}; heat flow measured perpendicular to the extrusion direction.
687*	895	Mason, I.B. and Knibbs, R.H.	1962	C	311-853	Reactor grade carbon stock	Heat-treated at 1500 C; density 1.64 g cm^{-3}; heat flow measured parallel to extrusion; Armco iron used as comparative material.
688*	895	Mason, I.B. and Knibbs, R.H.	1962	C	310-804	Reactor grade carbon stock	Heat-treated at 1800 C; density 1.61 g cm^{-3}; electrical resistivity measured parallel to extrusion reported as 3.59, 3.49, 3.37, 3.22, and 3.15 milliohm cm at 61, 148, 328, 447, and 516 C, respectively.
689*	1392	Taylor, R., Gilchrist, K.E., and Poston, L.J.	1967	P	125-923	PGA	Polycrystalline; density 1.70 g cm^{-3}; heat flow parallel to the direction of extrusion; thermal conductivity values calculated from thermal diffusivity data measured by the heat pulse method with specific heat capacity taken from Taylor, R. (Phil. Mag., 13 (121), 157-66, 1966).
690*	1392	Taylor, R., et al.	1967	P	91-789	PGA	Similar to above but density 1.69 g cm^{-3} and heat flow perpendicular to the direction of extrusion.
691*	1392	Taylor, R., et al.	1967	P	101-912	ZTA	Polycrystalline; density 1.92 g cm^{-3}; heat flow parallel to the direction of extrusion; same measuring method as above.
692*	1392	Taylor, R., et al.	1967	P	109-906	ZTA	Similar to above but density 1.95 g cm^{-3} and heat flow perpendicular to the direction of extrusion.
693*	1392	Taylor, R., et al.	1967	P	85-884	Gilsocarbon;A	Isotropic specimen; density 1.80 g cm^{-3}; same measuring method as above.
694*	1392	Taylor, R., et al.	1967	P	119-962	Gilsocarbon;B	Similar to above but density 1.60 g cm^{-3}.
695*	199	Breckenridge, R.G.	1960		1229-2386	C-132	Cut from a rod of the coke-base 1400 C gas-baked carbon; baked at 3000 C for 30 min; electrical resistivity reported as 0.75, 0.84, 0.86, 0.89, 0.91, 0.94, 0.98, 0.97, 1.00, 1.03, and 1.07 milliohm cm at 1229, 1372, 1484, 1580, 1652, 1751, 1863, 1974, 2131, 2263, and 2386 K, respectively.
696*	199	Breckenridge, R.G.	1960		1133-2346	C-132	Cut from the same rod as the above specimen; baked at 2200 C for 1 hr; electrical resistivity reported as 1.33, 1.33, 1.34, 1.34, 1.35, 1.33, 1.34, 1.34, 1.30, 1.30, 1.30, and 1.28 milliohm cm at 1133, 1213, 1308, 1406, 1507, 1614, 1717, 1841, 1970, 2066, 2203, and 2346 K, respectively.
697*	199	Breckenridge, R.G.	1960		1112-1800	C-132	Cut from the same rod as the above specimen; baked at 1600 C for 1 hr; electrical resistivity reported as 3.62, 3.39, 3.37, 3.31, 3.24, 3.23, 3.19, 3.19, 3.23, 3.20, 3.10, and 3.16 milliohm cm at 1112, 1183, 1246, 1320, 1368, 1434, 1497, 1566, 1632, 1697, 1774, and 1800 K, respectively.
698*	202	Brenden, B.B. and Newkirk, H.W.	1959	R	1368-1814	Graphite No.1	Specimen 0.635 cm in dia and 0.953 cm long; cut from spectroscopic electrodes; density 1.60 g cm^{-3} (71.1± 0.5% of theoretical value).
699*	202	Brenden, B.B. and Newkirk, H.W.	1959	R	1138-1680	Graphite No.2	Specimen 0.640 cm in dia and 0.953 cm long; spectroscopic electrodes; density 1.58 g cm^{-3} (70.2± 0.5% of theoretical value).

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
700*	1009	Mrozowski, S., Andres, J.F., Repetski, J., Strauss, H.E., and Wobschall, D.C.	1958	E	1593-3198		Prepared from raw Texas coke (calcined at 1200 C for 4 hrs in the baking furnace, crushed, ground, sorted into different granule sizes) and Medium No. 30 coal tar pitch; mixing 100 parts (by weight) of coke and 40 parts of resin in a paddle mixer with 3 parts of extrusion oil (Vacwax 80 from Socony Vacuum Co.) added, extruded at 120 C into rods of dimensions 0.5 in. dia x 8 in. long, the rods packed vertically in a sand-coke mixture in a silicon carbide crucible, baked at 150 C for 5 hrs, thereafter with temp increase at 8.9 C hr^{-1} up to 1000 C, then heat-treated in a graphitizing furnace in nitrogen atm at 3100 C for 10 min; measured in argon atm.
701*	1009	Mrozowski, S., et al.	1958	E	1595-3161		Prepared from raw Texas coke (as above) and phenol benzaldehyde resin; mixing 100 parts (by weight) of coke and 40 parts of resin at 110 C for 5 min, with 3 parts of extrusion oil (as above) added at 1 min before end of mixing, extruded at 120 C under a pressure of 6100 psi into rods of dimensions 0.5 in. dia x 8 in. long, the rods packed vertically in a sand-coke mixture in a silicon carbide crucible, baked at 150 C for 5 hrs, thereafter with temp increased at 8.9 C hr^{-1} up to 1000 C, then heat-treated in a graphitizing furnace in nitrogen atm at 3100 C for 10 min; particle size 100-150 μ; measured in argon atm.
702*	1009	Mrozowski, S., et al.	1958	E	1559-3145		Prepared from phenol formaldehyde resin (175 Durez) and Medium No. 30 coal tar pitch; mixing 100 parts (by weight) of resin and 50 parts of pitch at 160 C for 15 min with 3 parts of extrusion oil (Vacwax 80 from Socony Vacuum Co.) added 3 min before the end of mixing, extruded at 120 C under a pressure of 10200 psi into rods of dimensions 0.5 in. dia x 8 in. long, the rods packed vertically in a sand-coke mixture in a silicon carbide crucible, baked at 150 C for 5 hrs, thereafter with temp increased at 8.9 C hr^{-1} up to 1000 C, then heat-treated in a graphitizing furnace in nitrogen atm at 3100 C for 10 min; particle size 100-150 μ; measured in argon atm.
703*	1009	Mrozowski, S., et al.	1958	E	1633-2842		Prepared from 100 parts (by weight) of phenol formaldehyde resin (175 Durez) and 50 parts of phenol benzaldehyde resin; same fabrication method as above but mixed at 100 C for 5 min with 3 parts of extrusion oil added at 1 min before end of mixing, and extrusion pressure 14300 psi; particle size 150-200 μ; measured in argon atm.
704	1441	Tyler, W.W. and Wilson, A.C., Jr.	1952	L	22-277	Lampblack 86-16	0.425 in. dia; prepared by molding pitch bonded lampblack 86-16; specimen axis parallel to preferred c-axis.
705*	1404	Thielke, N.R. (compiler)	1959	E	1376-2228	Natural graphite	Specimen 0.25 in. in dia and 3.5 in. long; obtained from National Carbon Co.; pressed; thermal conductivity data extracted from a smooth curve which calculated from an average of repeated runs.

* Not shown in figure.

TABLE 38. THERMAL CONDUCTIVITY OF MISCELLANEOUS GRAPHITES - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
706*	1329	Smith, A.W. and Rasor, N.S.	1956	E	10-205	SA-25	Polycrystalline; molded from lampblack; pitch bonded; particle size 0.3 μ; crystallite size 0.05 μ; density 1.55 g cm^{-3} at 25 C.
707*	1329	Smith, A.W. and Rasor, N.S.	1956	E	22-101	SA-25	The above specimen exposed to neutron bombardment of 12.5 MWD/T at ~30 C.
708*	1329	Smith, A.W. and Rasor, N.S.	1956	E	21-115	SA-25	The above specimen exposed to neutron bombardment of 22.7 MWD/T at ~30 C.
709*	1329	Smith, A.W. and Rasor, N.S.	1956	E	15-120	SA-25	The above specimen exposed to neutron bombardment of 146 MWD/T at ~30 C.
710*	1329	Smith, A.W. and Rasor, N.S.	1956	E	13-63	SA-25	The above specimen exposed to neutron bombardment of 460 MWD/T at ~30 C.
711*	1329	Smith, A.W. and Rasor, N.S.	1956	E	46-112	SA-25	The above specimen exposed to neutron bombardment of 460 MWD/T at ~30 C (probably second run of the above specimen).
712*	1177	Rasor, N.S.	1955	E	10-290	SA-25	Made from lampblack; molded; room temp properties: density 1.55 g cm^{-3}, thermoelectric power +9.6 μvolt K^{-1}, Hall coefficient +0.14 emu, magneto resistivity 0.2 x 10^{-10} emu, electrical resistivity 43 milliohm cm, total magnetic susceptibility -21.02 x 10^{-6} cgs unit, orientation factor $(\rho_{max}/\rho_{min}) = 1.0$.
713*	1403	Thielke, N.R. (compiler)	1959	E	1246-2045	SA-25	Emissivity 0.83.
714*	190	Bowman, J.C., Krumhansl, J.A., and Meers, J.T.	1958	L	13-275	SA-25	Specimen prepared from lampblack base, molded with a coal-tar pitch binder, measurements made under high vacuo.
715*	1180	Rasor, N.S. and Smith, A.W.	1954	E	10-306	SA-25	Molded lampblack; density 1.55 g cm^{-3} at room temp; thermoelectricl power +9.0 μvolt K^{-1}; Hall coefficient +0.14 emu; magneto resistivity 0.2 x 10^{-10} emu; electrical resistivity 65.3 x 10^{-3} ohm cm; total susceptibility -21.02 x 10^{-6} cgs unit, and orientation factor $\rho_{max}/\rho_{min} = 1.0$.
716*	1180	Rasor, N.S. and Smith, A.W.	1954	E	18-302	SA-25	The above specimen exposed to neutron irradiation of 12.5 MWD/CT (megawatt days per central metric ton of uranium) at <30 C.
717*	1180	Rasor, N.S. and Smith, A.W.	1954	E	17-310	SA-25	The virgin specimen exposed to neutron irradiation of 22.7 MWD/CT at <30 C.
718*	1180	Rasor, N.S. and Smith, A.W.	1954	E	15-305	SA-25	The virgin specimen exposed to neutron irradiation of 146 MWD/CT at <30 C.
719*	1180	Rasor, N.S. and Smith, A.W.	1954	E	17-309	SA-25	The virgin specimen exposed to neutron irradiation of 460 MWD/CT at <30 C.
720*	1404	Thielke, N.R. (compiler)	1959	E	1085-2027	SA-25	Lampblack base graphite; 0.25 in. in dia and 3.5 in. long; thermal conductivity data extracted from a smooth curve derived from repeated measurements on several specimens.

* Not shown in figure.

Cerium

Cerium is a metal for which but few measurements are vailable. A smooth curve can be drawn through the teadily increasing values of Rosenberg [1220] (curve 1) or the range 2.7 to 22 K for a sample of 99.6 percent Ce nd the room temperature values of Legvold and Spedding 831] (curve 3) and of Powell and Jolliffe [1127] (curve). Such a smooth curve has no evidence of the maximum hat is usual for pure metals, and discontinuities may also ccur, since cerium undergoes phase transformations from dense face-centered cubic to the hexagonal crystal form t 95±5 K and returns to the face-centered cubic crystal orm at 263±10 K, and also undergoes a magnetic transormation at 13 K. Discontinuous changes in the electrical conductivity have been reported by McHargue, et al. [911] to occur at these temperatures. However, discontinuities have not been shown in the very tentatively suggested dashed curve of the figure, awaiting the outcome of experimental determinations.

Near room temperature the uncertainty is probably of the order of ±20 percent, but it will be greater at lower temperatures on account of the phase changes and the low purity of the one sample for which the measurements have been reported. The values below 270 K are applicable only to cerium having electrical resistivity ratio $\rho(293K)/\rho(20K) = 1.93$.

TABLE 39. Provisional thermal conductivity of cerium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
2	0.00260*	80	0.0521*
3	0.00373	90	0.0561*
4	0.00482	100	0.0600*
5	0.00584	123.2	0.0679*
6	0.00683	150	0.0766*
7	0.00776	173.2	0.0828*
8	0.00868	200	0.0900*
9	0.00959	223.2	0.0958*
10	0.0105	250	0.1025*
11	0.0113	273.2	0.108*
12	0.0122	298.2	0.113
13	0.0130	300	0.114
14	0.0138	323.2	0.119*
15	0.0147	350	0.124*
16	0.0155	373.2	0.128*
18	0.0171	400	0.133*
20	0.0186	473.2	0.145*
25	0.0224*	500	0.150*
30	0.0260*	573.2	0.161*
35	0.0293*	600	0.165*
40	0.0323*	673.2	0.176*
45	0.0352*	700	0.180*
50	0.0379*	773.2	0.189*
60	0.0432*	800	0.193*
70	0.0478*	873.2	0.202*
		900	0.206*
		973.2	0.215*
		1000	0.218*

†The provisional values are for high-purity cerium, and those below 270 K are applicable only to a specimen having electrical resistivity ratio $\rho(293K)/\rho(20K) = 1.93$.

*Extrapolated or interpolated.

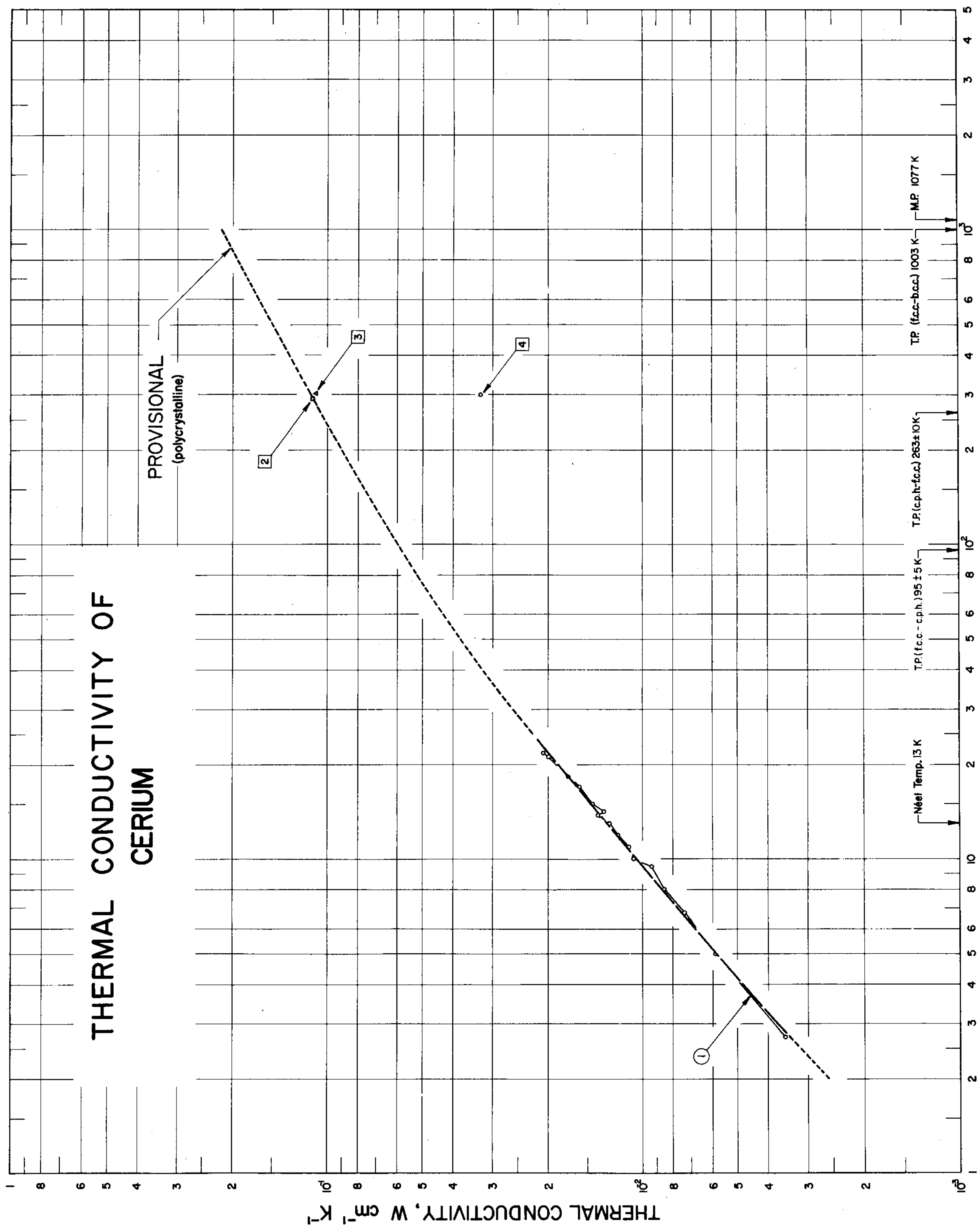

THERMAL CONDUCTIVITY OF
CERIUM
PROVISIONAL
(polycrystalline)
T.P. (f.c.c-b.c.c.) 1003 K
M.P. 1077 K
T.P.(c.p.h-f.c.c.) 263±10K
T.P.(f.c.c.-c.p.h.) 95±5K
Néel Temp. 13 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 52

TABLE 40. THERMAL CONDUCTIVITY OF CERIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1220	Rosenberg, H. M.	1955	L	2.7–22	Ce-1	99.6 pure; Mg and Ca as major impurities; specimen 1.085 cm long and 0.38 cm square cross section; electrical resistivity ratio $\rho(293K)/\rho(20K) = 1.93$.
2	1127	Powell, R. W. and Jolliffe, B. W.	1965	C	291		High-purity rod of cerium, about 0.25 in. dia and 0.25 in. long obtained from Johnson Matthey and Co., Ltd.; electrical resistivitv 74 μohm cm at ~18 C; monel metal used as comparative material; two measurements made using different thermal comparators.
3	831	Legvold, S. and Spedding, F. H.	1954		301.2		No details reported.
4	1609	Zhuze, V. P., Golubkov, A. V., Goncharova, E. V., and Sergeeva, V. M.	1963		300		2.5 x 0.5 x 0.5 cm; electrical conductivity 1.3×10^4 ohm^{-1} cm^{-1} at 300 K.

Cesium

The thermal conductivity of cesium has been measured for the solid phase over only a limited low-temperature range and at one other temperature. MacDonald, White, and Woods [873] (curves 1 and 2) covered the range 2.0 to 16 K and 2.2 to 11 K in different runs on the same sample. The only other value for solid cesium is a rather uncertain determination by Lemmon, et al. [837] (curve 13) who were mainly interested in the liquid state but included one point at 295.2 K where their sample was thought to be mainly solid.

MacDonald, et al., by using the electrical resistivity value of 20.8 $\mu\Omega$ cm at 295 K due to Hackspill [573] and their observed values for ρ_{295}/ρ_0 obtained what appeared to be satisfactory values of 2.51×10^{-8} and 2.47×10^{-8} V^2 K^{-2} for the Lorenz functions near 0 K. At 295 K a thermal conductivity of 0.347 W cm^{-1} K^{-1} is obtained from Hackspill's electrical resistivity and an assumed Lorenz function of 2.443×10^{-8} V^2 K^{-2}. This value is in fair agreement (6.5% lower) with the one point of Lemmon, et al., and a very tentative curve has been drawn to fit the mean of these two values and the low-temperature data of MacDonald, et al. Below 4 K, the values are calculated by using equation (7) with $n = 2.0$, $\alpha' = 0.0300$, and $\beta = 1.71$ which corresponds to the measured ρ_0(0.0418 $\mu\Omega$ cm) of the sample for curve 1 using the theoretical Lorenz function. Further determinations are clearly required for cesium in the solid state over its full temperature range.

For the liquid phase the figure contains estimated values by six independent groups of workers and two sets of experimental measurements, one by Lemmon, et al. (curve 13) and the other by Shpil'rain and Krainova [1305] (curves 14–17). Their general trend is similar although the measured values cross at about 600 K and at their upper and lower temperature limits tend to lie above and below the estimated curves.

Four sets of electrical resistivity determinations can be compared to about 1173 K and three to about 1373 K. These all agree to within 8 percent. As all but one assumed the theoretical Lorenz function to apply and the other used a 6 percent lower value, the derived thermal conductivity curves agree to within some 14 percent over their common range of 302 to 1373 K.

Grosse [546, 548] has found that the experimental electrical conductivity data of these workers fit the equation of a simple equilateral hyperbola

$$(\sigma' + 0.268)\ (T' + 0.268) = 0.340,$$

where the reduced electrical conductivity σ' is σ_T/σ_f, the reduced temperature T' is $(T - T_f)/(T_c - T_f)$, σ_f is the electrical conductivity of the liquid cesium at the melting point, and σ_T is the electrical conductivity at a temperature T between the melting point T_f and the critical temperature T_c. He has used electrical resistivity obtained from this relationship together with the theoretical Lorenz function to calculate the thermal conductivity of liquid cesium up to his then assumed critical temperature of 2150 K.

At 1914 K, about the upper limit of the electrical measurements of Hochman and Bonilla [613, 614] (curves 9–11) it appears that the derived thermal conductivity values of Hochman and Bonilla are about 70 percent greater than those evaluated by Grosse, and, since Hochman and Bonilla used a 6 percent lower Lorenz function, it would seem that the electrical resistivity which Grosse derived and used must have been some 80 percent greater than the measured value. Hochman and Bonilla had estimated the critical temperature to be 2027 K. The recommended curve follows a mean course between the several values, at 1914 K passes midway between the two suggested values, and continues to fall to meet the vapor value at 2060 K, the critical point of cesium as revised by Grosse [548]. There is clearly need for further investigation at these extreme temperatures.

The values are for high-purity cesium and those below 40 K are applicable only to cesium having a residual electrical resistivity of 0.0418 $\mu\Omega$ cm. The values are thought to be accurate to within ± 8 percent of the true values at temperatures below 15 K and from room temperature to about 1500 K, the uncertainty increasing to ± 15 percent at 2000 K. The values from 15 K to 273 K are provisional.

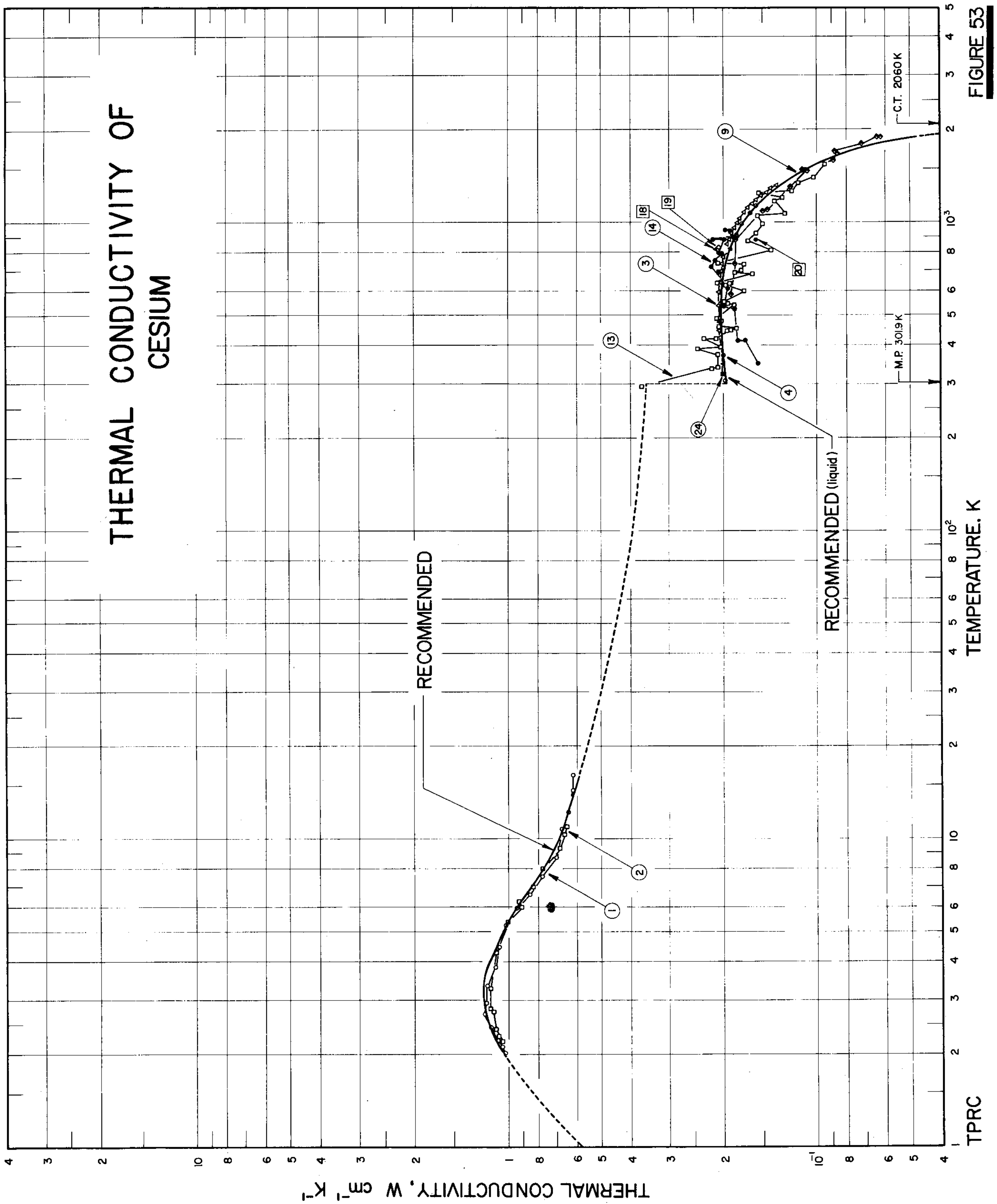
TABLE 41. Recommended thermal conductivity of cesium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Liquid	
T	k	T	k
0	0	301.9	0.197
1	0.574*	323.2	0.198
2	1.02*	350	0.200
3	1.19	373.2	0.201
4	1.14	400	0.203
5	1.04	473.2	0.205
6	0.935	500	0.205
7	0.837	573.2	0.206
8	0.769	600	0.205
9	0.720	673.2	0.202
10	0.689	700	0.201
11	0.666	773.2	0.196
12	0.647	800	0.194
13	0.630	873.2	0.187
14	0.615	973.2	0.177
15	0.600	1073.2	0.166
16	0.590	1100	0.163
18	0.572*	1173.2	0.153
20	0.554*	1200	0.150
25	0.523*	1273.2	0.140
30	0.500*	1300	0.136
35	0.483*	1373.2	0.126
40	0.470*	1400	0.122
45	0.457*	1473.2	0.112
50	0.447*	1500	0.108
60	0.430*	1573.2	0.098
70	0.420*	1600	0.094
80	0.410*	1673.2	0.084
90	0.402*	1700	0.080
100	0.397*	1773.2	0.070
123.2	0.387*	1800	0.066
150	0.378*	1873.2	0.055
173.2	0.373*	1900	0.051
200	0.368*	1973.2	0.036*
223.2	0.365*	2000	0.029*
250	0.363*		
273.2	0.361*		
298.2	0.359		
300	0.359		
301.9	0.359		

†The recommended values are for well-annealed high-purity cesium, and those below 40 K are applicable only to a specimen having $\rho_0 = 0.0418$ μΩ cm. Values from 15 K to 273 K are provisional.

*Extrapolated, interpolated, or estimated.


THERMAL CONDUCTIVITY OF CESIUM
FIGURE 53
RECOMMENDED
RECOMMENDED (liquid)
M.P. 301.9 K
C.T. 2060 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

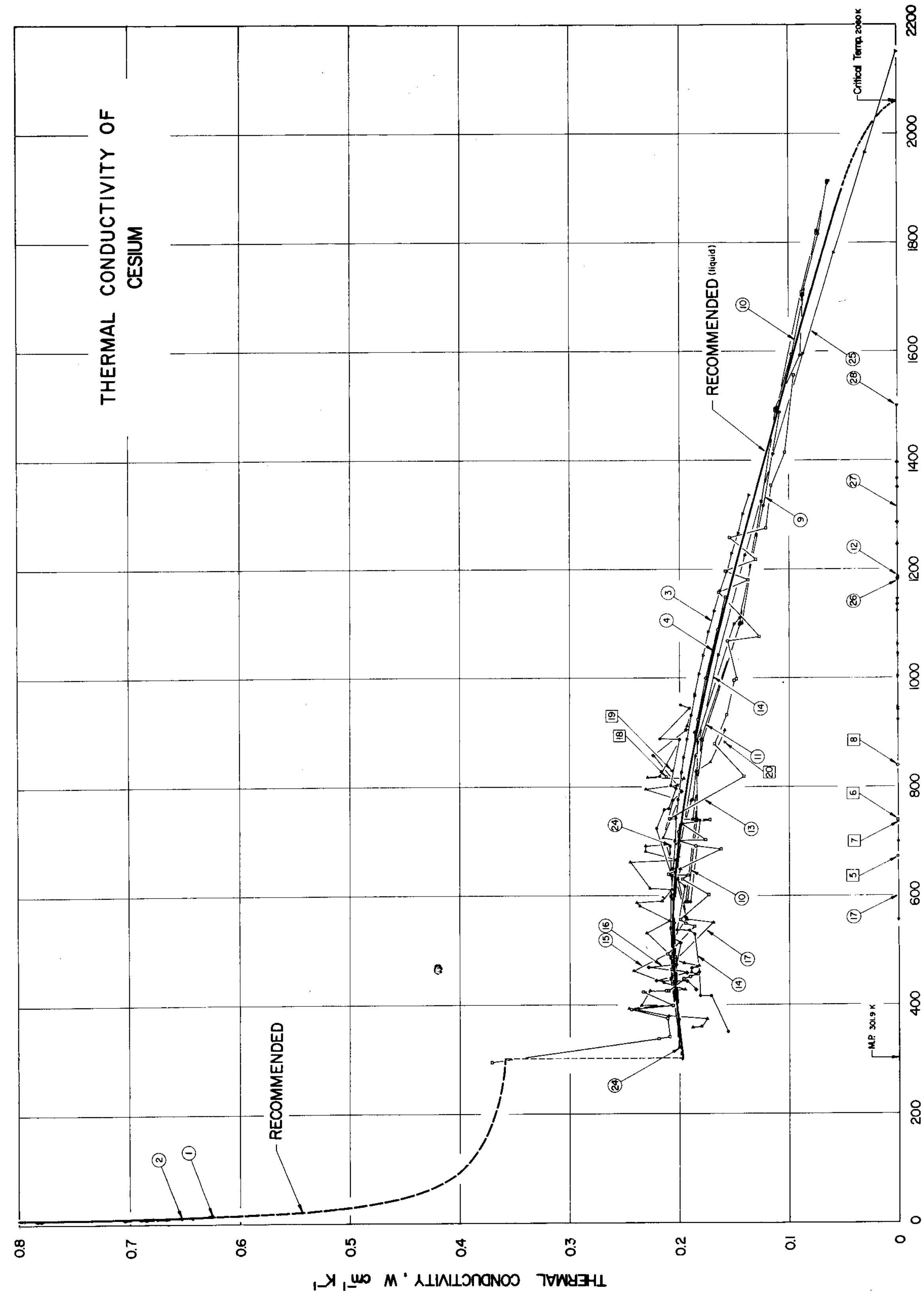

THERMAL CONDUCTIVITY OF
CESIUM
RECOMMENDED
RECOMMENDED (liquid)
M.P. 301.9 K
Critical Temp. 2060 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 54

TABLE 42. THERMAL CONDUCTIVITY OF CESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	873	MacDonald, D.K.C., White, G.K., and Woods, S.B.	1956	L	2.0–16	Cs 3	High purity; 1.6 mm in dia; melted in vacuo and run into soft-glass tube; run No. 1 yielded the following information: electrical resistivity ratio $\rho(295K)/\rho(0K)$ = 498 (using Hackspill's value ρ = 20.8 μohm cm at 295 K); $\rho(0K)$ = 0.0418 μohm cm; Lorenz function 2.51 x 10^{-8} V^2 K^{-2} near 0 K.
2	873	MacDonald, D.K.C., et al.	1956	L	2.2–11	Cs 3	The above specimen second run; electrical resistivity ratio $\rho(295K)/\rho(0K)$ = 465 (using Hackspill's value ρ = 20.8 μohm cm at 295 K); $\rho(0K)$ = 0.0447 μohm cm; Lorenz function 2.47 x 10^{-8} V^2 K^{-2} near 0 K.
3	1399, 1212	Tepper, F., Murchison, A., Zelenak, J.S., and Roehlich, F. Roehlich, F. and Tepper, F.	1964	→	349–1336		99.99 pure liquid specimen; thermal conductivity values calculated from electrical resistivity measurements using the theoretical Lorenz number; electrical resistivity reported as 20.29, 37.39, 42.57, 52.63, 63.59, 70.72, 83.92, 94.45, 112.48, 127.78, 153.48, 173.79, 211.94, and 241.12 μohm cm at 18.3, 28.3, 76, 174, 267, 326, 427, 503, 614, 696, 811, 887, 993, and 1063 C, respectively.
4	712	Kapelner, S.M. and Bratton, W.D.	1962	→	309–1050		Impurities (pretest): <0.0010 O, <0.0010 N, <0.0045 C, <0.0042 Rb, and traces of Si, Mg, Al, Cu, Na, Ca, and Fe; impurities (post test): 0.0017 O, 0.0020 N, <0.0020 C, <0.0100 Rb, and traces of Si, Mg, Al, Cu, Na, Ca, and Fe; liquid specimen; supplied by MSA Research Corp.; thermal conductivity values calculated from electrical resistivity data using the theoretical Lorenz number 2.45 x 10^{-8} V^2 K^{-2}; electrical resistivity reported as 37.42, 38.32, 45.77, 65.74, 77.28, 87.35, 123.63, 139.29, 161.26, and 178.63 μohm cm at 28.3, 35.8, 101.4, 276.9, 370.6, 444.2, 650.0, 725.8, 815.3, and 876.7 C, respectively.
5	1400	Tepper, F. and Roehlich, F.	1966	→	672.2		99.99 pure; vapor specimen filled in a test cell which is an 8-in. long (2.25 in.) schedule 40 pipe constructed from Hasteloy-C and is connected with a boiler; measured at a boiler pressure of 20 mm Hg; thermal conductivity measured by using the dynamic hot-wire method.
6	1400	Tepper, F. and Roehlich, F.	1966	→	739.2		Same as the above specimen except boiler pressure 40 mm Hg.
7	1400	Tepper, F. and Roehlich, F.	1966	→	738.2		Same as the above specimen except boiler pressure 62 mm Hg (saturated).
8	1400	Tepper, F. and Roehlich, F.	1966	→	839.2		Same as the above specimen except boiler pressure 65 mm Hg.
9	613, 614	Hochman, J.M. and Bonilla, C.F.	1965	→	589–1913	Run 1	~99.97 Cs, 0.0154 O_2, 0.0145 Rb, 0.004 Na, 0.0023 Ca, 0.0018 Fe, 0.0016 B, 0.0013 Si, 0.0006 K, 0.0003 each of Mg, Cr, and Ni; saturated liquid specimen filled in a test capsule 12 in. long, 1 in. OD and 1/16 in. in wall thickness with 1/4 in. thick discs welded to the ends of the tube made from Ta-10W alloy; specimen supplied by Dow Chemical Co.; thermal conductivity values calculated from electrical resistivity data using Lorenz number of 2.3 x 10^{-8} V^2 K^{-2}; electrical resistivity reported as 69.42, 77.54, 86.23, 95.54, 105.4, 116.2, 127.4, 139.7, 152.5, 166.6, 181.7, 197.6, 216.9, 235.4, 257.0, 280.8, 306.7, 336.7, 370.1, 403.8, 451.0, 500.5, 557.9, 618.2, and 702.4 μohm cm at 316, 371, 427, 482, 538, 593, 649, 704, 760, 816, 871, 927, 982, 1038, 1093, 1149, 1204, 1260, 1316, 1371, 1427, 1482, 1538, 1593, and 1649 C, respectively; critical temp of Cs was estimated to be 2027 K.

TABLE 42. THERMAL CONDUCTIVITY OF CESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
10	613, 614	Hochman, J. M. and Bonilla, C. F.	1965	→	589-1910	Run 2	Similar to the above; second loading of the test capsule.
11	613, 614	Hochman, J. M. and Bonilla, C. F.	1965	→	589-1914	Run 3	Similar to the above; third loading of the test capsule.
12	522, 520	Gottlieb, M., Zollweg, R. J., Richardson, L. S., DeSteese, J. G., Taylor, C. R., and Ennulat, D. F.	1962		945-1187		Vapor specimen.
13	837	Lemmon, A. W., Jr., Deem, H. W., Eldridge, E. A., Hall, E. H., Matolich, J., Jr., and Walling, J. F.	1964	C	295-1556		99.994 pure (estimated from freezing point curve and emission spectrography for impurities); freezing point 28.52 C; specimen clad in Nb-1 Zr alloy; specimen in liquid state except at 295.2 K where it was mostly solid; electrical resistivity reported as 44, 55, 67, 80, 96, 114, 134, 155, 179, 208, and 246 μohm cm at 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 C, respectively; Nb-1 Zr alloy used as comparative material.
14	1305	Shpil'rain, E. E. and Krainova, I. F.	1967	C	350-950		0.05 Na, 0.033 Rb, and 0.0133 K; liquid specimen contained in a hollow cylinder of I. D. 14 mm; prepared from cesium chloride by reduction with calcium and subsequent distillation in a vacuum of 10^{-1}~10^{-3} mm Hg; Armco iron used as comparative material.
15	1305	Shpil'rain, E. E. and Krainova, I. F.	1967	C	358-969		Similar to the above specimen.
16	1305	Shpil'rain, E. E. and Krainova, I. F.	1967	C	428-904		Similar to the above specimen.
17	1305	Shpil'rain, E. E. and Krainova, I. F.	1967	C	460-904		Similar to the above specimen.
18	824, 825	Lee, C. S. Bonilla, C. F. (principal investigator)	1967	E	820		99.999 Cs, 0.001 Rb, 0.0008 K, 0.0008 Na, and 0.0001 Li; in vapor state; supplied by Dow Chemical Co.; measured at 0.0974 atm pressure.
19	824, 825	Lee, C. S. Bonilla, C. F. (principal investigator)	1967	E	830		Similar to the above specimen except measured at 0.0984 atm pressure.
20	824, 825	Lee, C. S. Bonilla, C. F. (principal investigator)	1967	E	883		Similar to the above specimen except measured at 0.214 atm pressure.
21*	20	Achener, P. Y. and Jouthas, J. T.	1968	→	839-1070		<0.0010 O, 0.0008 C, 0.0002 N, and 0.0001 Na; in vapor state; measuring method based on the study of laminar flow in a long tube with a constant wall temp combined with the heat exchange theory; thermal conductivity values calculated from measured temp and flow rate with specific heat capacity data taken from Achener, P. Y., et al. (USAEC AGN-8195, Vol. 1, 1968); measured at test pressures of 0.288, 0.265, 0.242, 0.472, 0.800, 1.03, 1.32, and 2.11 atm at the respective (in increasing order) measuring temps.
22*	1242	Sanunu, J. H.	1962	→	603		Vapor specimen contained in a cell 0.500 in. in dia and 21.00 in. long; measured at 2 mm Hg by a hot wire method.
23*	1242	Sanunu, J. H.	1962	→	600		Similar to above but cell size 0.375 in. in dia and 21.00 in. in length.
24	650	Hyman, J., Jr.	1963	→	323, 692		In liquid state; thermal conductivity values calculated from measured electrical resistivity data using the theoretical Lorenz number 2.43 x 10^{-8} V^2 K^{-2}; electrical resistivity reported as 23.50, 39.05, 45.80, 53.10, 57.60, 59.00, 66.30, 68.40, 73.60, 78.30, and 82.90 μohm cm at 29, 50, 114, 179, 221, 230, 287, 295, 344, 388, and 419 C, respectively.

* Not shown in figure.

TABLE 42. THERMAL CONDUCTIVITY OF CESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
25	546	Grosse, A. V.	1966	→	302-2160		Liquid cesium; thermal conductivity values calculated from derived electrical resistivity by using the theoretical Lorenz number.
26	522, 520	Gottlieb, M., Zollweg, R. J., et al.	1962	→	942-1180		Vapor specimen; thermal conductivity data calculated from Lennard-Jones Potential with σ = 9.17 Å.
27	764	Kitrilakis, S. and Meeker, M.	1963	→	1135-1395		Vapor cesium; calculated values based on the kinetic theory of gases.
28	1509	Weatherford, W. D., Jr., Tyler, J. C., and Ku, P. M.	1964		622-1519		Saturated vapor; recommended values calculated from the frozen specific heat and viscosity of saturated vapor assuming a constant Prandtl number of 0.73.

Chlorine

No information is available for the thermal conductivity of solid chlorine. The thermal conductivities of the other physical states are discussed separately below.

Saturated Liquid

No experimental or other values were found for the thermal conductivity of saturated liquid chlorine apart from a correlation by Schaefer and Thodos [1257] for the thermal conductivity of liquid and gaseous states of diatomic substances. Their correlation was based principally on data for nitrogen and is thus subject to several uncertainties—in the original data, in the correlation process and in the validity of the principle of corresponding states. The proposed values here presented were derived using the above correlation and must thus be regarded as provisional and of uncertain accuracy. Experimental measurements are urgently required to confirm their correctness. In the absence of such measurements no departure plot appears.

Saturated Vapor

No experimental or other values were found for the thermal conductivity of saturated vapor chlorine apart from a correlation by Schaefer and Thodos [1257] for the thermal conductivity of liquid and gaseous states of diatomic substances. Their correlation was based principally on data for nitrogen and is thus subject to several uncertainties—in the original data, in the correlation process and in the validity of the principle of corresponding states. The proposed values here presented were derived using the above correlation and must thus be regarded as provisional and of uncertain accuracy. Experimental measurements are urgently required to confirm their correctness. In the absence of such measurements no departure plot appears.

Gas

The only data available for this substance are experimental values of Franck [454] from 198 to 676 K obtained for pressures between 50 and 250 mm Hg upon which a tabulation by Lenoir [839] was based. Examination of the Franck data shows that the variation of thermal conductivity with pressure in this temperature interval is irregular, hence in the analysis it was neglected. The Lenoir values show good agreement with the Franck data above the normal boiling point, and were selected as a basis for the most probable values. Below the normal boiling point the single experimental point was used in the construction of the recommended values. The recommended values should be accurate to within five percent.

TABLE 43. Recommended thermal conductivity of chlorine†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor	
T	$k \times 10^3$	T	$k \times 10^3$
		200	0.054*
		210	0.058*
172	1.93*	220	0.061*
180	1.89*	230	0.065*
190	1.85*	240	0.068*
200	1.81*	250	0.074*
210	1.76*	260	0.078*
220	1.72*	270	0.082*
230	1.67*	280	0.086*
240	1.63*	290	0.092*
250	1.58*	300	0.097*
260	1.54*	310	0.103*
270	1.49*	320	0.110*
280	1.44*	330	0.117*
290	1.39*	340	0.125*
300	1.34*	350	0.134*
310	1.29*	360	0.144*
320	1.24*	370	0.155*
330	1.18*	380	0.168*
340	1.13*	390	0.185*
350	1.07*	400	0.210*
360	1.01*	410	0.25*
370	0.95*	417	0.40*‡
380	0.88*		
390	0.80*		
400	0.72*		
410	0.62*		
417	0.40*‡		

†Values for saturated liquid and saturated vapor states are provisional.
*Estimated.
‡Pseudo-critical value.

TABLE 43. Recommended thermal conductivity of chlorine—Continued

(Temperature, T, K; Thermal Conductivity, W cm^{-1} K^{-1})

Gas
(At 1 atm)

T	$k \times 10^3$	T	$k \times 10^3$
239	0.068		
240	0.068		
250	0.071	500	0.156
260	0.075	510	0.160
270	0.078	520	0.163
280	0.082	530	0.166
290	0.085	540	0.170
300	0.089	550	0.173
310	0.093	560	0.176
320	0.096	570	0.180
330	0.100	580	0.183
340	0.103	590	0.186
350	0.107	600	0.190
360	0.110	610	0.192
370	0.114	620	0.195
380	0.117	630	0.197
390	0.120	640	0.200
400	0.124	650	0.202
410	0.127	660	0.205
420	0.131	670	0.207
430	0.134	680	0.210
440	0.137	690	0.212
450	0.141	700	0.215
460	0.144		
470	0.147		
480	0.150		
490	0.153		

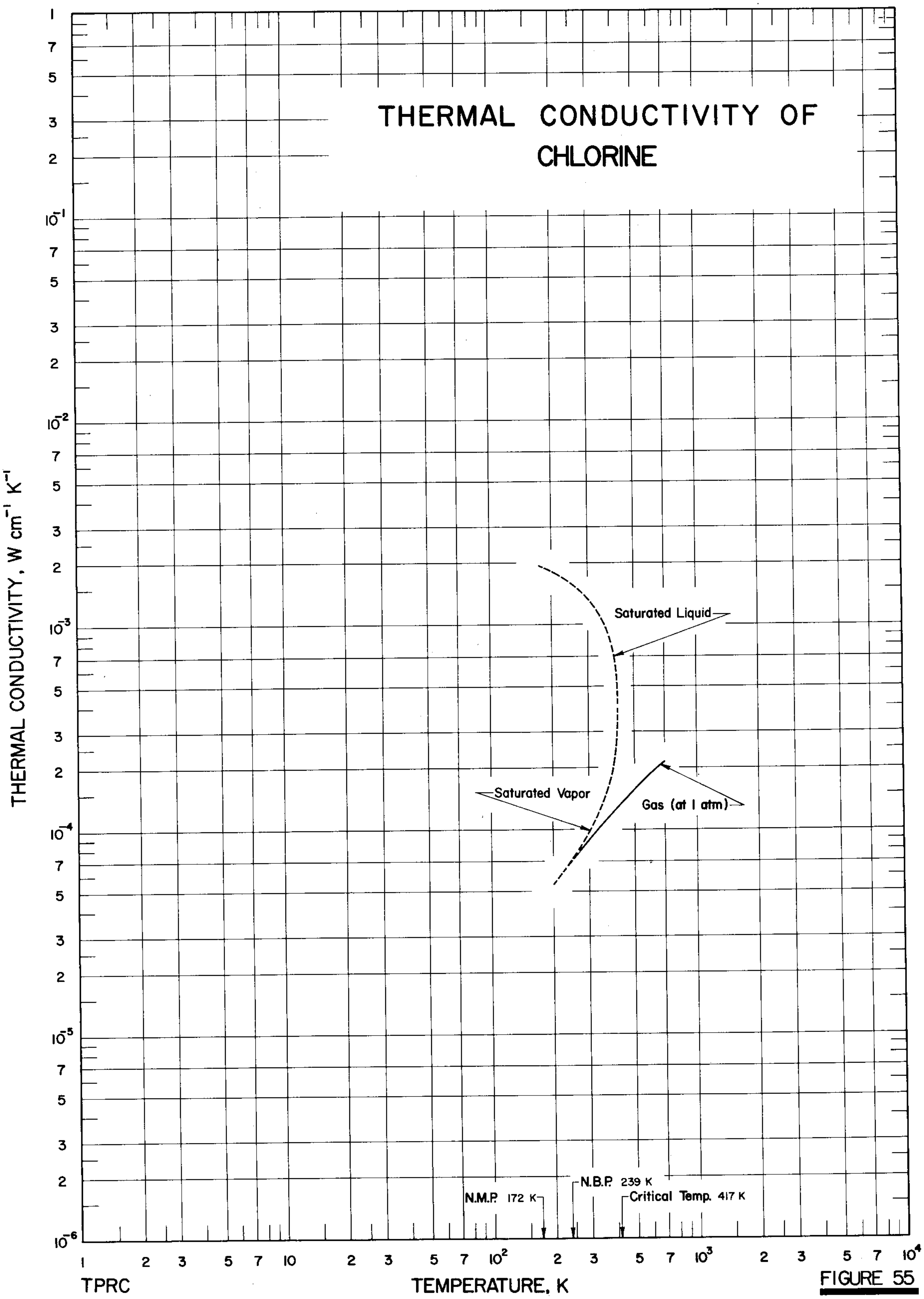
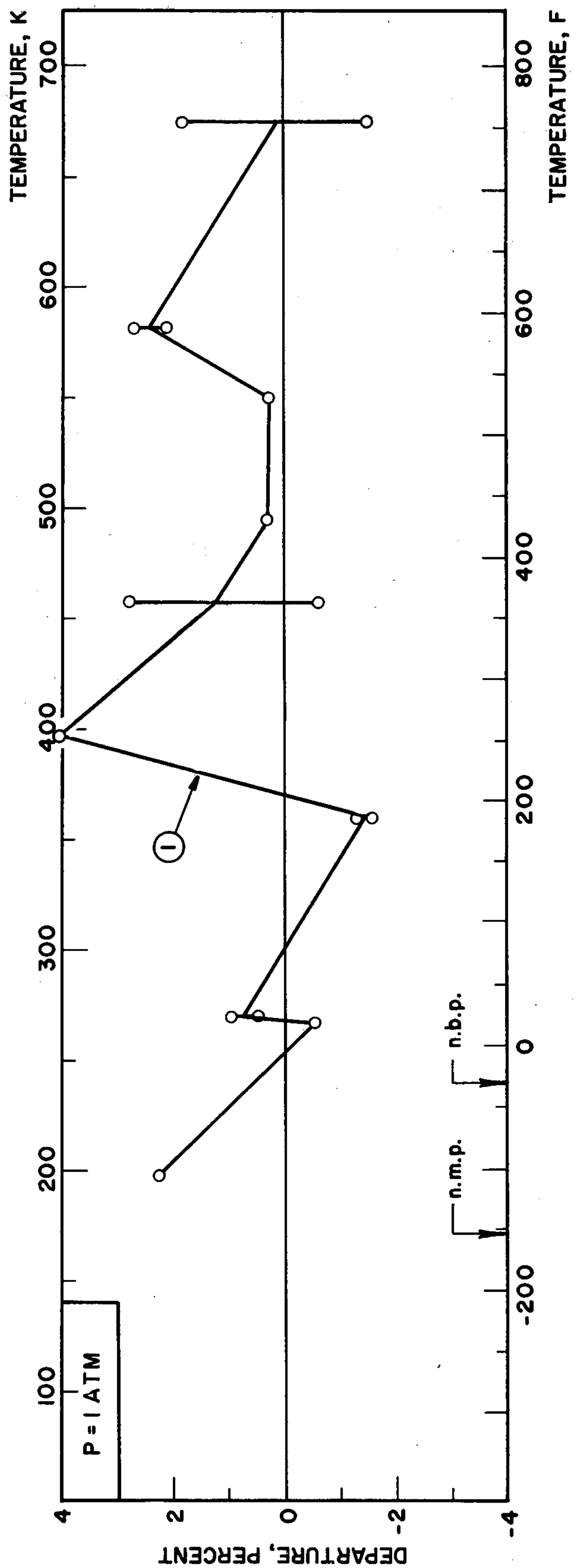

THERMAL CONDUCTIVITY OF CHLORINE
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.M.P. 172 K
N.B.P. 239 K
Critical Temp. 417 K
TPRC
TEMPERATURE, K

FIGURE 55

FIGURE 56. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS CHLORINE



Curve	Reference
1	454

Chromium

At low temperatures the thermal conductivity of different samples with small differences in purity and/or perfection differs greatly, and a particular set of recommended values applies only to a sample of a particular purity and/or perfection. The particular curve for which recommended values at low temperatures have been tabulated is based on the measurements by Harper, et al. [590] (curve 13) for 99.998 percent purity chromium made for five different conditions. The curve has been calculated to 30 K by using equation (7) and a β-value of 2.47 derived from their highest set of experimental data. From 30 to 120 K the curve has been continued to fit their data and it links smoothly on to the curve of Moore et al. [989] (curve 15) for the better conducting of their two samples, following this to normal temperatures.

Recommended values at low temperatures for chromium of other purity and/or perfection can similarly be derived. Some uncertainty still relates to the thermal conductivity of chromium in the region of its Néel temperature ($\sim$311 K). Meaden, et al. [915] (curve 19) claim that the thermal conductivity increases about 4 percent to a small peak, whereas Moore, et al. maintain that the thermal conductivity is almost constant in this region, despite the rather smaller peak that is well established for the electrical conductivity. No peak is shown in the recommended curve, however, until it receives confirmation. The need for more work in the room temperature region should, however, be noted.

The properties of chromium in the normal temperature region could also be influenced under some conditions by a change of phase. At temperatures below 299 K it has been found possible for electrolytically deposited chromium to have the close-packed hexagonal structure [1243, 1575]. The stable cubic form, to which the above thermal conductivity curve applies, is obtained on heating.

Only two groups of workers, Lucks and Deem [862] (curve 14) and Powell and Tye [1130] (curves 2–8) have made direct measurements of the thermal conductivity of chromium to temperatures appreciably above normal. The investigation of Powell and Tye was of interest in that they commenced with an electrolytically deposited tube of the metal and followed the changes brought about by heating to successively higher temperatures. After their final heating to 1410° C the thermal conductivity at 50° C was 3.66 times the initial value, and the density had increased from 6.975 to 7.15 g cm^{-3}. At 470 K the value of Lucks and Deem for a chemically pure ductile chromium is greater than Powell and Tye's final determinations by 1.7 percent, at 1000 K, the region of greatest difference, by 11 percent, and at 1270 K by 5 percent. In view of this good agreement for two quite independent determinations, the most probable curve from 520 to 720 K has been drawn as a smooth curve following the data of Lucks and Deem and from 720 to 1270 K through the mean values of Lucks and Deem and Powell and Tye. At lower temperatures this curve merges into the values of Moore, et al.

Zinov'ev, et al. [1620] (curves 20–22) have determined the thermal diffusivity of chromium for the range 930 to 1670 K. From these data, they deduce three curves for the thermal conductivity by using three different sets of available specific heat values. At 1000 K the recommended curve lies close to the middle of these, and has been continued to meet the lowest of Zinov'ev's curves at about 1350 K. With further temperature increase these derived curves all decrease much more rapidly. In view of the similar temperature behavior obtained by Zinov'ev, et al. [1620] when using a similar method for other metals, and the manner in which their data differ from the general nature of other results, the recommended curve at present proposed does not show this rapid decrease. It has been continued smoothly to a value at 1670 K which exceeds the three values derived by Zinov'ev, et al. by about 13, 11, and 5.5 percent.

The recommended thermal conductivity value at 1700 K, together with an electrical resistivity value obtained by extrapolation of the values of Powell and Tye [1130] yields a Lorenz function of 3.05×10^{-8} V^2 K^{-2}, a value which seems not unreasonable when compared with those of Powell and Tye. This also holds for the Lorenz function of 2.85×10^{-8} V^2 K^{-2} obtained by similar extension to the melting point, whereas similar extrapolation of the Zinov'ev, et al.'s curves would lead to unusually low values.

No information is available for the thermal conductivity of molten chromium.

Except possibly near the Néel temperature, the recommended values are thought to represent the thermal conductivity of chromium to within ± 3 percent of the true values at temperatures from 150 to 700 K and ± 10 percent above 700 K. At temperatures below 150 K, the values are highly conditioned by purity and the recommended values are only applicable to chromium having residual electrical resistivity $\rho_0 = 0.0608$ $\mu\Omega$ cm. These values should be good to within ± 10 percent.

Attention should however be drawn to the very much lower thermal conductivity values likely to apply at moderate temperatures for electrolytically deposited chromium prior to heat treatment and to the increase of its density during the heat treatment (see Powell and Tye [1130]).

TABLE 44. Recommended thermal conductivity of chromium†

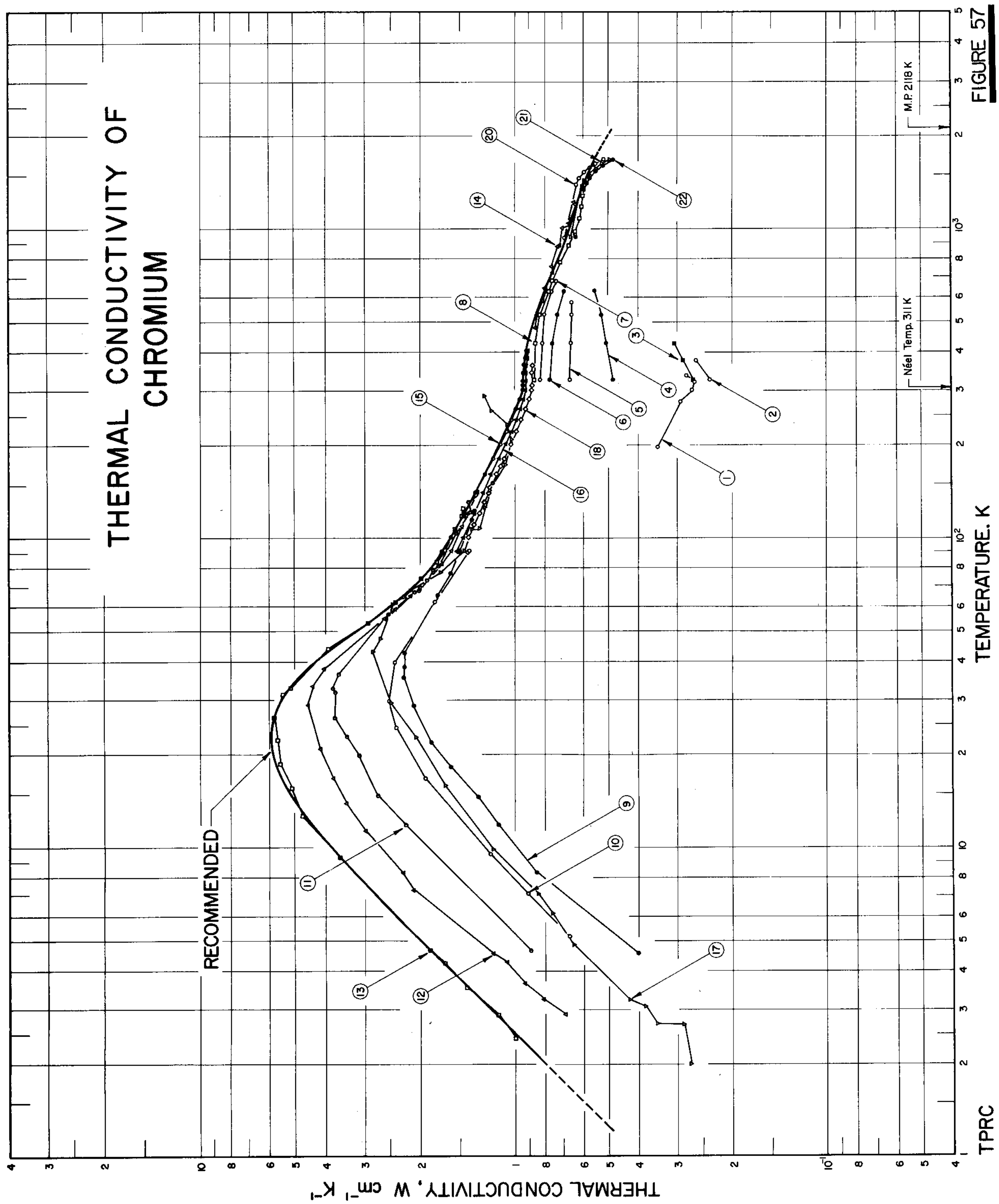
(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	k	T	k
0	0	350	0.929
1	0.402*	373.2	0.921
2	0.803	400	0.909
3	1.20	473.2	0.874
4	1.60	500	0.860
5	2.00	573.2	0.822
6	2.39	600	0.807
7	2.27	673.2	0.769
8	3.14	700	0.756
9	3.50	773.2	0.726
10	3.85	800	0.713
11	4.17	873.2	0.688
12	4.48	900	0.678
13	4.76	973.2	0.660
14	5.01	1000	0.654
15	5.24	1073.2	0.640
16	5.44	1100	0.636
18	5.74	1173.2	0.624
20	5.93	1200	0.619
25	5.93	1273.2	0.608
30	5.49	1300	0.604
35	4.88	1373.2	0.592
40	4.25	1400	0.588
45	3.67	1473.2	0.576
50	3.17	1500	0.572
60	2.48	1573.2	0.561
70	2.07	1600	0.556
80	1.84	1673.2	0.546*
90	1.69	1700	0.542*
100	1.59	1773.2	0.530*
123.2	1.43	1800	0.526*
150	1.29	1873.2	0.514*
173.2	1.20	1900	0.510*
200	1.11	1973.2	0.498*
223.2	1.06	2000	0.494*
250	1.00	2073.2	0.482*
273.2	0.965	2100	0.478*
298.2	0.939	2118	0.475*
300	0.937		
323.2	0.933		

†The recommended values are for well-annealed high-purity chromium, and those below 150 K are applicable only to a specimen having $\rho_0 = 0.0608$ $\mu\Omega$ cm.

*Extrapolated.


THERMAL CONDUCTIVITY OF
CHROMIUM
FIGURE 57
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
RECOMMENDED
M.P. 2118 K
Néel Temp. 311 K
TPRC

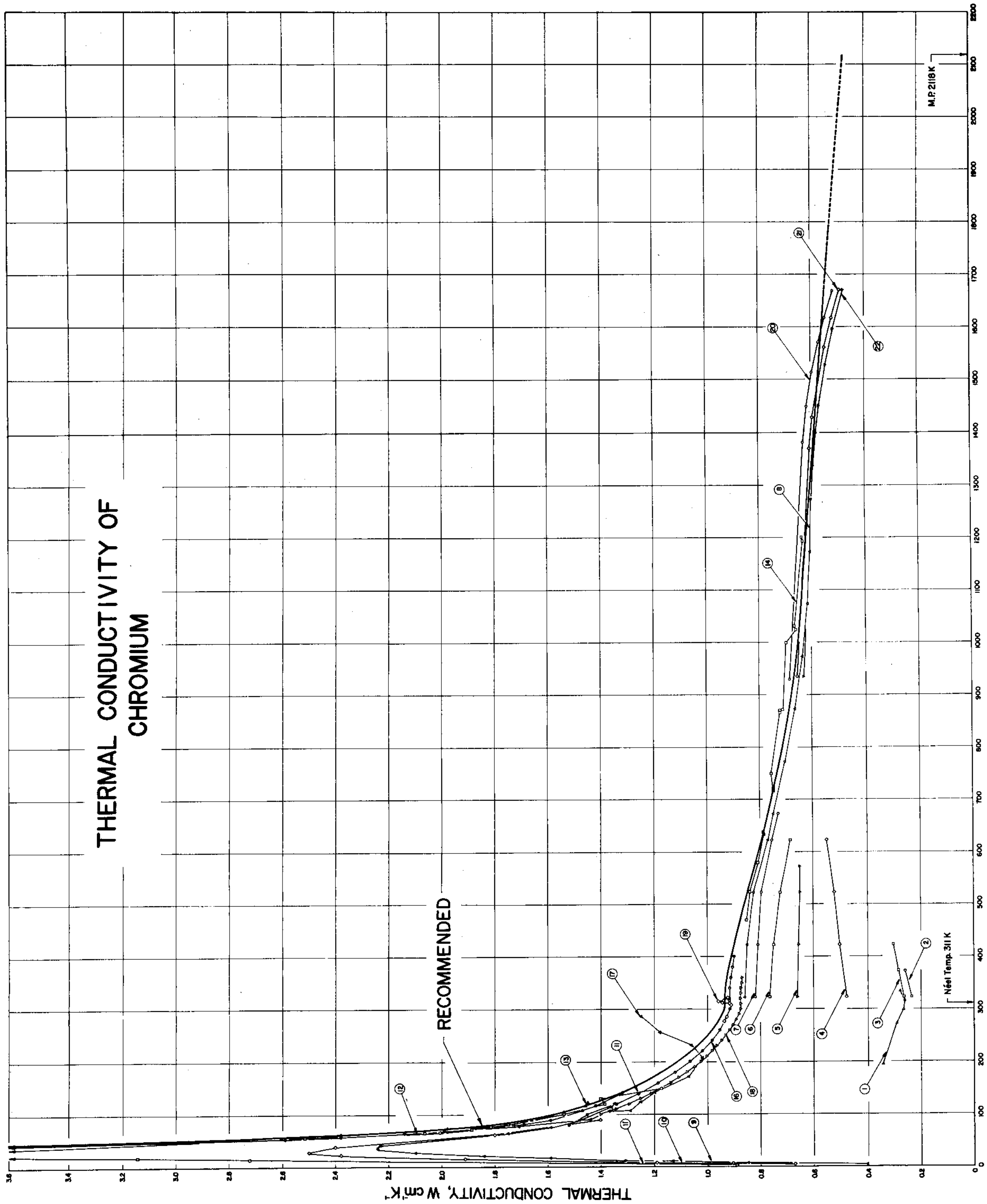

THERMAL CONDUCTIVITY OF CHROMIUM
RECOMMENDED
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
M.P. 2118 K
Néel Temp. 311 K
TPRC
FIGURE 58

TABLE 45. THERMAL CONDUCTIVITY OF CHROMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1341	Sochtig, H.	1940	L	196-334	Cr II	Electrolytic; specimen 0.7 x 0.23 x 0.21 cm; annealed at 1000 C for 30 min.
2	1130	Powell, R.W. and Tye, R. P.	1957	L, C	299-372		0.43 O; electrodeposited chromium tube 1.28 cm O.D., 0.63 cm I.D., and 18.05 cm long; as deposited; density 6.975 g cm^{-3}; electrical resistivity 39.0, 48.5, 49.8, and 52.0 μohm cm at -180, 20, 50, and 100 C, respectively; Lorenz function 3.6 x 10^{-8} V^2 K^{-2} at 50 and 100 C.
3	1130	Powell, R.W. and Tye, R.P.	1957	L, C	345-422		The above specimen heat treated at 213 C; electrical resistivity 30.0, 39.7, 40.7, 42.7, and 45.0 μohm cm at -180, 20, 50, 100 and 150 C, respectively; Lorenz function 3.3, 3.25, and 3.2 x 10^{-8} V^2 K^{-2} at 50, 100, and 150 C, respectively.
4	1130	Powell, R.W. and Tye, R.P.	1957	L, C	352-636		The above specimen heat treated at 405 C; density 7.08 g cm^{-3}; electrical resistivity 13.2, 25.5, 26.9, 32.0, 37.5, and 43.2 μohm cm at -180, 20, 50, 150, 250, and 350 C, respectively; Lorenz function 4.0, 3.85, 3.8, and 3.7 x 10^{-8} V^2 K^{-2} at 50, 150, 250, and 300 C, respectively.
5	1130	Powell, R.W. and Tye, R.P.	1957	L, C	334-595		The above specimen heat treated at 545 C; electrical resistivity 4.0, 19.3, 20.3, 25.4, 32.2, and 35.8 μohm cm at -180, 20, 50, 150, 250, and 300 C, respectively; Lorenz function 4.15, 3.9, 4.0, and 4.15 x 10^{-8} V^2 K^{-2} at 50, 150, 250, and 300 C, respectively.
6	1130	Powell, R.W. and Tye, R.P.	1957	L, C	351-606		The above specimen heat treated at 860 C; electrical resistivity 16.0, 16.8, 21.0, 26.5, and 32.1 μohm cm at 20, 50, 150, 250, and 350 C, respectively; Lorenz function 3.8, 3.7, 3.65, and 3.55 x 10^{-8} V^2 K^{-2} at 50, 150, 250, and 350 C, respectively.
7	1130	Powell, R.W. and Tye, R.P.	1957	L, C	333-683		The above specimen heat treated at 1054 C; electrical resistivity 0.215, 1.8, 15.0, 15.6, 19.8, 25.0, 30.6, and 33.5 μohm cm at -269, -180, 20, 50, 150, 250, 350, and 400 C, respectively; Lorenz function 3.95, 3.8, 3.8, 3.7, and 3.65 x 10^{-8} V^2 K^{-2} at 50, 150, 250, 350, and 400 C, respectively.
8	1130	Powell, R.W. and Tye, R.P.	1957	L, C	348-1266		The above specimen heat treated at 1410 C; density 7.15 g cm^{-3}; electrical resistivity 0.05, 1.45, 13.6, 14.1, 18.0, 22.7, 27.8, 30.3, 35.7, 41.2, 47.2, 53.2, 60.0, and 66.4 μohm cm at -269, -180, 20, 50, 150, 250, 350, 400, 500, 600, 700, 800, 900, and 1000 C, respectively; Lorenz function 3.75, 3.6, 3.6, 3.45, 3.4, 3.25, 3.15, 3.1, 3.05, 3.1, and 3.15 x 10^{-8} V^2 K^{-2} at 50, 150, 250, 350, 400, 500, 600, 700, 800, 900, and 1000 C, respectively.
9	590	Harper, A.F.A., Kemp, W.R.G., Klemens, P.G., Tainsh, R.J., and White, G.K.	1957	L	4.5-123	1	99.998 pure; 3 mm dia x 8 cm long; supplied by Aeronautical Res. Labs. of Commonwealth Dept. of Supply; cold-worked; residual electrical resistivity 0.255 μohm cm.
10	590	Harper, A.F.A., et al.	1957	L	5.1-91	2	The above specimen annealed at 1050 C for 4 hrs; residual electrical resistivity 0.181 μohm cm.
11	590	Harper, A.F.A., et al.	1957	L	4.6-151	3	99.998 pure; partially recrystallized; specimen 3 mm in dia and 8 cm long; supplied by the Aeronautical Res. Labs of the Commonwealth Dept. of Supply; residual resistivity 0.125 μohm cm.
12	590	Harper, A.F.A., et al.	1957	L	2.9-142	4	The above specimen annealed at 1050 C for 4 hrs; residual resistivity 0.090 μohm cm.

TABLE 45. THERMAL CONDUCTIVITY OF CHROMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	590	Harper, A. F. A., Kemp., W. R. G., Klemens, P. G., Tainsh, R. J., and White, G. K.	1957	L	2.4-123	5	99.998 pure; fully recrystallized; specimen 3 mm in dia and 8 cm long; supplied by the Aeronautical Res. Labs of the Commonwealth Dept. of Supply; residual resistivity 0.055 μohm cm. $\rho(273K)/\rho_0 = 217$.
14	862	Lucks, C. F. and Deem, H. W.	1956	C	470-1201		Chemically pure; ductile; supplied by the Bureau of Mines, Oregon; density 7.16 g cm^{-3} at 24 C.
15	989	Moore, J. P., Williams, R. K., and McElroy, D. L.	1968	L	90-400	Sample A	99.98$^+$ Cr, 0.007 C, 0.003 Fe, <0.002 each of Ga and Mg, 0.0015 S, 0.0014 O, 0.001 Mn, <0.001 Pt, 0.0006 Ca, 0.0005 each of Si and H, 0.0003 each of B, V, and N, 0.0002 each of Ba, Cu, Pb, and Zn, 0.0001 each of Ag and As, <0.0001 each of Hg, P, Pd, Ru, Sb, Sn, Te, Tl, U, W, and Zr, <0.00008 Cd, 0.00005 Ti, <0.00005 each of Mo, Ni, and Sr, 0.00004 each of Nb and K, <0.00004 Bi, <0.00003 Co, <0.00002 each of Ge, In, and Na, <0.00001 each of Li and Rn; polycrystalline; specimen machined to 0.96 cm in dia and 7.7 cm long; prepared from the starting iodide chromium crystal, purchased from Chromalloy Corp, West Nyak, N.Y., by compacting the cleaned crystal, sealing in evacuated steel jacket and hot extruding the assembly; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 280$; electrical resistivity reported as 0.860, 1.225, 1.63, 2.605, 3.76, 5.00, 6.315, 7.545, 8.79, 10.02, 11.10, 12.03, 12.71, 12.79, 12.81, 12.82, 12.79, 12.77, 12.78, 12.81, 12.93, 13.61, 14.34, 15.09, and 15.85 microhm cm at 80, 90, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 304, 306, 308, 310, 312, 314, 316, 320, 340, 360, 380, and 400 K, respectively; density 7.19 g cm^{-3}.
16	989	Moore, J. P., et al.	1968	L	90-400	Sample B	99.98$^+$ Cr, 0.006 C, 0.0028 N, <0.002 Ga, 0.0009 H, 0.0008 Mo, 0.0006 O, 0.0005 each of Cu, Ni, S, and Si, 0.0004 K, 0.0003 each of Co, Fe, Pt, and V, <0.0002 each of Sr and Zn, <0.0001 each of B, Hg, Pd, Rn, Ru, Sb, Sn, Te, Tl, U, W, and Zr, <0.00008 each of Cd and Pb, 0.00006 Ca, <0.00005 each of Ag and Ba, <0.00004 Bi, 0.00003 Mn, 0.00002 Nb, <0.00002 each of Ge, In, Mg, and Na, <0.00001 each of As, Li, P, and Ti; cast specimen machined to 0.96 cm in dia and 7.7 cm long; prepared from the starting iodine chromium crystal, purchased from Chromalloy Corp, West Nyak, N.Y., by inert gas tungsten electrode arc melting, drop-cast into a rod; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 58$; electrical resistivity reported as 1.06, 1.445, 1.86, 2.86, 4.05, 5.295, 6.575, 7.83, 9.10, 10.3, 11.39, 12.27, 12.88, 12.95, 12.96, 12.96, 12.93, 12.90, 12.90, 12.94, 13.08, 13.77, 14.47, 15.20, and 15.94 microhm cm at 80, 90, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 304, 306, 308, 310, 312, 314, 316, 320, 340, 360, 380, and 400 K, respectively; density 7.15 g cm^{-3}.
17	505	Goff, J. F.	1968	L	2.0-286		99.92 Cr, 0.005 Fe, 0.004 Mn, 0.003 Cu, 0.002 Mg, trace S, P, Ni, and Mn; polycrystalline; specimen 4 x 4 x 35 mm; cast in an oxygen-free copper boat by melting with an argon arc; annealed in vacuum at 900 C for 24 hrs and then ground to size; electrical resistivity ratio $\rho(297K)/\rho(4K) = 72$.

TABLE 45. THERMAL CONDUCTIVITY OF CHROMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	990	Moore, J. P., Williams, R. K., and McElroy, D. L.	1969	L	90-360		The above specimen, cur. No. 17, measured by the authors in Oak Ridge National Lab.; electrical resistivity reported as 1.495, 1.935, 2.415, 2.935, 3.515, 4.190, 4.870, 5.515, 6.170, 6.830, 7.480, 8.130, 8.805, 9.460, 10.125, 10.755, 11.325, 11.895, 12.385, 12.840, 13.230, 13.480, 13.560, 13.745, 14.11, 14.46, 14.83, and 15.19 microhm cm at 90, 100, 110, 120, 130, 140, 150, 160, 170, 180, 190, 200, 210, 220, 230, 240, 250, 260, 270, 280, 290, 300, 310, 320, 330, 340, 350, and 360 K, respectively; electrical resistivity ratio ρ 296K)/ρ4.2K) = 70.5; Lorenz function reported as 2.2, 2.4, 2.6, 2.7, 2.9, 3.3, 3.4, 3.3, 3.3, 3.3, 3.3, 3.3, 3.1, 3.1, 3.1, and 3.2 x 10^8 V^2 deg^{-2} at 103, 112, 122, 141, 161, 181, 200, 240, 279, 289, 298, 309, 318, 329, 339, and 360 K, respectively.
19	915	Meaden, G. T., Rao, K. V., and Loo, H. Y.	1969	L	277-321		99.999 Cr, 0.0010 C, 0.0009 O, 0.0003 Ca, 0.0002 Fe, 0.0001 each of Al, Cu, and Mg, and 0.00008 H; polycrystalline; electrical resistivity ratio ρ(r.t.)/ρ_0 = 178; electrical resistivity 12.077, 12.304, 12.446, 12.706, 12.757, 12.799, 12.816, 12.852, 12.862, 12.862, 12.829, 12.800, 12.784, 12.747, 12.751, 12.786, 12.907, and 12.094 μohm cm at 278.3, 283.5, 287.0, 294.2, 296.9, 299.0, 300.8, 302.1, 305.2, 306.9, 309.4, 310.3, 311.0, 312.1, 312.5, 313.8, 317.3, and 322.6 K, respectively; Lorenz function 4.073, 4.023, 3.947, 3.831, 3.840, 3.889, 3.891, 3.901, 3.888, 3.827, 3.810, 3.791, and 3.756 x 10^{-8} V^2 K^{-2} at 276.2, 283.7, 294.4, 306.2, 309.2, 311.2, 312.4, 313.4, 314.7, 315.5, 316.8, 318.4, and 320.9 K, respectively.
20	1620	Zinov'ev, V. E., Krentsis, R. P., and Gel'd., P. V.	1969	P	928-1669		99.95$^+$ pure; 8 x 8 x 0.214 mm; ground; annealed in a vacuum of 10^{-5} mm Hg at 900 K for three hrs, then heated to 1600 K for a short time; electrical resistivity ratio ρ(293K)/ρ(4.2K) = 65; thermal conductivity values calculated from measured thermal diffusivity using specific heat capacity data taken from Krentsis, R. P., et al. (Izv. Vuzor, chernaya Metallurgiya, 12, 5, 1960) and density data taken from Chirkin, V. S. ("Thermal-Physical Properties of Nuclear Technique Materials," Atomizdat, Moscow, p. 152, 1968); reported values taken from smoothed curve.
21	1620	Zinov'ev, V. E., et al.	1969	P	934-1671		Thermal conductivity values calculated from the above thermal diffusivity measurements using the same density data with the specific heat capacity data taken from Kohlhaas, R., et al. (Naturforsch., 20a, 1077, 1965).
22	1620	Zinov'ev, V. E., et al.	1969	P	934-1671		Thermal conductivity values calculated from the above thermal diffusivity measurements using the same density data with the specific heat capacity data taken from Kirillin, V. A., et al. (Teplofiz. Vys. Temp., 5, 1124, 1967).

Cobalt

Three sets of data are available for the thermal conductivity of cobalt at cryogenic temperatures, of which two include the maximum. White and Woods [1547] (curve 1), who were responsible for the higher of these reported values, covered the range 2.6 to 147 K for a sample that was stated to contain at least 99.999 percent cobalt. Radhakrishna and Nielson [1160] (curve 9) for a temperature range of 1.6 to 6.4 K obtained thermal conductivity values for another sample from the same supplier and these values were greater over their common temperature range by 20 percent at 2.6 K, and falling to 9 percent at 6.4 K. These later values were approaching those of White and Woods.

The curve for which recommended values at low temperatures have been tabulated is based on measurements of White and Woods. Recommended values have been calculated to 30 K by use of equation (7) and a β-value of 3.71 derived from the data of White and Woods, and from 30 to 130 K the curve has been continued to fit their data. These recommended values at low temperatures are only applicable to a sample having residual electrical resistivity of 0.09075 $\mu\Omega$ cm. Values for other samples can similarly be derived.

At higher temperatures there are two sets of published data covering rather limited temperature ranges which include room temperature and two discordant groups of data in the region of 1000 to 1500 K. Over their common range the two sets of data by Powell [1119] (curve 5) and Wilkes [1557] (curve 6) (see also Wilkes, et al. [1559]) differ by about 1.5 percent, the first mentioned being lower. On the other hand the lower-temperature values by Wilkes lie some 8 percent below those of White and Woods [1547] (curve 1). The recommended curve lies some 1 to 2 percent above the mean of the Wilkes-Powell curves and continues to a value of 0.747 W cm^{-1} K^{-1} at 500 K.

Cobalt undergoes a phase transition at about 690 K, but as the electrical resistivity measurements by Powell [1119] only indicated an associated drop of about 2 percent, no corresponding discontinuity has been shown in the recommended thermal conductivity curve as tentatively extrapolated to pass approximately through the mean of the values of Zinov'ev, et al. [1623] (curves 11–13) for the range 1300 to 1700 K. These values were derived from thermal diffusivity determinations, and differ according to the specific heat values used for the derivation. The minimum shown at about 1390 K corresponds to the Curie point of their sample. Each of the two much lower curves by Jain, et al. [672] (curves 7 and 8) also has a minimum at about 1400 K, but these data indicate Lorenz functions considerably below the theoretical value and are considered low.

The low values of the Lorenz functions found for cobalt at temperatures nearer normal have been commented on previously [608]. The Lorenz function increases slowly with temperature and, according to the present recommended thermal conductivity curve, will attain the theoretical value at about 850 K. This temperature can be compared with 200 K for iron and 570 K for nickel, and is seen to be abnormally high.

No information is available for the thermal conductivity of liquid cobalt.

The recommended values are probably accurate to within ±5 percent near room temperature, ±10 percent at low temperatures and up to 1000 K, and ±20 percent from 1000 K to the melting point. Values below 200 K are only for cobalt having $\rho_0 = 0.09075$ $\mu\Omega$ cm.

TABLE 46. Recommended thermal conductivity of cobalt†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid
Polycrystalline

T	k	T	k
0	0	250	1.10
1	0.270*	273.2	1.05
2	0.539*	298.2	1.00
3	0.808	300	1.00
4	1.08	323.2	0.963
5	1.34	350	0.922
6	1.61	373.2	0.890
7	1.87	400	0.854
8	2.13	473.2	0.771*
9	2.38	500	0.747*
10	2.63	573.2	0.692*
11	2.87	600	0.674*
12	3.10	673.2	0.633*
13	3.31	700	0.621*
14	3.52	773.2	0.592*
15	3.71	800	0.582*
16	3.89	873.2	0.556*
18	4.19	900	0.548*
20	4.43	973.2	0.527
25	4.70	1000	0.521
30	4.58	1073.2	0.509
35	4.24	1100	0.505
40	3.78	1173.2	0.495
45	3.34	1200	0.493
50	2.99	1273.2	0.482
60	2.49	1300	0.472
70	2.17	1373.2	0.425
80	1.94	1400	0.417
90	1.78	1473.2	0.424
100	1.67	1500	0.425
123.2	1.53	1573.2	0.428
150	1.38	1600	0.429
173.2	1.30	1673.2	0.430
200	1.22	1700	0.430
223.2	1.16	1767	0.431*

†The recommended values are for well-annealed high-purity cobalt, and those below 200 K are applicable only to a specimen having residual electrical resistivity of 0.09075 $\mu\Omega$ cm.

*Extrapolated or interpolated.

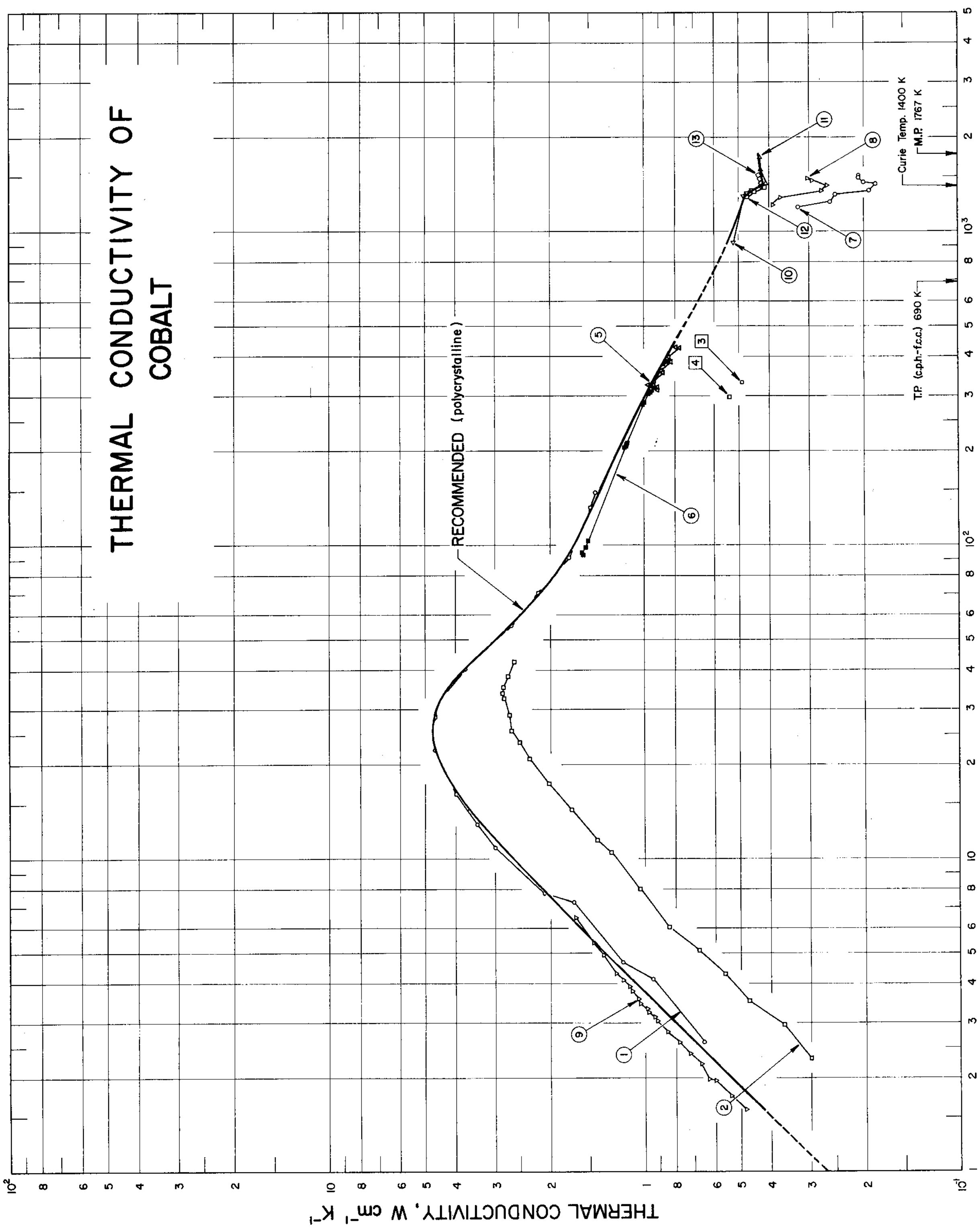

THERMAL CONDUCTIVITY OF COBALT
RECOMMENDED (polycrystalline)
Curie Temp. 1400 K
M.P. 1767 K
T.P. (c.p.h.-f.c.c.) 690 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 59

TABLE 47. THERMAL CONDUCTIVITY OF COBALT - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1547	White, G.K. and Woods, S.B.	1957	L	2.6-147	Co 1b	Impurities (by spectrographic analysis) approx 0.0002 Si, <0.0005 Fe, approx 0.0001 Al, Mg and Cu <0.0001 each; specimen 2 mm dia; supplied by Johnson, Matthey and Co., Ltd. (JM9484xx); annealed in vacuum for 2 hrs at 700 C; ρ_0 = 0.09075 μohm cm; $\rho(295K)/\rho_0$ = 64.5, L_0 = 2.55 x 10^{-8} W ohm K^{-2}.
2	1220	Rosenberg, H.M.	1955	L	2.3-43	Co 1	Polycrystalline rod; 3.03 cm long, 0.204 cm in dia; supplied by Johnson, Matthey and Co., Ltd.; annealed in vacuo for several hrs; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 29.4.
3	1327	Smith, A.W.	1925	L	332.2		Less than 0.03 impurities; supplied by Eimer and Amend; annealed at 900 C for 2 to 3 hrs before machining to size.
4	886	Martin Co.	1959		298.2		100 (nominal) pure; measured at room temp (assumed to be 25 C).
5	1119	Powell, R.W.	1964	C	313-430		99.97 pure; 0.951 cm dia, 4.346 cm long; supplied by Metallurgy Division of the National Physical Laboratory; Armco iron used as reference; electrical resistivity reported as 6.5, 6.7, 7.4, 7.7, 8.7, 8.9, 10.3, 11.4, and 11.6 μohm cm at 20, 22, 51, 55, 82, 87, 126, 151, and 155 C, respectively.
6	1557, 1559	Wilkes, K.E., Powell, R.W., and DeWitt, D.P.	1968	L	93-386		99.92 Co, 0.040 Fe, 0.012 Ni, 0.004 C, 0.001 Ca, 0.001 Cu, 0.001 Si, 0.0008 S, 0.0003 Al, 0.0003 Mn, 0.0002 Mg, and 0.0001 Pb; 1.000 cm dia x 10.05 cm long; supplied by Centre d'Information du Cobalt, Belgium; density 8.805 g cm^{-3} at 23 C; electrical resistivity reported as 0.655, 3.158, 5.23, 5.23, 5.26, 6.02, and 6.04 μohm cm at 77.84, 194.4, 273.2, 273.2, 273.2, 299.0, and 299.7 K, respectively; Lorenz function reported as 1.965, 1.995, and 2.016 x 10^{-8} V^2 K^{-2} at 177.9, 249.0, and 299.4 K, respectively; measured in a vacuum of 5 x 10^{-5} torr.
7	672	Jain, S.C., Narayan, V., and Goel, T.C.	1969	E	1192-1496	1	99.998 pure; 0.5 cm dia x 15 cm long; obtained from Koch Light Laboratories; electrical resistivity 65.2, 68.7, 71,1, 75.1, 77.3, 78.7, 81.1, 83.5, 83.5, 85.3, 86.3, 86.4, 88.2, 89.6, and 89.3 μohm cm at 1159, 1195, 1219, 1262, 1285, 1300, 1339, 1358, 1375, 1409, 1425, 1436, 1473, 1492, and 1498 K, respectively; Lorenz function 1.63, 1.47, 1.31, 1.20, and 1.27 x 10^{-8} V^2 K^{-2} at 1251, 1301, 1352, 1401, and 1453 K, respectively; Bäcklund's modification used.
8	672	Jain, S.C., et al.	1969	E	1218-1477	2	99.999 pure; impurities Cu, Fe, Mg, Ni, Si, and Ag; 0.5 cm dia x 15 cm long; obtained from Johnson Matthey and Co.; electrical resistivity 76.1, 78.9, 82.4, 85.4, 88.9, 91.3, and 92.9 μohm cm at 1214, 1243, 1285, 1326, 1382, 1430, and 1470 K, respectively; Lorenz function 2.42, 2.17, 2.09, and 1.93 x 10^{-8} V^2 K^{-2} at 1252, 1302, 1353, and 1450 K, respectively; Bäcklund's modification used.
9	1166	Radhakrishna, P. and Nielson, M.	1965	L	1.6-6.4		Polycrystalline; 1 mm dia x 6.6 cm long; obtained from Johnson Matthey and Co., Ltd.; annealed in a vacuum of 3 x 10^{-7} mm Hg at 1040 C for 3 hrs; residual electrical resistivity 0.0870 μohm cm; electrical resistivity ratio $\rho(295K)/\rho(4.2K)$ = 66.6; electrical resistivity 0.08715, 0.08719, 0.08721, 0.08724, 0.08728, 0.08734, 0.08735, 0.08740, 0.08747, and 0.08752 μohm cm at 1.68, 2.52, 2.96, 3.39, 3.97, 4.61, 4.82, 5.26, 5.88, and 6.36 K, respectively.

TABLE 47. THERMAL CONDUCTIVITY OF COBALT - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
10	1623	Zinov'ev, V. E., Krentsis, R. P., Petrova, L. N., and Gel'd, P. V.	1968	P	917-1382		99.95$^+$ pure; specimens 8 x 8 x 0.2 mm in size; prepared by grinding rolled sheet; annealed in vacuum at 1200 K for 7 hrs; electrical resistivity (calculated from given equations) 6.82, 11.3, 16.1, 21.5, 27.4, 34.0, 41.4, 49.8, 59.1, 69.5, 81.0, 86.9, 90.9, 94.9, and 98.9 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, and 1700 K, respectively; electrical resistivity ratio $\rho(298K)/\rho(4.2K) = 86$; Curie point 1390 K; thermal conductivity values calculated from measured thermal diffusivity using the specific heat capacity data taken from Braun, M. and Kohlhaas, R. (Z. Naturforsch., 19A, 663, 1964) and the density values taken from Bozorth, R. M. ("Ferromagnetism," Van Nostrand, New York, 1951).
11	1623	Zinov'ev, V. E., et al.	1968	P	1417-1711		The above specimens; reported values taken from smooth curve.
12	1623	Zinov'ev, V. E., et al.	1968	P	1285-1376		The above specimens; thermal conductivity values calculated from the same thermal diffusivity measurement results as above but using the specific heat capacity data taken from Kraftmakher, Ya. A. and Romashina, T. Yu. (Fiz. Tverd. Tela, 8, 1966, 1966); reported values taken from smooth curve.
13	1623	Zinov'ev, V. E., et al.	1968	P	1415-1505		The above specimens; reported values taken from smooth curve.

Copper

Over two hundred separate determinations of the thermal conductivity of copper are listed in Table 49, which now contains 60 percent more entries than in NSRDS-NBS-8 [1126]. At low temperatures, one of the three new curves (curve 155) due to Schrimpf [1276] has a maximum thermal conductivity value about 20 percent in excess of the highest previous value (curve 120), that of White and Tainish [1540]. The curve for which recommended values at low temperatures are now tabulated is based on curve 155. The values at temperatures 1.5 T_m are calculated to fit curve 155 using constants m, n, and a'' as listed in table 1 and $\beta = 0.0237$ as derived from the experimental residual electrical resistivity of 0.000579 $\mu\Omega$ cm.

To proceed from 1.5 T_m to room temperature, this curve follows curve 155 to 20 K, follows curve 120 from 20 to 55 K, and continues through the mean results of several workers. Notably from 80 to 130 K it lies within ± 2 percent of values by van Witzenburg and Laubitz [1467] (curve 149).

While at low temperatures a particular set of recommended thermal conductivity values applies only to a sample of a particular purity and perfection, at moderate and high temperatures one set of recommended values can be given for well-annealed high-purity copper. From 130 to 400 K the newly recommended curve lies within ± 0.5 percent of values by Moore, McElroy, and Graves [988] (curve 40) and to 1200 K follows close to values of Laubitz [817] (curve 139) which had agreed to within 1 to 1.5 percent with the previously estimated curve [1126]. The new curve is extrapolated to the melting point.

For liquid copper, near its melting point, the thermal conductivity as deduced by Mardykin and Filippov [884] (curve 151) from thermal diffusivity determinations agrees well with estimations due to Grosse [546] (curve 204). These last were based on electrical conductivity data [980] and assumed Lorenz functions approximating to the theoretical value. Pending confirmation of the decrease in Lorenz function with increase in temperature to much lower values, as found by recent Russian workers [435, 1592, 1593], the recommended curve follows that deduced by Grosse [546].

The probable uncertainty of the recommended values is ± 2 percent near room temperature, ± 4 percent at low and high temperatures, and ± 15 percent for the molten phase up to 2000 K. The values above 2000 K are provisional. At temperatures below 100 K the tabulated values are only for copper having $\rho_0 = 0.000579$ $\mu\Omega$ cm.

TABLE 48. Recommended thermal conductivity of copper†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	k	T	k	T	k	T	k
0	0	123.2	4.47	1357.6	1.66	3473	1.73*
1	42.2	150	4.29	1373.2	1.66	3600	1.70*
2	84.0	173.2	4.20	1400	1.67	3673	1.69*
3	125	200	4.13	1473.2	1.70	3800	1.66*
4	162	223.2	4.09	1500	1.71	3873	1.65*
5	195	250	4.06	1573.2	1.73	4000	1.61*
6	222	273.2	4.03	1600	1.74	4073	1.60*
7	239	298.2	4.01	1673.2	1.76	4273	1.54*
8	248	300	4.01	1700	1.77	4500	1.48*
9	249	323.2	3.99	1773.2	1.79	4773	1.40*
10	243	350	3.96	1800	1.79	5000	1.33*
11	232	373.2	3.95	1873.2	1.80	5273	1.24*
12	218	400	3.93	1900	1.81	5500	1.17*
13	202	473.2	3.88	1973.2	1.82	5773	1.07*
14	186	500	3.86	2000	1.82	6000	0.989*
15	171	573.2	3.81	2073.2	1.83	6273	0.889*
16	157	600	3.79	2173.2	1.84	6500	0.804*
18	131	673.2	3.74	2200	1.84	6773	0.698*
20	108	700	3.73	2273.2	1.84	7000	0.611*
25	68.3	773.2	3.68	2400	1.84	7273	0.503*
30	44.5	800	3.66	2473.2	1.84	7500	0.414*
35	30.4	873.2	3.61	2600	1.84*	7773	0.305*
40	21.7	900	3.59	2673.2	1.84*	8000	0.212*
45	16.2	973.2	3.54	2800	1.83*	8273	0.097*
50	12.5	1000	3.52	2873.2	1.82*	8500	0.036*
60	8.29	1073.2	3.47	3000	1.80*		
70	6.47	1100	3.46	3073	1.79*		
80	5.57	1173.2	3.41	3200	1.78*		
90	5.08	1200	3.39	3273	1.76*		
100	4.82	1273.2	3.34	3400	1.74*		
		1300	3.32				
		1357.6	3.28				

†The values are for well-annealed high-purity copper, and those below 100 K are applicable only to a specimen having residual electrical resistivity of 0.000579 $\mu\Omega$ cm. The values above 2000 K are provisional.

*Extrapolated or estimated.

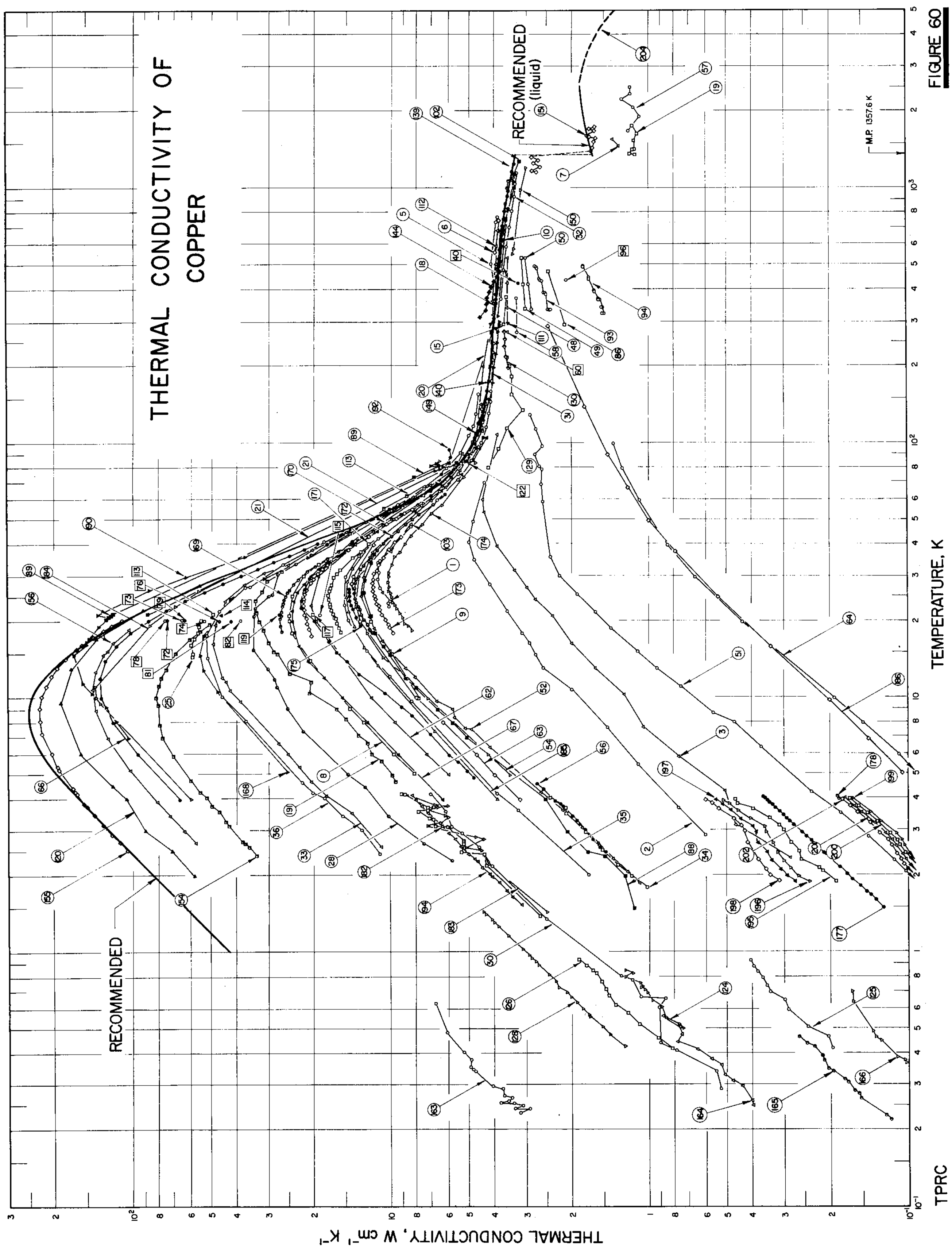

THERMAL CONDUCTIVITY OF COPPER
RECOMMENDED (liquid)
RECOMMENDED
M.P. 1357.6 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 60

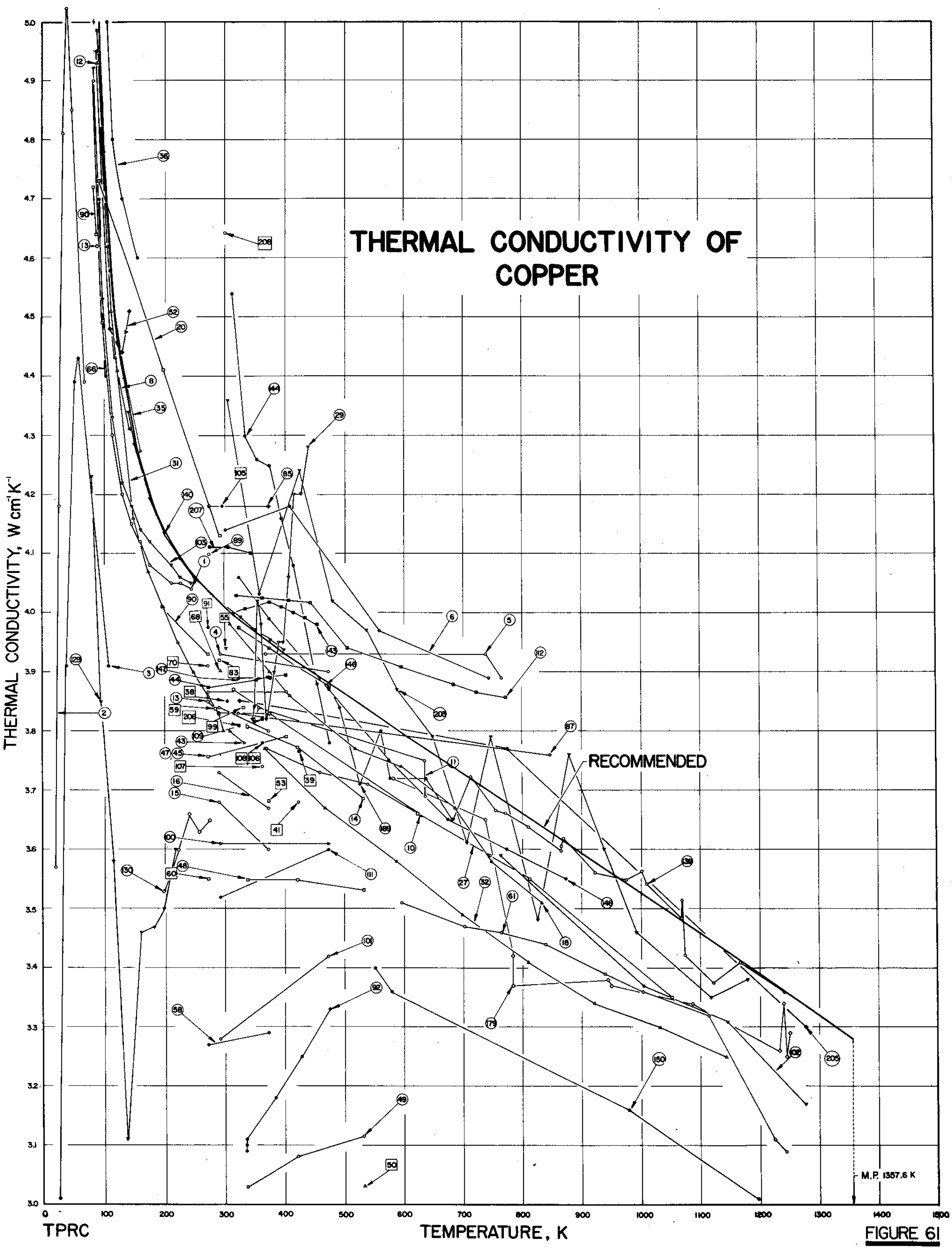

THERMAL CONDUCTIVITY OF
COPPER
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE, K
RECOMMENDED
M.P. 1357.6 K
TPRC
FIGURE 61

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1154	Powers, R.W., Schwartz, D., and Johnston, H.L.	1950	L	23-245	OFHC Cu	Free from oxygen; specimen 0.5 in. in dia and 20 in. long; obtained from American Brass Co.
2	1605	Zavaritskii, N.V. and Zeldovich, A.G.	1956	L	2.9-70	1	0.20 Ni, 0.10 O, 0.05 each of As, Sb, Fe, Pb, and Sn, 0.01 S, and 0.003 Bi (composition according to All-Union Standard); annealed to 800 C.
3	1605	Zavaritskii, N.V. and Zeldovich, A.G.	1956	L	2.4-108	2	Similar to the above specimen except unannealed.
4	1332	Smith, C.S. and Palmer, E.W.	1935	L	293,473	2	99.986 pure; 0.022 O, 0.0016 Fe, and 0.0015 S; annealed at 550 C for 1 hr; electrical conductivity 58.962 and 34.16 x 10^4 ohm^{-1} cm^{-1} at 20 and 200 C, respectively.
5	1234	Sager, G.F.	1930	P	368-766	1	Electrolytically pure; specimen ~0.25 cm in dia; annealed for about 10 min at a bright red heat; electrical conductivity 4.47, 3.14, 2.07, and 1.99 x 10^5 ohm^{-1} cm^{-1} at 95, 235, 466, and 497 C, respectively; density 8.87 g cm^{-3}.
6	1234	Sager, G.F.	1930	P	302-744	2	Electrolytically pure; specimen ~0.25 cm in dia; annealed for about 10 min at a bright red heat; electrical conductivity 5.55, 4.0, 2.84, and 2.06 x 10^5 ohm^{-1} cm^{-1} at 29, 136, 286, and 471 C, respectively; density 8.87 g cm^{-3}.
7	863	Lucks, C.F. and Deem, H.W.	1957	L	1456,1550		0.036 O, 0.02 Ag, 0.002 Al, 0.002 Fe, 0.001 Ni, 0.001 Mg, 0.001 Si, 0.0005 Ca, traces of H and N; electrolytic tough-pitch copper; in molten state.
8	1104	Powell, R.L., Rogers, W.M., and Coffin, D.O.	1957	L	5.1-142	Coalesced Copper	High purity commercial coalesced copper; 0.0013 O, 0.0008 Pb, 0.0007 Ni, <0.0005 each of Fe, As, and Sb, 0.0002 Sn, <0.0001 Te and Ag, and <0.00005 Bi; specimen 0.367 cm in dia and 23.2 cm long; annealed in helium for 4 hrs at 400 C, cooled slowly to 200 C, and then kept in helium at 200 C for 8 hrs; density 8.90 g cm^{-3}; reported data taken from smoothed curve.
9	1560	Wilkinson, K.R. and Wilks, J.	1949	L	10-20		Electrical copper; specimen 0.47 mm in dia and 900 mm long; annealed.
10	1097	Pott, F.P.	1958	E	315-1058		Commercial electrolytic copper.
11	761	King, R.W.	1918	P	349-636		Specimen drawn wire 2.5 mm in dia.
12	920	Meissner, W.	1915	E	21-374	Cu 1	Electrolytically pure; specimen 1 mm in dia; supplied by Siemens and Halske Co.; electrical conductivity 2477, 64.4, 59.8, and 45.0 x 10^4 ohm^{-1} cm^{-1} at 20.3, 273.1, 291.2, and 378.1 K, respectively.
13	920	Meissner, W.	1915	E	22-375	Cu II	Electrolytically pure but purity lower than the above specimen; electrical conductivity 5422, 62.9, 58.4, and 44.0 x 10^4 ohm^{-1} cm^{-1} at 20.3, 273.1, 291.2, and 373.1 K, respectively.
14	509	Goglia, M.J., Hawkins, G.A., and Deverall, J.E.	1952	L	339-533	A	Oxygen-free (<0.01 O) high-conductivity copper.
15	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373	Cu II	<0.05 (Fe + Zn); specimen 1.108 cm in dia and 27 cm long; density 8.65 g cm^{-3} at 18 C; electrical conductivity 55.3 and 41.7 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
16	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373	Cu II W	<0.05 (Fe + Zn); specimen 1.107 cm in dia and 27 cm long; electrical conductivity 56.1 and 42.4 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17*	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Cu III	0.05 Pb, traces of Ni and Fe; specimen 1.107 cm in dia and 27 cm long; drawn; density 8.88 g cm^{-3} at 18 C; electrical conductivity 57.2 and 43.5 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
18	1312	Sidles, P.H. and Danielson, G.C.	1951	P	309-834		0.125 in. in dia and at least 50 cm long.
19	428	Fieldhouse, I.B., Hedge, J.C., Lang, J.I., and Waterman, T.E.	1956	C	1362-1761		Electrolytic tough-pitch copper; before measurement: 0.012 O, 0.0048 N, and traces of Al, Ca, Mg, Ni, Si, and Ti; after measurement: 0.0059 O, 0.0055 N, and all the metallic impurities reduced about ten fold; density 8.83 g cm^{-3}; in molten state.
20	708	Kannuluik, W.G. and Laby, T.H.	1928	L	95-293		Single crystal; specimen 0.6 cm in dia and 12 cm long; supplied by General Electric Co.
21	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 2b	Very high purity; porous natural crystal from Lake Superior; hammered from 3 mm to 1.3 mm and then annealed for 3 hrs at 380 C; electrical resistivity 1.562, 0.235, and 0.00187 μohm cm at 273, 83, and 21 K, respectively.
22*	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 3	"Purest" electrolytic copper; fine grains; electrical resistivity 1.552, 0.239, and 0.00424 μohm cm at 273, 83, and 21 K, respectively.
23*	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 4a	"Purest" electrolytic copper with fine grains; annealed for 4.5 hrs at 380 C; electrical resistivity 1.56, 0.240, and 0.00406 μohm cm at 273, 83, and 21 K, respectively.
24*	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 6a	Not very pure; single crystal; annealed for 7.5 hrs at 380 C; electrical resistivity 1.58, 0.249, and 0.01356 μohm cm at 273, 83 and 21 K, respectively.
25	201	Bremmer, H. and deHaas, W.J.	1936	L	15-20		Specimen 0.2 mm in dia.
26*	561	Grüneisen, E. and Reddemann, H.	1934	L	22, 79	Cu 2b	Very high purity; probably somewhat deformed.
27	1267	Schofield, F.H.	1925	L	369-898		99.9 pure; supplied by Bolton and Sons, Ltd; density 8.92 g cm^{-3} at 21 C; electrical resistivity 1.69, 2.60, 3.73, 4.88, and 6.03 μohm cm at 14.0, 144.7, 306.0, 470.0, and 630.2 C, respectively.
28	937	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-40		99.999 pure; polycrystalline; JM 4234 from Johnson, Matthey and Co.; annealed for several hrs at two-thirds of the melting point.
29	269	Child, C.D. and Quick, R.W.	1894	E	347-440		Electrolytic copper; specimen a prismatic bar with 5 cm x 2 cm cross section.
30	1034	Nicol, J. and Tseng, T.P.	1953	L	0.29-4.2		Polycrystalline; commercial grade high purity magnet wire; 0.025 cm in dia and 27.2 cm long; supplied by General Electric Co.
31	830	Lees, C.H.	1908	L	107-299		Turned from soft-drawn high-conductivity copper conductor; specimen 0.585 cm in dia and 7-8 cm long; electrical resistivity 0.375, 0.543, 0.637, 0.909, 0.989, 1.365, 1.506, and 1.750 μohm cm at -176.8, -151.2, -136.9, -102.0, -91.1, -36.0, -15.5, and 16.9 C, respectively; density 8.84 g cm^{-3} at 23 C.
32	862	Lucks, C.F. and Deem, H.W.	1956	C	367-1144		99.9^+ pure; electrolytic tough-pitch copper; density 8.92 g cm^{-3} at 24 C.
33	145	Berman, R. and MacDonald, D.K.C.	1952	L	2.6-91		99.999 pure; about 0.0005 Ag, <0.0003 Ni, and <0.0004 Pb; JM 4234 from Johnson, Matthey and Co.; drawn and annealed in a helium atmosphere at 450 C for 6 hrs; electrical resistivity in the range 12-15 K given as $\rho = 5.27 \times 10^{-3} + 2.64 \times 10^{-10} T^5$ (μohm cm).

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
34	49	Allen, J. F. and Mendoza, E.	1948	L	1.8-4.1		0.003 Ag, 0.003 Ni, and 0.003 Pb; approximate composition; free from oxygen; Johnson, Matthey and Co., Ltd. No. 1562; annealed in air; $\rho_0 = 0.055$ μΩ cm.
35	1538	White, G. K.	1953	L	2.0-160	Cu 1	99.999 pure; JM 4272 from Johnson, Matthey and Co.; about 0.0005 Ag, 0.0004 Pb, <0.0003 Ni, and barely visible spectral lines of Ga and Fe; rod specimen 2 mm in dia; as drawn.
36	1538	White, G. K.	1953	L	2.5-155	Cu 2	The above specimen Cu 1 annealed in vacuo at 550 C for 3 hrs; electrical resistivity in the range 10 to 35 K given as $\rho = 0.00458 + 2.75 \times 10^{-10} T^5$ (μohm cm).
37*	1162	Quick, R. W., and Lanphear, B. S.	1895	F	219-260		Electrolytic copper.
38	392	Ellis, W. C., Morgan, F. L., and Sager, G. F.	1928	P	305.2		Electrolytically pure; specimen 2.5 mm in dia and 4.69 cm long; electrical conductivity 5.58×10^5 ohm^{-1} cm^{-1} at 32 C; density 8.93 g cm^{-3} at 32 C.
39	1564	Williams, H. M. and Bihlman, V. W.	1923	L	363, 483	Electrolytic Copper	99.98 pure; annealed.
40	1564	Williams, H. M. and Bihlman, V. W.	1923	L	363, 493	Electrolytic Copper	99.98 pure; cast.
41	1564	Williams, H. M. and Bihlman, V. W.	1923	L	363, 483	Electrolytic Copper	99.97 pure; hard-drawn.
42*	1564	Williams, H. M. and Bihlman, V. W.	1923	L	363, 498		99.76 pure; cast.
43	760	King, R. W.	1915	P	308, 333		Specimen 0.25 cm in dia and 30 cm long; density 8.93 g cm^{-3} at room temp (from Tabellen of Landolt and Börnstein).
44	277	Chubb, W. F.	1938	L	273-403		≈0.079 O.
45	277	Chubb, W. F.	1938	L	273-403		≈0.079 O and 0.106 Ni.
46*	277	Chubb, W. F.	1938	L	273-403		≈0.022 O.
47	277	Chubb, W. F.	1938	L	273-403		≈0.022 O and 0.106 Ni.
48	509	Goglia, M. J., Hawkins, G. A., and Deverall, J. E.	1952	L	339-533	B	0.015 Fe and 0.011 P; cast.
49	509	Goglia, M. J., et al.	1952	L	339-533	C	0.061 Fe and 0.016 P; cast.
50	509	Goglia, M. J., et al.	1952	L	339-533	D	0.089 Fe and 0.015 P; cast.
51	1542	White, G. K. and Woods, S. B.	1954	L	1.9-130		0.056 Fe (nominal composition); homogenized and annealed; residual electrical resistivity (at helium temp) = 0.53 μohm cm; ~5% higher than a minimum value at ~25 K; electrical resistivity 0.56, 0.56, 0.55, 0.55, 0.54, 0.57, 0.57, 0.55, 0.55, 0.53, 0.53, 0.54, 0.62, 0.68, 0.74, 0.73, 0.74, 0.80, and 2.18 μohm cm at 2.0, 3.3, 3.7, 4.6, 5.8, 8.2, 8.8, 13.0, 15.2, 18.7, 30.6, 35.9, 58.6, 68.3, 77.4, 79.1, 79.4, 90.0, and 295 K, respectively.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
52	1542	White, G.K. and Woods, S.B.	1954	L	1.9-142		0.0043 Fe (nominal composition); homogenized and annealed; residual electrical resistivity (at helium temp) = 0.041 μohm cm, ~8% higher than a minimum value at ~15 K; electrical resistivity 0.041, 0.041, 0.040, 0.040, 0.041, 0.041, 0.040, 0.040, 0.041, 0.041, 0.040, 0.040, 0.047, 0.055, 0.061, and 1.75 μohm cm at 2.0, 4.1, 4.1, 5.1, 8.0, 9.0, 10.9, 12.4, 13.4, 15.6, 17.1, 25.3, 29.5, 34.9, 37.5, and 295 K, respectively.
53	805	Maybrey, H.J.	1928	L	373.2		Electrolytic.
54	1538	White, G.K.	1953	L	5.0-58	Cu 3	99.999 pure; JM 4272 from Johnson, Matthey and Co.; about 0.0005 Ag, 0.0004 Pb, <0.0003 Ni, and barely visible spectral lines of Ga and Fe; specimen 1 mm dia rod; as drawn.
55	1379	Sutton, W.H.	1960	L	303.2	ETP	Electrolytic tough pitch copper; specimen 0.75 in. in dia and 9 in. long.
56	69	Andrews, F.A., Webber, R.T., and Spohr, D.A.	1950	L	2.5-4.6		99.998$^+$ pure; polycrystal; supplied by Johnson, Matthey and Co.
57	907	McClelland, J.D., Rasor, N.S., Dahleen, R.C., and Zehms, E.H.	1957	R	1673-2500		In liquid state.
58	1282	Sedström, E.	1919	T	273,373		Rolled, drawn, and then heated for 0.5 hr at temp close to melting point.
59	469	Gabler, F.	1937	R	285.7		Pure.
60	1283	Sedström, E.	1924	T	273.2		Pure; rolled and drawn to wire of 1 mm^2 cross section and 3 cm long and heated at temp close to melting point.
61	969	Mikryukov, V.E. and Rabotnov, S.N.	1944	E	597-1245		Polycrystal.
62	1103	Powell, R.L., Roder, H.M., and Rogers, W.M.	1957	L	5.0-40	Coalesced Cu	99.98 pure; 0.0013 O_2, 0.0007 Ni, 0.0008 Pb, 0.0002 Sn, <0.0005 each of Fe, As, and Sb, 0.0001 Te, and <0.00005 Bi; cold rolled, annealed for 1 hr at 650 C, redrawn and reannealed for 17 min at 760 C, followed by grinding to sample size of 0.144 in. in dia; density 8.899 g cm^{-3}; porosity 0.5%.
63	1103	Powell, R.L., et al.	1957	L	4.0-40	Electrolytic tough pitch	0.01 Fe, 0.001 each of Ag and Zn, <0.0001 each of Al, Cr, Pb, Mg, Mn, and Sn; electrolytic tough pitch; density 8.914 g cm^{-3}; ground.
64	1103	Powell, R.L, et al.	1957	L	5.0-100	Phosphorus deoxidized Cu	0.027 P, 0.01 each of Fe, Ag, and Zn, 0.001 each of Ni and Si, <0.0001 each of Al, Cr, Pb, Mg, and Mn; density 8.917 g cm^{-3}; ground.
65*	76	Aoyama, S. and Ito, T.	1940	L	78.2	Electrolytic Cu	0.015 Sb, 0.010 Fe, 0.007 S, and trace of Pb.
66	1208, 1102	Powell, R.L, Roder, H.M., and Hall, W.J.	1958	L	4.0-105		99.999 pure; swaged from about 0.375 in. down to about 0.072 in., cleaned with a 1:1 solution of HCl and a 1:10 solution of HNO_3, annealed in vacuum for 2 hrs at 400 C, drawn through tungsten carbide dies to 0.070 in., cleaned with acids, and finally annealed again in vacuum for 2 hrs at 400 C; slight unavoidable work hardening of the sample during installation in the apparatus; electrical resistivity 0.00112, 0.00116, 0.00124, 0.00142, 0.00168, 0.00203, 0.00283, 0.00404, 0.00721, 0.0358, 0.0670, 0.122, and 0.233 μohm cm at 4.1, 7.7, 10.0, 12.5, 15.6, 18.9, 22.4, 25.5, 31.3, 49.4, 59.7, 71.4, and 85.1 K, respectively.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
67	1208, 1102	Powell, R.L., Roder, H.M., and Hall, W.J.	1958	L	4.0-105		99.999 pure; swaged from about 0.375 in. down to about 0.0816 in., cleaned with acids, annealed in vacuum for 2 hrs at 400 C, and then drawn through tungsten carbide dies to 0.070 in. in which the cross-section area reduced by 26.4%; electrical resistivity 0.0131, 0.0138, 0.0146, 0.0157, 0.0177, 0.0206, 0.0274, 0.0457, 0.115, 0.196, and 0.249 μohm cm at 4.1, 13.4, 17.3, 21.1, 25.4, 28.8, 34.5, 42.7, 61.4, 73.1, and 82.4 K, respectively.
68	553	Grüneisen, E.	1900	L	291.2		Pure.
69*	553	Grüneisen, E.	1900	L	291.2		Trace of As.
70	407	Eucken, A. and Warrentrup, H.	1935	R	273.2		Pure; electrical conductivity 62.8 x 10^4 ohm^{-1} cm^{-1} at 273.2 K.
71*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.17	Cu 12	Natural single crystal; tempered for 3 hrs at 380 C; measured at H (the transverse magnetic field strength) = 0 and θ (the angle between magnetic field direction and a line perpendicular to rod axis) = 0° at which the electrical resistivity nearly minimum and H nearly parallel to [100] direction.
72	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.17	Cu 12	The above specimen measured at H = 2280 oersteds and θ = 0°.
73	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Cu 12	The above specimen measured at H = 4490 oersteds and θ = 0°.
74	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.21	Cu 12	The above specimen measured at H = 8750 oersteds and θ = 0°.
75*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.23	Cu 12	The above specimen measured at H = 10880 oersteds and θ = 0°.
76	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.25	Cu 12	The above specimen measured at H = 12200 oersteds and θ = 0°.
77*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.17	Cu 12	The above specimen measured at H = 0 oersteds and θ = -40° at which the electrical resistivity nearly maximum and H nearly parallel to [110] direction.
78	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Cu 12	The above specimen measured at H = 2280 oersteds and θ = -40°.
79	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.19	Cu 12	The above specimen measured at H = 4490 oersteds and θ = -40°.
80*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.24	Cu 12	The above specimen measured at H = 8750 oersteds and θ = -40°.
81	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.24	Cu 12	The above specimen measured at H = 10800 oersteds and θ = -40°.
82	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.30	Du 12	The above specimen measured at H = 12200 oersteds and θ = -40°.
83	1258	Schaufelberger, W.	1902	E	291.2		Pure.
84*	1624	Zolotukhin, G.E.	1956	P	354.2		Pure.
85	919	Meissner, W.	1914	E	21-373		Electrolytic copper wire; specimen heated considerably during soldering.
86	1332	Smith, C.S. and Palmer, E.W.	1935	L	293, 473	Bar 104	99.80 Cu, 0.19 Si, and 0.02 Fe; specimen 0.75 in. in dia and 8 in. long; annealed at 700 C for 2 hrs; electrical conductivity 29.58 and 21.30 x 10^4 ohm^{-1} cm^{-1} at 20 and 200 C, respectively.
87	1169	Ranque, G., Henry, P., and Chaussain, M.	1935	L	323-848		99.9 pure.
88	1543	White, G.K. and Woods, S.B.	1955	L	1.5-142		99.98 Cu and 0.02 Ge; specimen 1-2 mm in dia and 6 cm long; drawn and annealed; electrical resistivity 1.92 and 0.087 μohm cm at 295 and 4.2 K with a minimum of 0.084 μohm cm at ~13 K.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
89	1268	Schott, R.	1916	L	20-273		High purity single crystal natural copper.
90	1268	Schott, R.	1916	L	22-273		Commercially pure; fine crystalline.
91	78	Aoyama, S. and Ito, T.	1940	L, R	78, 273	Electrolytic Cu	Impurities: 0.015 Sb, 0.010 Fe, 0.007 S, and 0.003 As; annealed in nitrogen stream for 20 hrs at 380-400 C; electrical conductivity 6.22 and 43.1 x 10^5 ohm^{-1} cm^{-1} at 273 and 78 K, respectively.
92	1331	Smith, C.S.	1931	L	337-477	93	99.94 Cu, 0.042 P, and 0.04 Fe; annealed at 650 C for 1 hr and cooled in air.
93	1331	Smith, C.S.	1931	L	337-494	82	99.97 Cu, 0.075 P, and 0.04 Fe; annealed at 650 C for 1 hr and cooled in air.
94	1331	Smith, C.S.	1931	L	325-496	95	99.74 Cu and 0.18 P; annealed at 650 C for 1 hr and cooled in air.
95*	589	Hansen, D. and Rogers, C.E.	1932	L	438		99.917 Cu and 0.083 P; specimen 0.5 in. in dia and 6.5 in. long; annealed.
96	589	Hansen, D. and Rogers, C.E.	1932	L	438		99.865 Cu and 0.135 P; specimen 0.5 in. in dia and 6.5 in. long; annealed.
97*	589	Hansen, D. and Rogers, C.E.	1932	L	438		99.93 Cu and 0.07 As; specimen 0.5 in. in dia and 6.5 in. long; annealed.
98*	589	Hansen, D. and Rogers, C.E.	1932	L	438		99.856 Cu and 0.144 As; specimen 0.5 in. in dia and 6.5 in. long; annealed.
99	1327	Smith, A.W.	1925	L	332.2		Impurity <0.03; electrical conductivity 50.8 x 10^4 ohm^{-1} cm^{-1} at 296.2 K.
100	1332	Smith, C.S. and Palmer, E.W.	1935	L	293, 473	Bar 114	0.07 Mn, 0.02 Mg, and 0.01 Fe; specimen 0.75 in. in dia and 8 in. long; electrical conductivity 52.55 and 32.18 x 10^4 ohm^{-1} cm^{-1} at 20 and 200 C, respectively; annealed at 700 C for 2 hrs.
101	1332	Smith, C.S. and Palmer, E.W.	1935	L	293, 473	Bar 115	0.14 Mn, 0.01 Fe, and 0.01 Mg; specimen 0.75 in. in dia and 8 in. long; electrical conductivity 45.79 and 29.4 x 10^4 ohm^{-1} cm^{-1} at 20 and 200 C, respectively; annealed at 700 C for 2 hrs.
102	427	Fieldhouse, I.B., Hedge, J.C., Lang, J.I., Takata, A.N., and Waterman, T.E.	1956	L	764-1287	Electrolytic tough pitch	Electrolytic tough pitch copper meeting Federal Specification QQC 576 (minimum 99.9 Cu); specimen 7 in. in dia and 1.5 in. thick; density 8.83 g cm^{-3}.
103	1148	Powers, R.W. (Johnston, H.R., editor)	1949	L	23-245	OFHC	Oxygen-free high conducting (OFHC) copper.
104*	77	Aoyama, S. and Ito, T.	1940	C	80, 273		Pure.
105	1065	Parker, W.J., Jenkins, R.J., Butler, C.P., and Abbott, G.L.	1961	P	295.2	OFHC	Specimen 1.9 cm^2 in cross-sectional area and 0.312 cm thick.
106	1384	Taga, M.	1960	P	363.2		Commercial grade; 99.82 pure; density 8.3 g cm^{-3}.
107	1384	Taga, M.	1960	P	363.2		The above specimen; second run.
108	1384	Taga, M.	1960	P	363.2		The above specimen; third run.
109	1384	Taga, M.	1960	P	363.2		The above specimen; fourth run.
110*	332	deHaas, W.J. and Biermasz, Th.	1936	L	15-20		"Very pure."
111	1332	Smith, C.S. and Palmer, E.W.	1935	L	293, 473	Bar No. 99	0.07 Al and 0.01 Fe; annealed at 750 C for 2 hrs; electrical conductivity 52.58 and 31.69 x 10^4 ohm^{-1} cm^{-1} at 20 and 200 C, respectively.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
112	962	Mikryukov, V. E.	1956	E	320-773		99.99 pure; polycrystalline; electrical resistivity 1.92, 2.50, 3.17, 3.81, 4.43, and 5.03 μohm cm at 46.9, 134.5, 232.2, 323.3, 411.1, and 499.3 C, respectively.
113	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 4	"Purest" electrolytic; with fine grains.
114	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 4b	The above specimen hammered, then annealed for 4.5 hrs at 380 C, and recrystallized at 950 C for 5 min.
115	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 6	Not very pure; single crystal; sawed from larger block and lathed into rod.
116*	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 6b	From the same block as the above specimen Cu 6; hammered from 6 mm to 2.5 mm dia and annealed for 3 hrs at 380 C.
117	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 6c	Similar to the above specimen Cu 6b except further annealed in vacuum for 5 min at 950 C; about 25 grain cross-sections per 1 mm^2.
118*	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 7	Lathed from the same block as specimen 6; 3 to 4 crystal grains on the measuring length; unannealed.
119	966	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 7a	Similar to the above specimen Cu 7 except annealed for 4 hrs at 380 C.
120	1540	White, G. K. and Tainsh, R. J.	1960	L	2.0-55		99.999 pure copper from the Central Research Lab. of the American Smelting and Refining Co.; <0.0001 each of Fe, Sb, and Se, and <0.0002 each of Te and As; 0.030 in. dia wire, rolled and drawn from a 0.75 in. dia rod, annealed at 530 C in vacuo for several hrs; residual electrical resistivity $0.865 \pm 0.01 \times 10^{-9}$ ohm cm.
121*	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 2a	Very high purity; porous natural crystal hammered from 3 mm to 1.3 mm dia.
122	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Cu 9	Not very pure; single crystal solidified from melt; completely undeformed and unworked.
123*	813	Larson, K. B. and Koyama, K.	1968	P	298.2	No. 1	Specimen 0.042 cm thick and 1.25 cm in dia; obtained from Dupont Detaclad stock; thermal conductivity value calculated from the measurement of thermal diffusivity, with density value taken from Metals Handbook (T. Lyman Ed., 8th ed., Vol. 1) and specific heat value taken from Kelley, K. K. (U. S. Bureau of Mines Bulletin 584, 1960).
124	318	Davey, G. and Mendelssohn, K.	1963		0.50-0.88	Cu 1	Commercial, polycrystalline wire; electrical resistivity measured by Mendelssohn, K., et al. (Bull. Inst. Intern. Froid. Annexe, (2), 49-56, 1965) reported as 0.119 μohm cm in the range 0.35 to 1.08 K.
125	318	Davey, G. and Mendelssohn, K.	1963		0.42-0.93	Cu 2	99.999 pure; polycrystalline wire.
126	318	Davey, G. and Mendelssohn, K.	1963		0.42-0.94	Cu 3	99.999 pure; polycrystalline wire; annealed at 898.2 K for 3 hrs.
127*	859	Lorenz, L.	1881	L	273, 373		Density 8.82 g cm^{-3}; electrical conductivity 45.74 and 33.82×10^4 ohm^{-1} cm^{-1} (the author reported 45.74 and 33.82×10^6, probably a typographical error) at 0 and 100 C, respectively.
128	847	Lindenfeld, P., Lynton, F. A., and Soulen, R.	1965	L	0.4-1.5		Specimen a foil of 0.05 mm thickness supplied by Chase Brass and Copper Co.; annealed at 530 C for 3 hrs; residual resistance ratio 270.
129	1580	Wright, W. H.	1960	L	80-217		Commercial copper; specimen 0.375 in. in dia and 2.975 in. long cylinder with a part of 1.1 in. long at one end turned down to a dia of 0.125 in.; data corrected for drift rate.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
130	1580	Wright, W. H.	1960	L	199-275		Similar to the above specimen.
131*	1382	Swift, D. L.	1966	→	298.2		Nearly spherical grains supplied by Belmont Smelting and Refining Co.; mesh size -30 +35; specimen contained in a 0.75 in. dia and 2 in. long cylindrical cell; thermal conductivity measured by using the transient line-source method; measured in Freon-12 under a pressure of ~100 psig.
132*	1382	Swift, D. L.	1966	→	298.2		Similar to the above specimen; measured in argon under a pressure of ~100 psig.
133*	1382	Swift, D. L.	1966	→	298.2		Similar to the above specimen; measured in nitrogen under a pressure of ~100 psig.
134*	1382	Swift, D. L.	1966	→	298.2		Similar to the above specimen; measured in methane under a pressure of ~100 psig.
135*	1382	Swift, D. L.	1966	→	298.2		Similar to the above specimen; measured in helium under a pressure of ~100 psig.
136*	1382	Swift, D. L.	1966	→	298.2		Similar to the above specimen; measured in hydrogen under a pressure of ~100 psig.
137*	216	Brown, H. M.	1927	E	273.2		Specimen No. 10 gauge commercial wire 10 cm in length; electrical resistivity 1.73 μohm cm at 0 C.
138*	216	Brown, H. M.	1927	E	273.2		The above specimen measured in a longitudinal magnetic field of 10000 gauss.
139	817	Laubitz, M. J.	1967	F	308-1241		0.00005 Cr, 0.00005 Ag, 0.000035 Fe, and 0.00003 Mg; supplied by American Smelting and Refining Co.; density 8.943 ± 0.001 g cm^{-3} at 291 K; electrical resistivity 1.545, 1.725, 2.398, 3.078, 3.771, 4.481, 5.213, 5.973, 6.766, 7.563, and 8.470 μohm cm at 273, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively; $\rho(273K)/\rho(4.2K) = 900$; measured in an atmosphere of argon at a pressure of 10-25 cm Hg; thermal conductivity data obtained from the author in a private communication; data corrected for "digit inversion" errors in reading and error caused by thermocouple contamination at highest temp.
140	988	Moore, J. P., McElroy, D. L., and Graves, R. S.	1967	L	85-400		99.999 pure (nominal); polycrystalline; supplied by National Research Council, Ottawa, Canada; electrical resistivity ratio ρ 273.16)/$\rho(4.2) = 900$; average grain size 574 μ; electrical resistivity 0.248, 0.350, 0.488, 0.631, 0.876, 1.219, 1.546, 1.893, and 2.229 μohm cm at 85, 100, 120, 140, 175, 225, 273.16, 325 and 375 K, respectively; thermal conductivity values calculated from the equation $k = 4.1631 - 5.904 \times 10^{-4} T + (7.0872 \times 10^{5}) T^{-3}$ given by the author.
141*	1325	Smirnov, E. V., Muchnik, G. F., and Shklyarenskii, E. E.	1967	L	751-1075		Traces of Mg, Mn, and Si; specimen 0.35-0.4 mm thick; thin metal layer depositing done by electro-air metallization; porosity 23%.
142*	1325	Smirnov, E. V., et al.	1967	L	607-1157		Traces of Mg, Mn and Si; specimen 1.13-1.14 mm thick; thin metal layer depositing done by plasma metallization; porosity 16%.
143	1364	Stewart, R. W.	1893	F	313-453		0.5 in. dia x 7 ft long; density 8.907 g cm^{-3}.
144	1364	Stewart, R. W.	1893	F	313-473		Second run of the above specimen.
145*	972	Miller, V. S.	1960		473.2		No details reported.
146	1137	Powell, R. W. and Tye, R. P.	1967	L	323-473	J. M. Sample; No. 1	0.0005 Ag, <0.0004 Pb, and <0.0003 Ni (estimated composition); Johnson, Matthey and Co. spectrographically standardized rod; 7 mm in dia and 15 cm long; heat treated to 1173 K; electrical resistivity at 293, 323, 373, 473, 573, 673, 773, 873, and 1173 K, reported as 1.75, 1.93, 2.25, 2.93, 3.60, 4.33, 5.08, 5.88, and 8.30 μohm cm, respectively.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
147	1137	Powell, R. W. and Tye, R. P.	1967	L	323,373	Q. M. C. Sample; No. 2	Pure; 1 cm in dia and 10 cm long; electrical resistivity at 293, 323, and 373 K reported as 1.78, 1.95, and 2.28 μohm cm, respectively.
148	1137	Powell, R. W. and Tye, R. P.	1967	C	323-873	M. S. Sample; No. 3	Pure; rod of 1.27 cm in dia and 10 cm long; electrical resistivity at 293, 323, 373, 473, 573, 673, 773, and 873 K reported as 1.73, 1.93, 2.27, 2.97, 3.68, 4.43, 5.17, and 5.95 μohm cm, respectively.
149	1467	Van Witzenburg, W. and Laubitz, M. J.	1969	L	80-130		99.999^+ pure; 1.6 mm dia wire supplied by Asarco; annealed in a vacuum of 10^{-6} mm Hg at 1140 K for 114 hrs; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 1330$; residual electrical resistivity 0.0012 μohm cm; reported thermal conductivity values calculated from measurements of the two (electrical and thermal) relative magneto resistances and the two normal resistances.
150	1018, 1017	Neel, D. S. and Pears, C. D.	1962	R	550-1194		1 in. dia x 1 in. long.
151	844	Mardykin, I. P. and Filippov, L. P.	1968	P	1169-1732		Thermal conductivity values calculated from measured data of thermal diffusivity and specific heat capacity; in both solid and liquid states.
152*	217	Brown, H. M.	1928	E	279.7		Effective length 10 cm and cross-sectional area 0.0510 cm^2; electrical resistivity 1.575 μohm cm at 6.52 C; no changes in thermal conductivity and electrical resistivity observed during the application of transverse magnetic fields up to 8000 gauss.
153*	217	Brown, H. M.	1928	E	279.7		The above specimen measured in longitudinal magnetic fields of 8000 and 10000 gauss.
154	1276	Schriempf, J. T.	1968	L	2.4-19	Cu 1	99.999 pure (spectrographic purity, but ~0.01 Mn reported by colorimetric chemical analysis); prepared by American Smelting and Refining Co.; swaged from the stock dia of 0.375 to 0.125 inch, annealed at 1000 C for 12 hrs in air at a pressure of $\sim 10^{-3}$ torr; etched to final dia of 0.119 in.; residual electrical resistivity $\rho_0 = 1.73 \times 10^{-3}$ μohm cm; electrical resistivity 1.746, 1.742, 1.738, 1.736, 1.740, 1.743, 1.758, 1.779, 1.809, 1.853, 1.922, 2.017, 2.127, 2.247, 2.420, 2.638, 2.827, 3.206, 3.584, and 17.7×10^{-3} μohm cm at 2.562, 3.240, 4.439, 5.227, 5.783, 6.713, 7.867, 9.001, 9.902, 10.869, 12.034, 13.225, 14.197, 15.094, 16.017, 17.092, 17.829, 19.025, 19.991, and 24 C, respectively; Lorenz number 2.40×10^{-8} V^2 deg^{-2}. (Tabulated data obtained from the author.)
155	1276	Schriempf, J. T.	1968	L	2.5-20	Cu 2	99.999 Cu and < 0.0010 Mn; made from the same stock as the above specimen by swaging to a dia of ~0.080 in.; etched in 50% nitric acid to a dia of ~0.076 in; annealed at 530 C for 3 hrs in vacuum of $\sim 1 \times 10^{-6}$ torr; residual electrical resistivity $\rho_0 = 0.579 \times 10^{-3}$ μohm cm; electrical resistivity 0.5842, 0.5831, 0.5815, 0.5805, 0.5799, 0.5789, 0.5786, 0.5784, 0.5807, 0.5810, 0.5879, 0.5958, 0.6063, 0.6214, 0.6475, 0.6847, 0.7201, 0.7707, 0.8343, 0.9171, 0.9868, 1.1604, 1.2707, and 16.9×10^{-3} μohm cm at 2.507, 2.572, 3.050, 3.541, 4.015, 4.301, 4.433, 5.214, 5.820, 6.624, 7.767, 8.856, 9.768, 10.757, 11.832, 13.049, 13.899, 14.839, 15.808, 16.778, 17.470, 18.801, 19.500, and 24 C, respectively; Lorenz number 2.47×10^{-8} V^2 deg^{-2}. (Tabulated data obtained from the author.)

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
156	1276	Schriempf, J. T.	1968	L	2.7-19	Cu 2-0	The above specimen annealed at 1000 C for 22 hrs in an atmosphere achieved by using a continuous air leak to reduce the 1 x 10^{-6} torr vacuum to 5 x 10^{-4} torr; metallographic examination revealed the presence of "holes", presumably pockets of copper oxide formed during the oxidation annealing process; residual electrical resistivity ρ_0 = 1.12 x 10^{-3} μohm cm; electrical resistivity 1.122, 1.122, 1.116, 1.122, 1.127, 1.135, 1.149, 1.194, 1.258, 1.367, 1.546, 1.772, and 6.9 x 10^{-3} μohm cm at 2.754, 3.748, 4.319, 4.483, 5.803, 7.538, 9.028, 11.354, 13.319, 15.272, 17.235, 18.904, and 24 C, respectively; Lorenz number 2.48 x 10^{-8} V^2 deg^{-2}.
157*	1324	Smart, D.	1960	P	323.2		2.9 cm dia x 11.4 cm long; measured by a transient method.
158*	1324	Smart, D.	1960	P	323.2		2.9 cm dia x 15.2 cm long; measured by a transient method.
159*	510	Golde, H.	1965	L	373-673		25 mm dia x 180 mm long.
160*	572	Habachi, M., Azou, P., and Bastien, P.	1965	P	293-723	15	0.01 Bi; tempered at 750 C; thermal conductivity values calculated from measured thermal diffusivity.
161*	321	Day, R. K.	1965	C	373.2		Highest commercial purity; 0.5 in. dia x 0.5 in. thick; copper used as comparative material.
162*	1198, 1197	Richter, W. and Wahn, G.	1963	R	309-326		99.982 pure; 90 mm O.D., 15 mm I.D., and 30 mm thick.
163	380	Dupré, A., Van Itterbeek, A., and Michiels, L.	1964	L	0.23-0.63	1	Extremely pure; impurities <0.001; prepared by the Société Métallurgique de Hoboken (Belgium).
164	380	Dupré, A., et al.	1964	L	0.25-0.56	2	3 mm dia commercial wire.
165	380	Dupré, A., et al.	1964	L	0.22-0.46	3	0.0002 Fe, 0.0002 Si, 0.0001 Co, 0.0001 Ni, and 0.00005 Mn; spectrographically standardized rod specimen obtained from Johnson, Matthey series CB 8.
166	380	Dupré, A., et al.	1964	L	0.21-0.70	4	0.0029 Fe, 0.0026 Ni, 0.0021 Si, 0.0018 Co, and 0.0015 Mn; spectrographically standardized rod specimen obtained from Johnson-Matthey series CB 4.
167*	380	Dupré, A., et al.	1964	L	0.26-0.66	5	0.0160 Si, 0.0140 Ni, 0.0130 Mn, 0.0110 Fe, and 0.0097 Co; spectrographically standardized rod specimen obtained from Johnson-Matthey series CB 2.
168	1208	Roder, H. M., Powell, R. L., and Hall, W. J.	1958	L	5.2-116		0.0343 Ag; fabricated by American Smelting and Refining Co.; annealed; electrical resistivity 0.00404, 0.00411, 0.00438, 0.00485, 0.00555, 0.00667, 0.00895, 0.0157, 0.0449, 0.104, 0.169, 0.248, and 0.330 μohm cm at 4.1, 9.4, 12.1, 16.7, 20.0, 23.2, 26.5, 33.0, 48.3, 62.5, 74.1, 86.7, and 98.6 K, respectively.
169	494	Gladun, C. and Holzhäuser, W.	1964	L	18-83	Electrolytic Copper	Rod specimen, residual electrical resistivity 0.012 μohm cm.
170	494	Gladun, C. and Holzhäuser, W.	1964	L	17-83	Electrolytic Copper	The above specimen under a strain of 7.8% longitudinal elongation; residual electrical resistivity 0.017 μohm cm.
171	494	Gladun, C. and Holzhäuser, W.	1964	L	18-84	Electrolytic Copper	Similar to above but with 14.0% longitudinal elongation; residual electrical resistivity 0.0235 μohm cm.
172	494	Gladun, C. and Holzhäuser, W.	1964	L	18-84	Electrolytic Copper	Similar to above but with 19.9% longitudinal elongation; residual electrical resistivity 0.0325 μohm cm.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
173	494	Gladun, C. and Holzhäuser, W.	1964	L	18-84	Electrolytic copper	Similar to above but with 25.4% longitudinal elongation; residual electrical resistivity 0.041 μohm cm.
174	494	Gladun, C. and Holzhäuser, W.	1964	L	18-84	Electrolytic copper	Similar to above but with 30.8% longitudinal elongation; residual electrical resistivity 0.048 μohm cm.
175	494	Gladun, C. and Holzhäuser, W.	1964	L	19-84	Electrolytic copper	The above specimen measured without load after recovery at room temp.
176*	622	Holland, M. G.	1962	L	2-300	Electrolytic tough-pitch copper	Shop-grade; 0.252 x 0.252 $in.^2$ in cross-section; data taken from smoothed curve.
177	848	Lindenfeld, P. and Pennebaker, W. B.	1962	L	1.5-4.1		0.071 Ge (calculated); 3 x 0.125 x 0.0313 in.; prepared from 99.999 pure Cu and 99.99^+ pure Ge; materials melted, outgassed for 3 min in vacuum, stirred for 0.5 hr in helium, cast; annealed at 700 C for 22 hrs; residual electrical resistivity 0.301 μohm cm.
178	848	Lindenfeld, P. and Pennebaker, W. B.	1962	L	1.5-4.1		0.143 Ge (calculated); same dimensions and fabrication method as above; residual electrical resistivity 0.600 μohm cm.
179	1347	Sparrell, J. K., Coumou, K. G., and Plunkett, J. D.	1963	L	582-1249	Electrolytic tough-pitch copper	99.95 pure; 12 x 12 x 2.5 in. specimen consisted of nine 4 x 4 x 2.5 in. blocks; measured in argon atmosphere at 15 psi.
180*	1279	Schulze, A.	1921	L	307.2	Electrolytic copper	Pure; electrical conductivity 53.9 x 10^4 ohm^{-1} cm^{-1} at 30 C.
181*	1484	Vernotte, P.	1932	F	298.2		0.5 mm dia x 45 cm long. (Measuring temp assumed 25 C.)
182	1432	Tseng, T. P.	1954	L	1.4-4.2		Commercial grade pure magnetic wire 0.025 cm in dia; obtained from General Electric Co.; measured on the bath to middle block segment of the specimen.
183	1432	Tseng, T. P.	1954	L	1.4-4.2		Measured on the middle block to heater segment of the above specimen.
184	1105	Powell, R. L., Rogers, W. M., and Roder, H. M.	1957	L	4.0-26		99.999 pure; cylindrical rod specimen; reported data taken from smoothed curve.
185	1105	Powell, R. L., et al.	1957	L	4.0-89	Electrolytic tough-pitch copper	99.9^+ pure; cylindrical rod specimen; reported data taken from smoothed curve.
186	1105	Powell, R. L., et al.	1957	L	5.1-288		99.8 pure; 0.1 P; cylindrical rod specimen; reported data taken from smoothed curve.
187*	804	Küster, W., Bode, K. H., and Fritz, W.	1968	L	315-353		99.995 Cu, 0.0012 Sb, 0.0010 Ag, 0.0005 Pb, 0.0003 S, 0.0002 As, 0.0001 K, 0.0001 Sn, <0.0001 each of Cr, Fe, Ni, and P, and <0.0006 others; 50 mm dia x 70 mm long; density 8.925 g cm^{-3}; measured in a standard apparatus.
188*	804	Küster, W., et al.	1968	L	702		Similar to the above specimen but dimensions 50 mm dia x 90 mm long; measured in another apparatus.
189	804	Küster, W., et al.	1968	L	475-681		Similar to above.
190*	189	Bowman, H. F., Ziebold, T. O., and Smith, J. L., Jr.	1968	L	7.0-85	A	99.999^+ pure; specimen 0.120±0.0005 in. square by 2.0 in. long; unirradiated.

* Not shown in figure.

TABLE 49. THERMAL CONDUCTIVITY OF COPPER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
191	189	Bowman, H. F., Ziebold, T. O., and Smith, J. L., Jr.	1968	L	4.7-62	B	Similar to the above specimen except irradiated at 54 C in the M. I. T. reactor with total exposure 1.6×10^{19} neutrons cm^{-2}.
192	189	Bowman, H. F., et al.	1968	L	4.9-95	C	Similar to the above specimen except irradiation dose 4.3×10^{19} neutrons cm^{-2}.
193	189	Bowman, H. F., et al.	1968	L	6.5-91	D	Similar to the above specimen except irradiation dose 6.5×10^{19} neutrons cm^{-2}.
194	259	Charsley, P. and Salter, J. A. M.	1965	L	1.5-4.2		Wire specimen; annealed.
195	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.9-4.0	0.11 at% Mn	99.905 Cu and 0.095 Mn (calculated composition); polycrystalline; supplied by Kamerlingh Onnes Laboratory, Leiden, Holland; prepared in vacuo from pure Johnson-Matthey Cu and Mn; strained; electrical resistivity reported as 0.191, 0.193, 0.196, 0.198, 0.202, and 0.205 μohm cm at 1.47, 2.05, 2.55, 3.05, 3.55, and 4.16 K, respectively; measured in a vacuum of $\sim 10^{-6}$ torr.
196	1012	Natarajan, N. S., and Chari, M. S. R.	1970	L	1.9-4.0	0.11 at% Mn	The above specimen measured in transverse magnetic field of 10.4 kilo-Oersteds.
197	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.9-4.0	0.11 at% Mn	The above specimen except measured in transverse magnetic field of 13.75 kilo-Oersteds.
198	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.9-4.0	0.11 at% Mn	The above specimen except measured in transverse magnetic field of 17.4 kilo-Oersteds.
199	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8-4.0	0.21 at% Mn	99.82 Cu and 0.18 Mn (calculated composition); similar to the above specimen except no magnetic field applied to the specimen; electrical resistivity reported as 0.578, 0.583, 0.592, 0.594, 0.601, and 0.611 μohm cm at 1.62, 2.19, 2.95, 3.34, 3.47, and 4.15 K, respectively; measured in a vacuum of $\sim 10^{-6}$ torr.
200	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8-4.0	0.21 at% Mn	The above specimen measured in transverse magnetic field of 10.4 kilo-Oersteds; data taken from smoothed curve.
201	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8-4.0	0.21 at% Mn	The above specimen measured in transverse magnetic field of 13.75 kilo-Oersteds; data taken from smoothed curve.
202	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8-4.0	0.21 at% Mn	The above specimen measured in transverse magnetic field of 17.4 kilo-Oersteds.
203	393	Emery, A. F. and Smith, J. R.	1968	P	304-1178		Oxygen-free; 0.5 in. in diameter; thermal conductivity values calculated from measured thermal diffusivity data using the specific heat values taken from Touloukian, Y. S. (editor) ("Thermophysical Properties of High Temperature Solid Materials", MacMillan Co., New York, Vol. 1. p. 456, 1967).
204	546	Grosse, A. V.	1964	→	1356-8500		Thermal conductivity values calculated from electrical resistivity using the Wiedemann-Franz-Lorenz law.
205	74	Angell, M. F.	1926	R	323-1273		Long hollow cylindrical specimen.
206	75	Angström, A.J.	1861	P	323.2		Thermal conductivity measured by the Angström method which was originated in this measurement; units not given and here assumed to be in cal cm^{-1} min^{-1} C^{-1}.
207	75a	Angström, A.J.	1863	P	273-343		35 mm diameter x 1.78 mm long; thermal conductivity measured by the Angström method; data given in the form of the formula $k = 58.94\ (1 - 0.001519\ t)$; units not given and here assumed to be in cal cm^{-1} min^{-1} C^{-1}.
208	1025a	Neumann, F.	1862	P	298.2		Density 8.73 g cm^{-3}; measuring temperature not given and here assumed to be 25 C.

* Not shown in figure.

Curium

No information is available for the thermal or electrical conductivity of curium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidences show that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of curium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. The estimated value is probably good to ±50 percent.

Dysprosium

The information on the thermal conductivity of dysprosium has recently been supplemented by the measurements made by Boys and Legvold [192] (curves 5 and 6) on single crystal samples for the approximate range 5 to 300 K and by Ratnalingam [1181] (curves 7–9) on polycrystalline samples at temperatures below 4 K. Previous measurements by Colvin and Arajs [288] (curve 1) had covered the temperature range 6.5 to 306 K, but their sample was presumably less pure since it had a lower electrical resistivity ratio, $\rho_{300\text{ K}}/\rho_{4.2\text{K}}$, of about 9.6, whereas the corresponding ratio for the single crystals examined by Boys and Legvold in directions parallel and perpendicular to the c-axis had been 13.4 and 24.2. Moreover, the thermal conductivity values of Colvin and Arajs are tending to be too high towards room temperature.

The measurements of Boys and Legvold indicate that at room temperature the thermal conductivity for the direction parallel to the c-axis is about 12 percent greater than for the perpendicular direction. In the region of the Néel temperature, 174 K, the two curves cross and at lower temperatures the perpendicular direction becomes the better conducting. Both curves rise sharply with decrease in temperature in the region of the antiferromagnetic to ferromagnetic transformation, and both have maxima near 24 K where the thermal conductivity perpendicular to the c-axis is the greater by about 25 percent. These two curves have been provisionally accepted as representing the thermal conductivity of dysprosium for the two main crystal directions from 6 to 300 K. A curve derived from them by calculation is shown for polycrystalline dysprosium. At the low temperature end this has been extrapolated following the general trend of the curves obtained by Ratnalingam [1181].

The first measurements on dysprosium at temperatures below 4.5 K were made by Rao [1170] (curve 4) on a polycrystalline sample. He considers the unusual form of his curve to be associated with heat transfer by magnons. Rao's sample was later re-measured by Ratnalingam [1181], and he obtained very different results. Indeed, his measurements yield a Lorenz function of 2.43×10^{-8} V^2 K^{-2} near 0 K, which is very close to the theoretical value, compared with about 3.66×10^{-8} V^2 K^{-2} obtained by Rao, and the anomaly of Rao's curve was not found. The other two curves obtained by Ratnalingam are also of similar shape and with Lorenz functions near 0 K only 4.8 and 6.0 percent above the theoretical value. It is puzzling that data obtained for the same sample by different workers at the same laboratory can be so much different. This same situation of conflicting data also exists in the cases of erbium, gadolinium, holmium, terbium, and ytterbium. Further determinations are required for resolving the disagreements. The present provisional curve below 5 K for polycrystalline dysprosium which follows the general trend of the curves of Ratnalingam is very tentative.

At room temperature the value due to Powell and Jolliffe [1127, 690] (curve 2) agrees to within a few percent with the provisional curve for the polycrystalline metal. Their electrical resistivity value is however some 13 percent greater than that of Colvin, Legvold, and Spedding [289]. A probable resistivity curve satisfying the room temperature value of Jolliffe, et al. and drawn parallel to data reported to 1473 K (see [723]) has been used to estimate thermal conductivity values to 1500 K. In making this estimation, the theoretical Lorenz function has been assumed to hold for the electronic component and the lattice component to be given by AT^{-1} where A is 10.4.

The values are thought to be accurate to within ±15 percent of the true values at temperatures from 200 to 300 K and ±15 to ±25 percent above 300 K. At temperatures below 200 K the values are highly conditioned by purity, and the values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are only for samples having $\rho_0 = 5.77$, 4.59, and 4.93 $\mu\Omega$ cm, respectively. The values below 200 K are very uncertain.

TABLE 50. Provisional thermal conductivity of dysprosium†

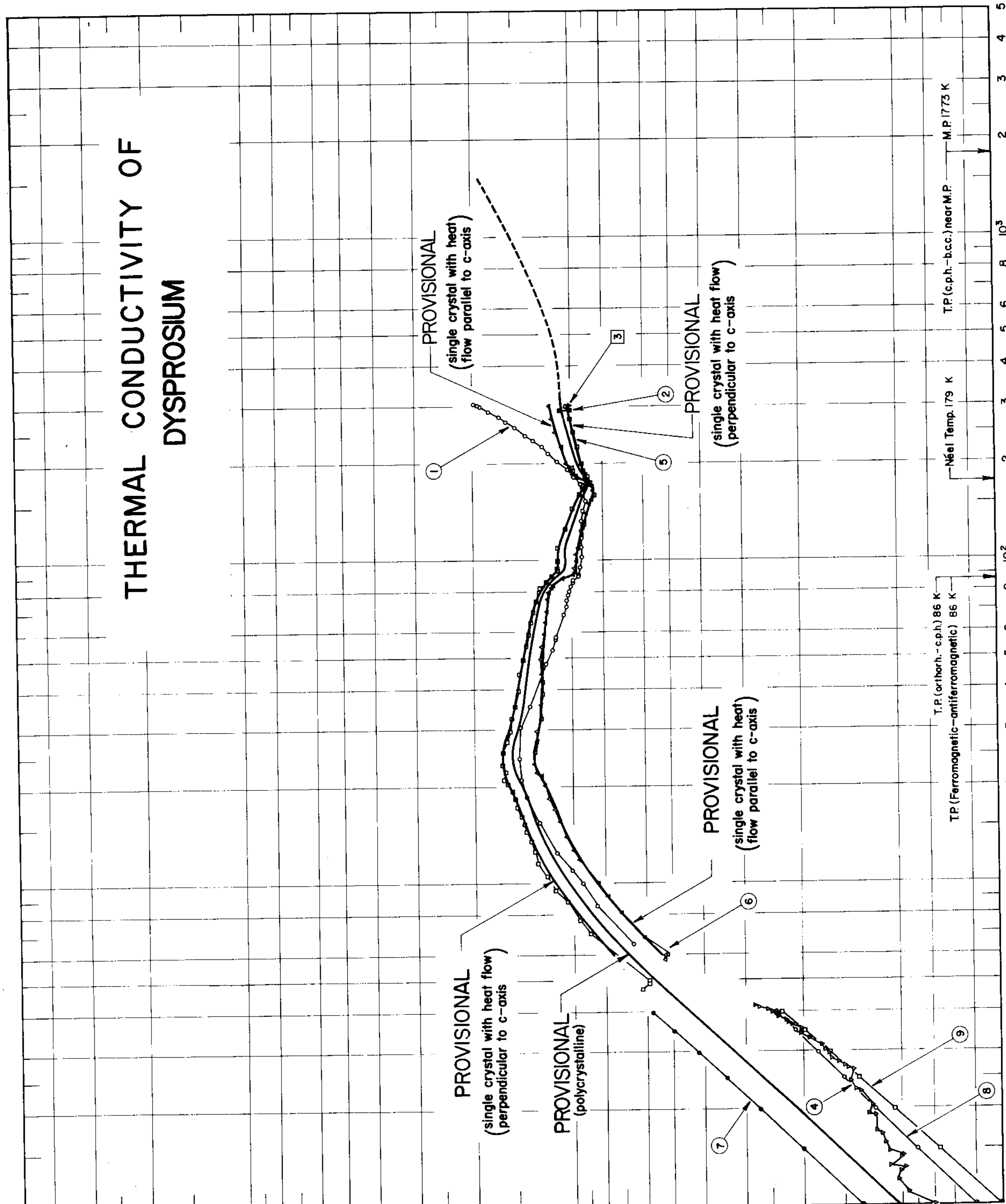
(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	‖ to c-axis k	⊥ to c-axis k	Poly-crystalline k
1			0.0102
2			0.0208
3			0.0324
4			0.0442
5			0.0561
6	0.0539	0.0757	0.0677
7	0.0626	0.0865	0.0776
8	0.0704	0.0964	0.0868
9	0.0778	0.106	0.0953
10	0.0844	0.113	0.102
11	0.0901	0.120	0.109
12	0.0956	0.126	0.115
13	0.100	0.131	0.120
14	0.104	0.136	0.124
15	0.108	0.139	0.128
16	0.111	0.142	0.131
18	0.116	0.148	0.136
20	0.121	0.156	0.143
25	0.132	0.165	0.153
30	0.127	0.158	0.147
35	0.125	0.151	0.142
40	0.124	0.148	0.139
45	0.123	0.145	0.137
50	0.123	0.142	0.135
60	0.121	0.136	0.130
70	0.120	0.131	0.127
80	0.117	0.124	0.123
90	0.101	0.113	0.109
100	0.0969	0.110	0.105
123.2	0.0929	0.106	0.101
150	0.0874	0.0968	0.937
173.2	0.0887	0.0887	0.0887
200	0.103	0.0931	0.0960
223.2	0.107	0.0960	0.0990
250	0.111	0.0987	0.102
273.2	0.114	0.101	0.105
298.2	0.117	0.103	0.107
300	0.117	0.103	0.107
323.2			0.108*
350			0.108*
373.2			0.108*
400			0.109*
473.2			0.113*
500			0.115*
573.2			0.119*
600			0.121*
673.2			0.127*
700			0.129*
773.2			0.135*
800			0.137*
873.2			0.143*
900			0.145*
973.2			0.150*
1000			0.152*
1073.2			0.158*
1100			0.160*
1173.2			0.165*
1200			0.167*
1273.2			0.172*
1300			0.174*
1373.2			0.180*
1400			0.182*
1473.2			0.187*
1500			0.189*

†The provisional values are for well-annealed high-purity dysprosium, and those below 200K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_o = 5.77$, 4.59, and 4.93 $\mu\Omega$ cm, respectively.

*Extrapolated or estimated.



THERMAL CONDUCTIVITY OF DYSPROSIUM
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
PROVISIONAL (polycrystalline)
T.P. (orthorh.–c.p.h.) 86 K
T.P. (Ferromagnetic–antiferromagnetic) 86 K
Néel Temp. 179 K
T.P. (c.p.h.–b.c.c.) near M.P.
M.P. 1773 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 62

TABLE 51. THERMAL CONDUCTIVITY OF DYSPROSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	288	Colvin, R. V. and Arajs, S.	1964	L	6.5-306		0.2 Ta, 0.1 Tb, 0.05 Ca, 0.05 Ho, 0.02 Er, 0.02 Si, 0.02 Y, 0.01 Fe, 0.01 Mg, and traces of Cu and La; polycrystalline; 0.476 cm dia x 5 cm long; supplied by St. Eloi Corp; electrical resistivity 9.55 μohm cm at 4.2 K; measured in a vacuum of ~6 x 10^{-6} mm Hg; T. P. (ferro-antiferromagnetic) 85 K; Néel temp 180 K.
2	1127, 690	Powell, R. W. and Jolliffe, B. W.	1965	C	291.2		High purity; polycrystalline; 0.25 in. dia x 0.25 in. thick; supplied by Johnson Matthey and Co., Ltd.; electrical resistivity 105 μohm cm at 18 C; measurements made using 2 different thermal comparators; Monel metal used as comparative material.
3	831	Legvold, S. and Spedding, F. H.	1954		301.2		No information given.
4	1170	Rao, K. V.	1967	L	1.0-4.2		<0.1 other rare earth metals and <0.02 other base metals; pure polycrystalline specimen 1.5 mm in dia and 5 cm long; supplied by Johnson Matthey and Co., Ltd.; residual electrical resistivity 4.653 μohm cm; $\rho(298K)/\rho_0$ = 25.2.
5	192	Boys, D. W. and Legvold, S.	1967	L	4.7-300		0.0500 Er, 0.0500 Tb, 0.0400 Ta, <0.0200 Gd, 0.0157 O, 0.0100 Fe, <0.0100 Ho, <0.0100 Si, <0.0050 Al, <0.0050 Cr, 0.0029 H, 0.0020 Ca, 0.0010 Mg, 0.0010 N, and <0.0010 Y; single crystal; 9.48 x 2.30 x 2.12 mm; grown from arc-melted buttons using the strain anneal method; <11$\bar{2}$0> direction (a-axis) along the specimen axis; electrical resistivity reported as 4.598, 4.595, 4.620, 4.735, 5.473, 6.318, 8.195, 13.36, 20.72, 31.21, 35.050, 36.460, 38.055, 42.328, 52.720, 71.802, 83.195, 88.436, 93.387, 94.959, 99.458, and 111.513 μohm cm at 4.2, 6.9, 9.0, 12.0, 18.0, 22.1, 28.2, 40.1, 55.3, 75.0, 83.5, 86.0, 88.9, 94.4, 114.0, 143.8, 160.2, 167.6, 178.3, 188.6, 219.1, and 299.4 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 24.2; residual electrical resistivity 4.59 μohm cm; Lorenz function reported as 5.80, 4.99, 4.54, 4.76, 4.83, 5.14, 5.32, 5.16, 4.99, 4.97, 5.01, 4.96, 4.85, 4.64, 4.64, 4.26, 3.96, and 3.83 x 10^{-8} V^2 K^{-2} at 6.9, 11.6, 17.8, 25.7, 33.8, 45.5, 61.1, 78.8, 87.5, 94.2, 115.9, 146.2, 163.4, 175.6, 180.8, 227.8, 273.8, and 300.0 K, respectively; heat flow along a-axis.
6	192	Boys, D. W. and Legvold, S.	1967	L	5.8-300		Single crystal; 12.79 x 2.21 x 2.19 mm; grown from arc-melted buttons using the strain anneal method; <0001> direction (c-axis) along the specimen axis; electrical resistivity reported as 5.788, 5.790, 5.876, 6.324, 7.005, 8.832, 11.68, 17.28, 26.72, 13.84, 33.797, 34.997, 36.088, 41.449, 42.026, 47.175, 63.096, 80.074, 83.055, 83.155, 82.965, 77.031, 70.587, 70.315, 70.255, 70.880, 73.731, and 77.217 μohm cm at 4.2, 8.0, 11.1, 16.0, 20.2, 26.0, 35.2, 49.6, 71.0, 81.1, 84.9, 87.0, 88.1, 88.9, 89.9, 98.1, 124.0, 150.1, 160.2, 163.2, 165.9, 174.3, 186.6, 194.6, 199.9, 219.1, 259.8, and 299.4 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 13.4; residual electrical resistivity 5.77 μohm cm; Lorenz function reported as 5.26, 4.53, 4.24, 4.28, 4.15, 4.46, 4.58, 4.56, 4.79, 4.64, 4.75, 4.72, 4.42, 3.91, 3.80, 3.59, 3.61, 3.37, 3.16, and 3.03 x 10^{-8} V^2 K^{-2} at 8.0, 13.7, 19.5, 23.9, 33.9, 58.7, 78.7, 86.1, 88.5, 91.4, 125.4, 141.5, 159.5, 174.9, 184.5, 192.9, 198.1, 228.3, 262.9, and 300.0 K, respectively; heat flow along c-axis.

TABLE 51. THERMAL CONDUCTIVITY OF DYSPROSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
7	1181	Ratnalingam, R.	1970	L	0.5-4.0	Dy 1	Electrical resistivity ratio $\rho(295K)/\rho_0 = 31.3$; residual electrical resistivity 2.02 μohm cm; electrical resistivity 64 μohm cm at 295 K; thermal conductivity values calculated from the given formula $k = 12.75\ T + 0.422\ T^2$ (mW cm^{-1} K^{-1}).
8	1181	Ratnalingam, R.	1970	L	0.5-4.0	Dy 2	Electrical resistivity ratio $\rho(295K)/\rho_0 = 24.2$; residual electrical resistivity 4.05 μohm cm; electrical resistivity 108.0 μohm cm at 295 K; thermal conductivity values calculated from the given formula $k = 6.01\ T + 0.01\ T^2$ (mW cm^{-1} K^{-1}).
9	1181	Ratnalingam, R.	1970	L	0.5-4.0	Dy 2	The above specimen annealed; electrical resistivity ratio $\rho(295K)/\rho_0 = 20.4$; residual electrical resistivity 5.39 μohm cm; electrical resistivity 109.8 μohm cm at 295 K; thermal conductivity values calculated from the formula $k = 4.75\ T + 0.268\ T^2$ (mW cm^{-1} K^{-1}) given by the author.

Einsteinium

No information is available for the thermal or electrical conductivity of einsteinium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidences show that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of einsteinium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Erbium

The thermal conductivity of erbium has been measured at temperatures below normal by five groups of workers, Ratnalingam [1181] (curves 9 and 10) from 0.5 to 4 K, Rao [1171] (curve 8) from 1.3 to 4.3 K, Aliev and Volkenshtein [45] (curve 1) from 2 to 99 K, Arajs and Dunmyre [83] (curves 3 and 4) from 6.5 to 310 K and Boys and Legvold [192] (curves 6 and 7) from 4.9 to 300 K. The first four studied polycrystalline samples but the last studied a single crystal with heat flow perpendicular to the *c*-axis and, from 6.6 to 300 K, another single crystal with heat flow parallel to this axis. Electrical resistivity measurements were also made, and these would indicate the sample of Rao to be the purest and that of Aliev and Volkenshtein to be the least pure. Yet the latter sample has the highest thermal conductivity and the most pronounced maximum.

Clearly there are problems requiring more study, particularly as relatively little is known about metals such as erbium which are magnetic and appear to possess an appreciable lattice component of thermal conductivity [1171].

For the time being, smooth curves have been drawn through the data of Boys and Legvold and are used as provisional curves for the two crystal directions. The curve for polycrystalline erbium has been derived from the single crystal values assuming the value for a polycrystalline sample to be the mean of those given by equations (11) due to Voigt [1487] and (12) due to Nichols [1032] (see Meaden [912]). This curve has been extrapolated to lower temperatures following the slope of the higher curve of Ratnalingam. At 291 K this derived curve is 3.5 percent greater than the mean of the two measurements reported for polycrystalline erbium by Jolliffe, Tye, and Powell [690] (curve 2). The electrical resistivity of Jolliffe, et al. is also greater by about 9 percent.

In order to extrapolate the proposed curve for polycrystalline erbium to higher temperatures use has been made of the electrical resistivity values to 1473 K (see Kaye and Laby [723]) but adjusted approximately to the lower value of 72.6 $\mu\Omega$ cm at 300 K as derived from Boys and Legvold's data. In making the derivation the thermal conductivity is assumed to be the sum of an electronic component given by $2.443 \times 10^{-8}\, T\, \rho^{-1}$ and a lattice component given by $12.45\, T^{-1}$.

The provisional values are thought to be accurate to within ±15 percent at temperatures from 200 to 300 K and ±20 percent above 300 K. At temperatures below 200 K the values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 4.62, 5.05, and 4.90 $\mu\Omega$ cm, respectively. The values below 200 K are very uncertain.

TABLE 52. Provisional thermal conductivity of erbium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k	T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k
0	0	0	0	250	0.188	0.128	0.146
1			0.00856	273.2	0.187	0.127	0.145
2			0.0171	298.2	0.184	0.126	0.143
3			0.0261	300	0.184	0.126	0.143
4			0.0356	323.2			0.141*
5			0.0442	350			0.140*
6			0.0515	373.2			0.140*
7	0.0612	0.0558	0.0576	400			0.140*
8	0.0660	0.0612	0.0628	473.2			0.140*
9	0.0696	0.0658	0.0672	500			0.141*
10	0.0722	0.0698	0.0706	573.2			0.142*
11	0.0743	0.0731	0.0735	600			0.143*
12	0.0760	0.0761	0.0762	673.2			0.145*
13	0.0774	0.0788	0.0783	700			0.146*
14	0.0787	0.0810	0.0802	773.2			0.149*
15	0.0797	0.0830	0.0819	800			0.150*
16	0.0809	0.0845	0.0833	873.2			0.153*
18	0.0840	0.0880	0.0867	900			0.154*
20	0.0639	0.0863	0.0782	973.2			0.158*
25	0.0729	0.0934	0.0866	1000			0.159*
30	0.0762	0.0938	0.0875	1073.2			0.163*
35	0.0820	0.0955	0.0908	1100			0.165*
40	0.0858	0.0963	0.0926	1173.2			0.169*
45	0.0876	0.0966	0.0935	1200			0.171*
50	0.0874	0.0957	0.0929	1273.2			0.176*
60	0.0992	0.0974	0.0980	1300			0.178*
70	0.107	0.101	0.103	1373.2			0.183*
80	0.121	0.102	0.108	1400			0.185*
90	0.139	0.104	0.115	1473.2			0.190*
100	0.150	0.108	0.120	1500			0.191*
123.2	0.163	0.113	0.128				
150	0.174	0.119	0.135				
173.2	0.180	0.123	0.140				
200	0.185	0.126	0.144				
223.2	0.187	0.128	0.145				

†The provisional values are for well-annealed high-purity erbium, and those below 200 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_0 = 4.62$, 5.05, and 4.90 $\mu\Omega$ cm, respectively.

*Extrapolated or estimated.

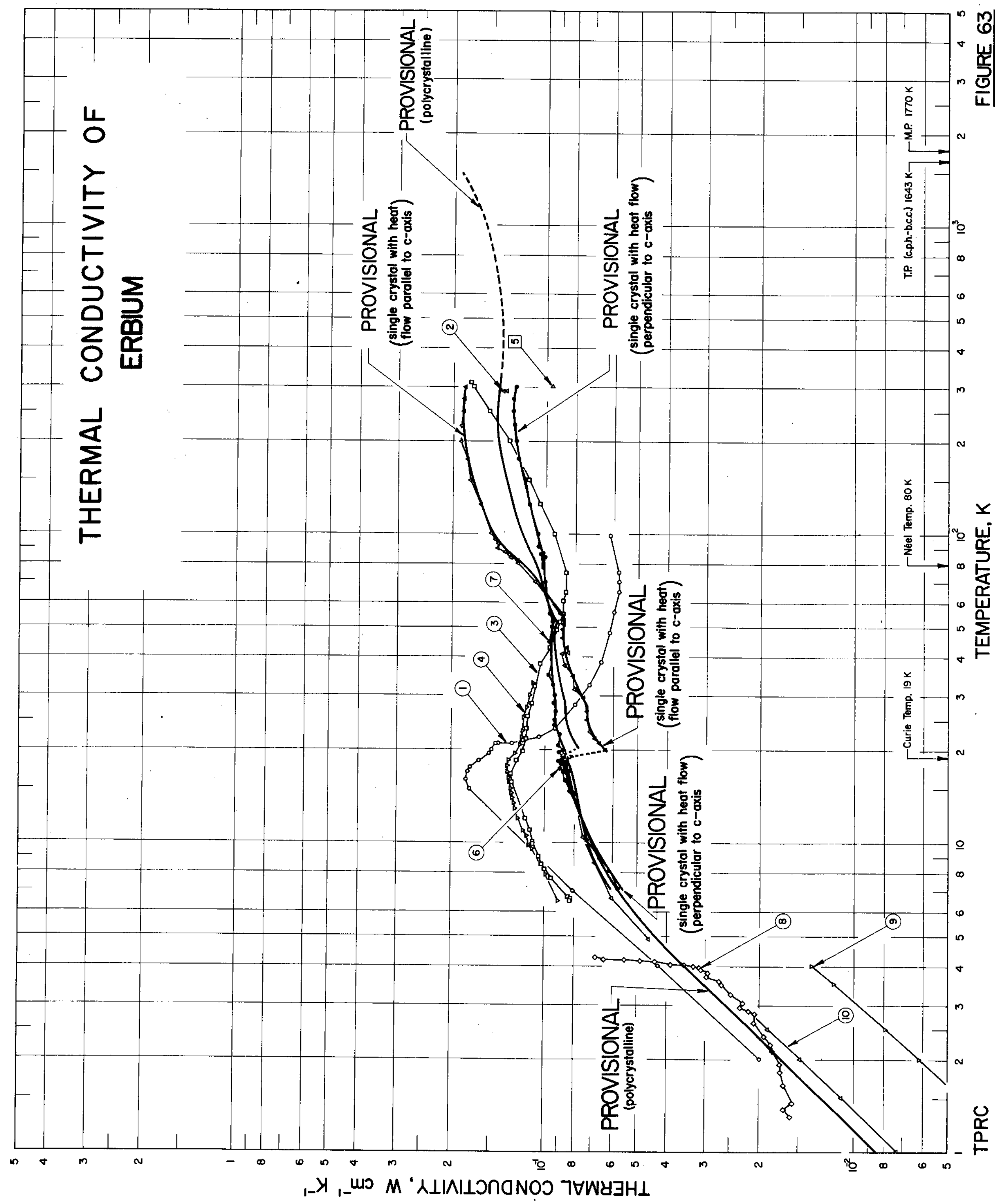

THERMAL CONDUCTIVITY OF ERBIUM
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
PROVISIONAL (polycrystalline)
M.P. 1770 K
T.P. (c.p.h.-b.c.c.) 1643 K
Neel Temp. 80 K
Curie Temp. 19 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 63

TABLE 53. THERMAL CONDUCTIVITY OF ERBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	45	Aliev, N.G. and Volkenshtein, N.V.	1965	L	2-99		99.9 pure; polycrystalline; dimensions 3 x 0.2 x 0.025 cm; annealed at 850 C for 2 hrs in vacuum of 10^{-6} mm Hg; electrical resistivity 8.44 μohm cm; electrical resistivity ratio $\rho(298K)/\rho(4.2K) = 10.2$; ferromagnetic below 20 K, antiferromagnetic between 20 and 80 K, and paramagnetic above 80 K; data from smooth curve.
2	1127, 690	Powell, R.W. and Jolliffe, B.W.	1965	C	291.2		High purity; polycrystalline; 0.25 in. dia and 0.25 in. long; supplied by Johnson Matthey and Co. Ltd.; electrical resistivity 79 μohm cm at 18 C; thermal conductivity data obtained from two measurements using different thermal comparators; Monel used as standard.
3	83	Arajs, S. and Dunmyre, G.R.	1965	L	6.5-310		Impurities: 0.01 Ca, 0.02 Ho, 0.005 Mg, 0.07 O, 0.01 Si, and trace Tm; polycrystalline; 0.476 cm dia, 6 cm long; Er supplied by Research Chemicals; arc-melted, machined, swaged, and annealed in vacuum (~10^{-5} torr) at 800 K for 50 hrs; electrical resistivity 3.79 μohm cm at 4.16 K; measured in a vacuum of 6 x 10^{-6} mm Hg; ferromagnetic - antiferromagnetic and antiferromagnetic - paramagnetic transitions occurred at 19 and 86 K, respectively; data above 75 K extracted from smooth curve.
4	83	Arajs, S. and Dunmyre, G.R.	1965	L	6.5-33		The second run of the above specimen; measured during cooling.
5	831	Legvold, S. and Spedding, F.H.	1954		301.2		No information given.
6	192	Boys, D.W. and Legvold, S.	1967	L	6.9-300		0.0500 Ta, 0.0235 O, 0.0200 Mg, <0.0200 Ca, 0.0150 Cr, 0.0150 Fe, <0.0100 Dy, <0.0100 Ho, <0.0050 Si, <<0.0050 Y, 0.0017 H, 0.0011 N, <0.0010 Tm, <0.0010 Yb, and traces of Cu and W; single crystal; 5.81 x 1.88 x 1.86 mm; <10$\bar{1}$0> direction (b-axis) along the specimen axis; grown from arc-melted buttons using the strain- anneal method; electrical resistivity reported as 5.106, 5.230, 6.299, 7.856, 8.971, 14.57, 20.01, 25.97, 28.34, 29.25, 30.23, 34.64, 41.981, 42.965, 43.583, 44.085, 47.112, 56.107, 64.992, 73.100, 81.166, and 88.812 μohm cm at 4.3, 7.1, 13.0, 18.1, 20.3, 30.8, 40.8, 50.1, 53.2, 55.0, 57.1, 66.3, 80.2, 82.8, 84.9, 87.2, 99.7, 139.9, 180.6, 219.9, 259.8, and 299.4 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 17.4$; residual electrical resistivity 5.05 μohm cm; Lorenz function reported as 4.42, 3.91, 3.71, 3.99, 4.52, 4.90, 5.17, 5.24, 5.08, 4.73, 4.42, 3.94, and 3.75 x 10^{-8} V^2 K^{-2} at 6.4, 10.3, 15.9, 22.0, 31.3, 43.8, 65.1, 80.0, 101.8, 126.4, 179.2, 260.1, and 299.9 K, respectively; heat flow along b-axis.
7	192	Boys, D.W. and Legvold, S.	1967	L	4.9-300		0.0900 Fe, <0.0500 Ta, 0.0280 O, 0.0200 Ca, 0.0200 Cr, 0.0200 Mg, 0.0130 Y, <0.0100 Dy, <0.0100 Ho, <0.0050 Si, 0.0014 H, <0.0010 Tm, <0.0010 Yb, 0.0008 N, and traces of Cu, Ni, and W; single crystal; 6.13 x 1.51 x 1.31 mm; same preparation method as above; <0001> direction (c-axis) along the specimen axis; electrical resistivity reported as 4.847, 5.619, 7.768, 9.258, 17.21, 23.38, 28.103, 37.256, 39.512, 39.547, 39.512, 39.119, 34.484, 29.084, 27.616, 26.662, 26.663, 27.369, 30.740, 34.774, 38.900, 43.235, and 47.756 μohm cm at 4.3, 10.0, 16.1, 19.0, 25.0, 35.1, 44.5, 51.9, 54.2, 55.0, 56.0, 59.8, 75.2, 82.1, 83.8, 86.3, 87.2, 99.7, 139.9, 180.6, 219.9, 259.8, and 299.4 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 10.1$; residual electrical resistivity 4.62 μohm cm; Lorenz function reported as 4.45, 4.03, 3.88, 3.82, 3.88, 4.68, 5.30, 5.76, 6.48, 6.03, 5.31, 4.20, 3.83, 3.32, and 2.90 x 10^{-8} V^2 K^{-2} at 4.2, 8.5, 11.6, 15.2, 18.4, 19.8, 32.1, 43.9, 53.0, 64.5, 73.3, 81.8, 131,6, 220.0, and 300 K, respectively; heat flow along c-axis.

TABLE 53. THERMAL CONDUCTIVITY OF ERBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
8	1171	Rao, K. V.	1967	L	1.3-4.3		<0.1 other rare earth metals and 0.02 other base metals; polycrystalline specimen 1.5 cm in dia and 5 cm long; specific gravity 9.051 at 20 C; electrical resistivity ratio $\rho(298.2K)/\rho_0$ = 25.11; residual electrical resistivity 3.318 μohm cm; Lorenz function 5.53 x 10^{-8} V^2 K^{-2} at 4.2 K.
9	1181	Ratnalingam, R.	1970	L	0.5-4.0	Er 1	Electrical resistivity 92.34 μohm cm at 295 K; electrical resistivity ratio $\rho(295K)/\rho_0$ = 10.7; residual electrical resistivity 8.6 μohm cm; thermal conductivity values calculated from the formula k = 2.82 T + 0.155 T^2 (mW cm^{-1} K^{-1}).
10	1181	Ratnalingam, R.	1970	L	0.5-4.0	Er 2	Electrical resistivity 83.36 μohm cm at 295 K; electrical resistivity ratio $\rho(295K)/\rho_0$ = 25.11; residual electrical resistivity 3.32 μohm cm; thermal conductivity values calculated from k = 7.26 T + 0.132 T^2 (mW cm^{-1} K^{-1}).

Europium

No determinations appear to have been made of the thermal conductivity of europium. The electrical resistivity has been reported at room temperature by Spedding, Hanak, and Danne [1348] as 81 μΩ cm, by Colvin, Legvold, and Spedding [289] as 90 μΩ cm, and by Meaden and Sze as 92 μΩ cm [916, 914]. When Jolliffe, Tye, and Powell [690] determined the thermal conductivity and electrical resistivity of most of the rare earth metals at room temperature, they plotted the derived values for the Lorenz function against the atomic number, and suggested that from this correlating curve the probable Lorenz functions for the other metals of this series might be predicted. This procedure leads to a Lorenz function of $4.29 \times 10^{-8}\ V^2\ K^{-2}$ for europium, and, using this value and taking the electrical resistivity as 90 μΩ cm yields a thermal conductivity of 0.139 W cm^{-1} K^{-1} at 291 K.

This single point is the extent of the information relating to the thermal conductivity of europium. The curve represented by the broken line passing through this point has been estimated by using the slightly adjusted resistivity values of Meaden and Sze and on the assumption that the theoretical value of the Lorenz function holds for the electronic component of thermal conductivity, and that the lattice component varies inversely as the absolute temperature. These provisional values are probably good to within ±20 percent.

TABLE 54. Provisional thermal conductivity of europium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1} K^{-1})

Solid	
T	*k*
123.2	0.182*
150	0.165*
173.2	0.156*
200	0.148*
223.2	0.144*
250	0.141*
273.2	0.140*
298.2	0.139*
300	0.139*

†The provisional values are for high-purity europium.
*Estimated.

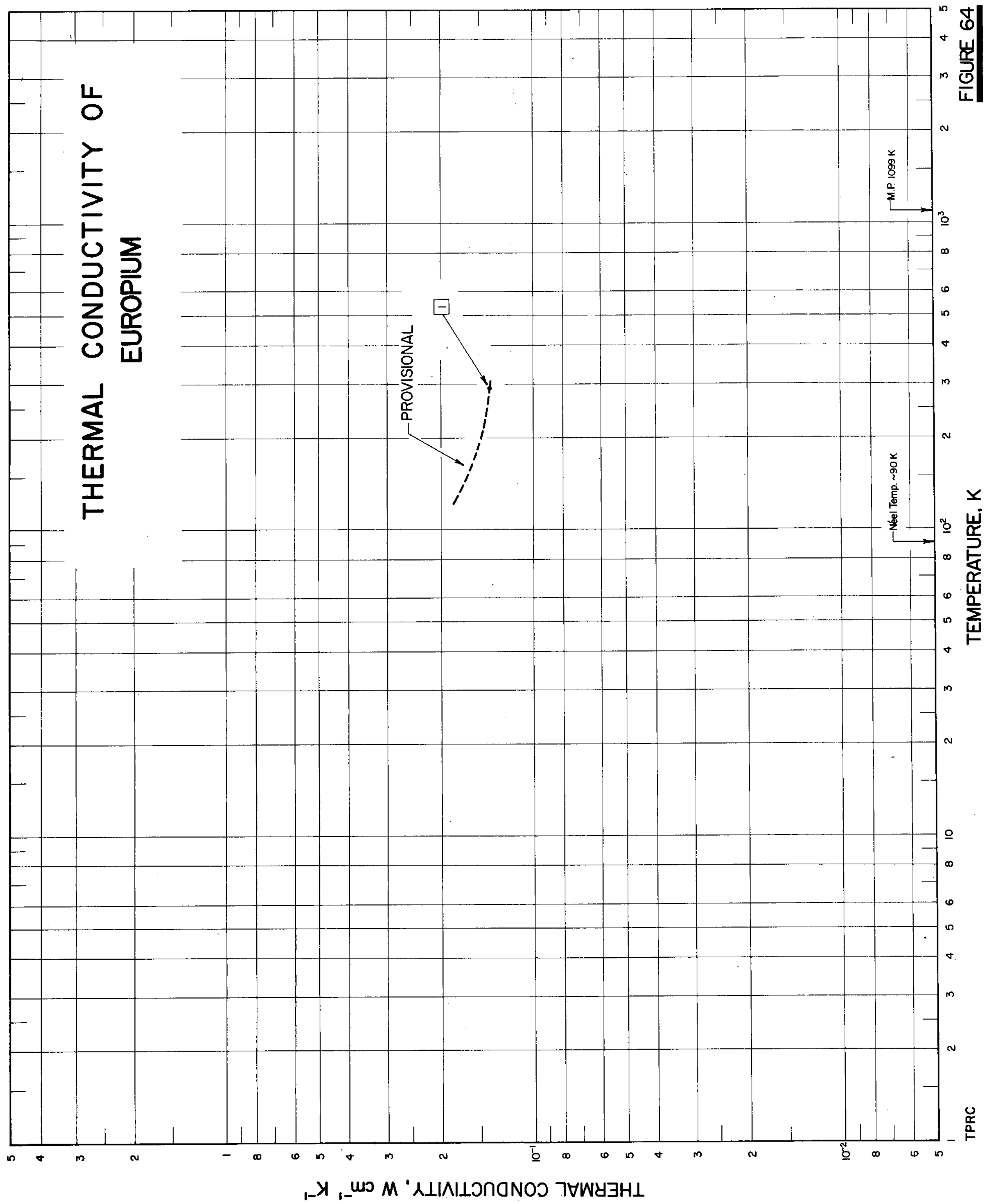

THERMAL CONDUCTIVITY OF EUROPIUM
PROVISIONAL
1
M.P. 1099 K
Néel Temp. ~90 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
FIGURE 64
TPRC

TABLE 55. THERMAL CONDUCTIVITY OF EUROPIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	→	291		Predicted value calculated from electrical resistivity value averaged from data of Spedding, F.H., et al. (Trans. AIME, 212, 379, 1958) and Colvin, R.V., et al. (Phys. Rev. 120, 741, 1960), and the Lorenz number 4.29 x 10^{-8} V^2 K^{-2} based on the smoothed curve of Lorenz number vs. atomic number given by the authors.

Fermium

No information is available for the thermal or electrical conductivity of fermium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidence shows that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of fermium at 300 K is or the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ± 50 percent.

Fluorine

No information is available for the thermal conductivity of solid fluorine. The thermal conductivities for the other physical states are discussed separately below.

Saturated Liquid

The values here presented for the thermal conductivity of saturated fluorine liquid are interpolated from a graph drawn in the engineering system [24]. No experimental data were located for the thermal conductivity of the saturated liquid in the unclassified literature. In the source cited [24], it was stated that the saturated values were adjusted from those derived from the Stiel and Thodos correlation [1365] although no detailed description of the adjustment method was given.

In view of the uncertainty possible in the original correlations [1365] plus that introduced in the adjustment procedure [24], no detailed error estimate can be given. An assessment of ten percent below 125 K and unknown above 125 K would appear reasonable. Due to the lack of experimental data no departure plot is given. Experimentation is highly desirable to confirm the estimates here reproduced.

Saturated Vapor

The values here presented for the thermal conductivity of saturated fluorine vapor are interpolated from a graph drawn in the engineering system [24]. No experimental data were located for the thermal conductivity of the saturated vapor in the unclassified literature. In the source cited [24], it was stated that the saturated values were adjusted from those derived from the Stiel and Thodos correlations [1365] although no detailed description of the adjustment method was given.

In view of the uncertainty possible in the original correlation [1365] plus that introduced in the adjustment procedure [24], no detailed error estimate can be given. An assessment of ten percent below 125 K and unknown above 125 K would appear reasonable. Due to the lack of experimental data no departure plot is given. Experimentation is highly desirable to confirm the estimates here reproduced.

The only experimental data reported for the thermal conductivity of fluorine is that due to Franck and coworkers [454, 456] for pressures below atmospheric. These data have been correlated by Franck [454] and Lenoir [839].

Analysis of the experimental data was made difficult by the fact that with one exception, only two pressures were studied by Franck at any one temperature. No information is given by either Franck or Lenoir on the method of obtaining conductivity values for atmospheric pressure. In this analysis a linear variation was assumed. Extrapolation of the data to atmospheric pressure yielded a set of values which appear to be consistently higher by about five percent than either the Lenoir or Franck tabulations. It appears that the Franck smoothed values are not for atmospheric pressure and that Lenoir erroneously assumed this. The recommended values were calculated from the equation

$$k(\text{mW cm}^{-1}\,\text{K}^{-1}) = 0.003453 + 8.28691 \cdot 10^{-4}\,T + 5.22561 \cdot 10^{-7}\,T^2 - 7.47978 \cdot 10^{-10}\,T^3,$$

which fitted the extrapolated values to within 2.2 percent.

The accuracy of the recommended data is difficult to estimate accurately due to the scatter in the original experimental values at lower pressures and the possibility of dimerization in the vapor but a value of ten percent should be adequate for all temperatures tabulated.

TABLE 56. Recommended thermal conductivity of fluorine

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$
54	2.04*	54	0.048*
60	1.95*	60	0.053*
70	1.80*	70	0.062*
80	1.65*	80	0.071*
90	1.50*	90	0.081*
100	1.35*	100	0.092*
110	1.21*	110	0.105*
120	1.06*	120	0.125*
130	0.90*	130	0.16*
140	0.66*	140	0.22*
144	0.40*‡	144	0.40*‡

*Estimated or extrapolated, hence provisional.
‡Pseudo-critical value.

TABLE 56. Recommended thermal conductivity of fluorine—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (At 1 atm)			
T	$k\times10^3$	T	$k\times10^3$
85	0.076*		
90	0.081		
100	0.090	450	0.413
110	0.100	460	0.421
120	0.109	470	0.430
130	0.118	480	0.438
140	0.128	490	0.446
150	0.137	500	0.455
160	0.146	510	0.463
170	0.156	520	0.471
180	0.165	530	0.479
190	0.174	540	0.486
200	0.184	550	0.493
210	0.193	560	0.500
220	0.202	570	0.507
230	0.212	580	0.514
240	0.221	590	0.520
250	0.231	600	0.527
260	0.241	610	0.534
270	0.251	620	0.541
280	0.260	630	0.547
290	0.269	640	0.552
300	0.279	650	0.557
310	0.288	660	0.563
320	0.298	670	0.568
330	0.307	680	0.573
340	0.316	690	0.579
350	0.326	700	0.583
360	0.335	710	0.588
370	0.344	720	0.592
380	0.354	730	0.596
390	0.363	740	0.599
400	0.371	750	0.603
410	0.378	760	0.607
420	0.388	770	0.610
430	0.397	780	0.613
440	0.405	790	0.616
		800	0.618

*Extrapolated.

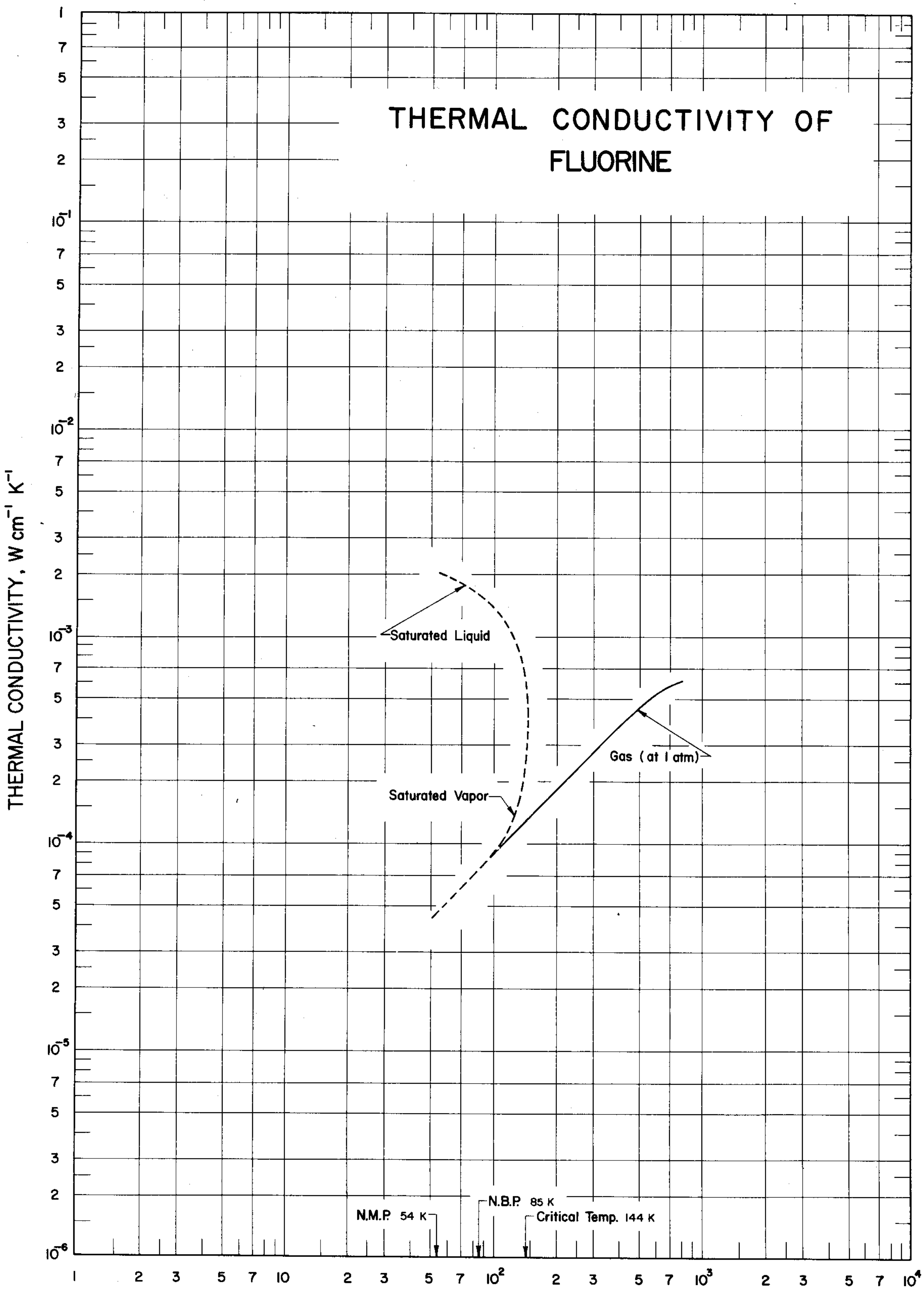

THERMAL CONDUCTIVITY OF FLUORINE
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.M.P. 54 K
N.B.P. 85 K
Critical Temp. 144 K
TEMPERATURE, K
TPRC

FIGURE 65

Francium

No information is available for the thermal or electrical conductivity of francium. However, very rough estimation of its room-temperature thermal conductivity may be made on the basis of the expected similarities between francium and the other alkali metals. The thermal conductivity values at 300 K of the other five members lithium, sodium, potassium, rubidium, and cesium of Group I A are 0.847, 1.41, 1.024, 0.582, and 0.359 W cm^{-1} K^{-1}, respectively. The extrapolation to atomic number 87 of a curve drawn through these points plotted in a large working graph of thermal conductivity versus atomic number similar to figure 15 gives a value of 0.145 W cm^{-1} K^{-1} for francium at 300 K. This estimated value is probably good to ±50 percent.

Gadolinium

The situation of the available experimental information on the thermal conductivity of gadolinium has been improved since the completion of the preliminary report [608]. In addition to the data then available, recent measurements on single crystal samples have been reported by Nellis and Legvold [1021] (curves 6 and 7) for the two principal directions over the temperature range 4.6 to 330 K. The sample of Karagyozyan and Rao [714] (curve 5) has been remeasured by Ratnalingam and Sousa [1183] (curve 8) over the range of 0.64 to 4.2 K, and these two sets of data are very much different both in magnitude and in temperature variation. Furthermore, Ratnalingam [1181] (curves 9–11) has measured another sample under different cold-work conditions over the range 0.5 to 4.0 K. His three new curves are approximately of the same shape and slope as those of the curve of Ratnalingam and Sousa.

To derive provisional curves for single crystal gadolinium, smooth curves have been drawn through the data of Nellis and Legvold, from which the provisional values for polycrystalline gadolinium have been derived by assuming the value for the polycrystal to be the mean of those given by equation (11) due to Voigt [1487] and by equation (12) due to Nichols [1032] (see Meaden [912]). The curve for polycrystalline gadolinium has been extrapolated from 4 K to lower temperatures following the slope of the curve of Ratnalingam and Sousa.

The provisional values are thought to be accurate to within ±10 percent at temperatures above 100 K. Below 100 K the values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to samples having ρ_0 = 2.62, 4.43, and 3.71 $\mu\Omega$ cm, respectively. These values are very uncertain.

TABLE 57. Provisional thermal conductivity of gadolinium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

	Solid		
T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k
0			0
1			0.0113
2			0.0231
3			0.0357
4	0.0594	0.0442	0.0488
5	0.0754	0.0563	0.0621
6	0.0902	0.0686	0.0752
7	0.104	0.0803	0.0875
8	0.116	0.0918	0.0994
9	0.127	0.103	0.110
10	0.137	0.113	0.121
11	0.145	0.123	0.130
12	0.152	0.130	0.137
13	0.158	0.136	0.143
14	0.164	0.142	0.149
15	0.168	0.147	0.154
16	0.170	0.152	0.158
18	0.174	0.161	0.165
20	0.175	0.168	0.170
25	0.171	0.179	0.176
30	0.166	0.182	0.177
35	0.162	0.180	0.174
40	0.158	0.178	0.171
45	0.155	0.175	0.168
50	0.152	0.172	0.165
60	0.147	0.167	0.160
70	0.143	0.162	0.155
80	0.139	0.157	0.151
90	0.136	0.153	0.147
100	0.133	0.149	0.143
123.2	0.127	0.141	0.136
150	0.121	0.133	0.129
173.2	0.117	0.127	0.123
200	0.112	0.119	0.117
223.2	0.108	0.113	0.112
250	0.105	0.107	0.107
273.2	0.104	0.103	0.104
298.2	0.108	0.103	0.105
300	0.108	0.104	0.106
310	0.110	0.106	0.107

†The provisional values are for well-annealed high-purity gadolinium, and those below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_0=2.62$, 4.43, and 3.71 $\mu\Omega$ cm, respectively.

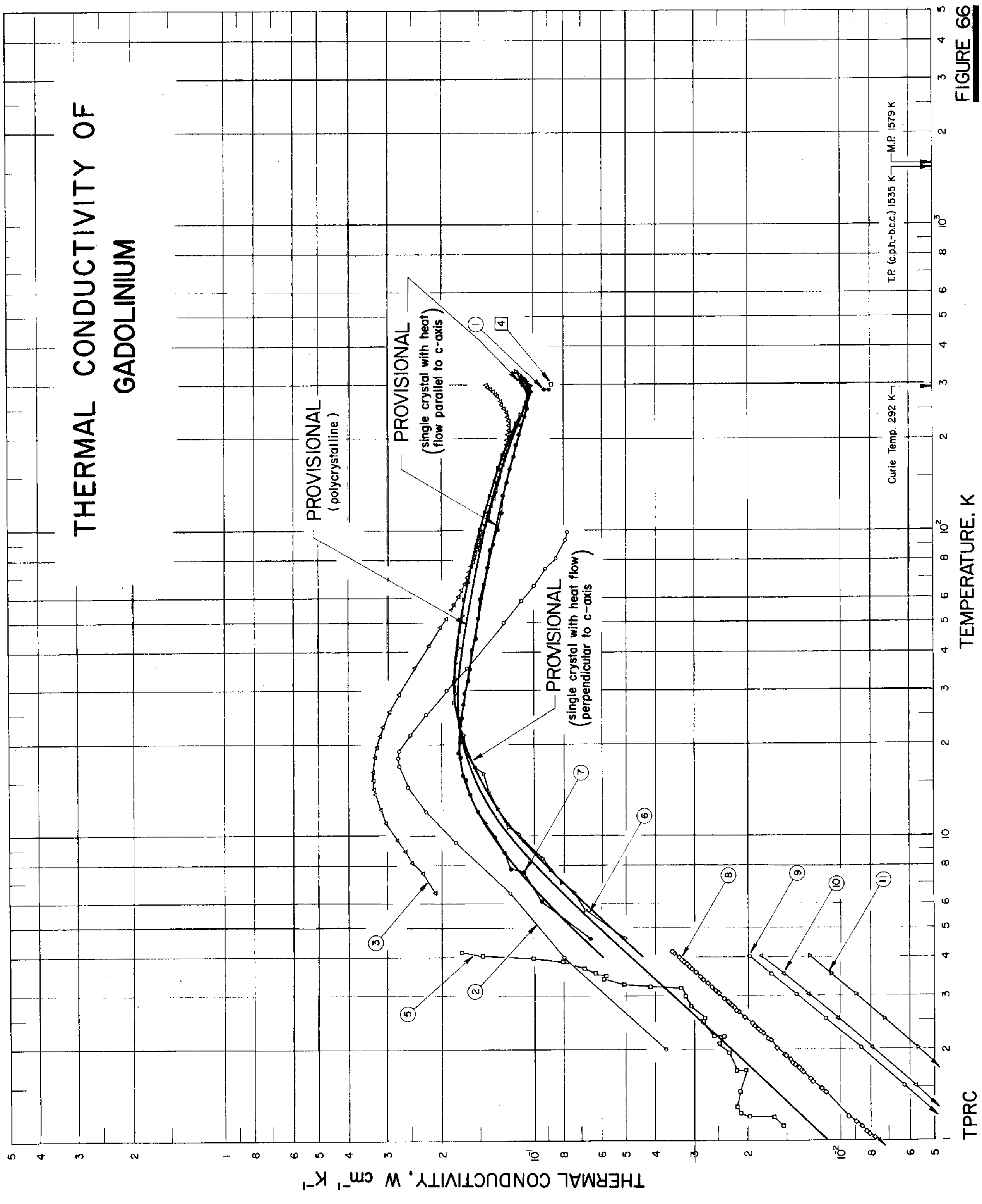

THERMAL CONDUCTIVITY OF GADOLINIUM
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
T.P. (c.p.h.-b.c.c.) 1535 K
M.P. 1579 K
Curie Temp. 292 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC
FIGURE 66

TABLE 58. THERMAL CONDUCTIVITY OF GADOLINIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1127	Powell, R.W. and Jolliffe, B.W.	1965	C	291.2		High purity; polycrystalline; specimen 0.25 in. in dia and 0.25 in. long; supplied by Johnson Matthey Co.; electrical resistivity reported at about 18 C as 134 μohm cm; Monel metal used as comparative material; thermal conductivity data obtained from two measurements using different thermal comparators.
2	48	Aliev, N.G. and Volkenshtein, N.V.	1966	L	2.0–99		99.9 pure; strip specimen 0.25 mm thick; baked for 1.5 hrs at 650 C; measured in helium atm; electrical resistivity reported at 4.2 K as 3.00 μohm cm; electrcial resistivity ratio ρ(293 K)/ρ(4.2 K) = 47.4; Lorenz function 5.75 x 10^{-8} V^2 K^{-2} at 4.2 K.
3	80	Arajs, S. and Colvin, R.V.	1964	L	6.5–300		Polycrystalline gadolinium; measured in vacuum at about 6 x 10^{-6} mm Hg; electrical resistivity reported at 4.18 K as 2.41 μohm cm; antiferromagnetic-paramagnetic transition occurred at ~270 K; Lorenz function ~8 x 10^{-8} V^2 K^{-2} at 4.2 K.
4	831	Legvold, S. and Spedding, F.H.	1954		301.2		No information given.
5	714	Karagyozan, A.G. and Rao, K.V.	1967	L	1.1–4.2		Polycrystalline; wire specimen 1.24 mm in dia and 5 cm long; supplied by Messrs. Johnson Matthey and Co.; anomalies at about 1.3 and 3.5 K.
6	1021	Nellis, W.J. and Legvold, S.	1969	L	4.6–330	a-axis	<0.0500 Ho, <0.0500 Tb, 0.0218 O_2, <0.0200 Dy, <0.0200 Ta, <0.0020 Fe, and <0.0020 Ni; single crystal; specimen 2 x 2 mm in cross section and 6 to 20 mm long; grown by the strain-anneal technique; mechanically polished, etched, and electropolished; Curie temp reported at 293 K; residual electrical resistivity 4.43 μohm cm at 4.2 K; electrical resistivity ratio ρ(300K)/ρ(4.2K) = 31.4; Lorenz function reported as 4.48, 4.69, 4.79, 4.57, 4.59, 4.69, 5.00, 5.66, 6.19, 6.42, 6.65, 6.83, 6.88, 6.76, 6.45, 6.16, 5.81, 5.45, 4.94, 4.76, and 4.85 x 10^{-8} V^2 K^{-2} at 5.0, 7.7, 11.5, 18.3, 22.9, 26.4, 33.0, 42.7, 53.3, 59.7, 68.6, 82.9, 96.6, 121.4, 149.7, 172.0, 210.6, 240.0, 273.9, 293.9, and 330.5 K, respectively; heat flow measured along the <11$\bar{2}$0> direction (a-axis) of the hexagonal close-packed crystal structure.
7	1021	Nellis, W.J. and Legvold, S.	1969	L	4.6–310	c-axis	Same dimensions and fabrication method as the above specimen; residual electrical resistivity 2.62 μohm cm at 4.2 K; electrical resistivity ratio ρ(300K)/ρ(4.2K) = 46.8; Lorenz function reported as 3.52, 3.63, 3.68, 3.49, 3.29, 3.25, 3.36, 3.59, 3.86, 4.29, 4.57, 4.70, 4.85, 4.95, 5.02, 5.00, 4.86, 4.70, 4.55, 4.46, and 4.32 x 10^{-8} V^2 K^{-2} at 4.5, 7.2, 10.5, 15.5, 20.0, 24.5, 29.2, 35.1, 43.2, 58.8, 71.9, 84.9, 108.0, 143.9, 182.9, 207.9, 237.9, 260.0, 278.5, 294.2, and 309.1 K, respectively; heat flow measured along the <0001> direction (c-axis) of the hexagonal close-packed crystal structure.
8	1183	Ratnalingam, R. and Sousa, J.B.	1969	L	0.64–4.2		The same specimen as for curve No. 5; residual electrical resistivity ρ(4.2K) = 3.37 μohm cm; Lorenz number L = 2.53 x 10^{-8} V^2 K^{-2}.

TABLE 58. THERMAL CONDUCTIVITY OF GADOLINIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
9	1181	Ratnalingam, R.	1970	L	0.5–4.0	Gd 2	Electrical resistivity 143.4 μohm cm at 295 K; residual electrical resistivity 6.44 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0 = 22.3$; thermal conductivity values calculated from the formula $k = 3.75\ T + 0.307\ T^2$ (mW cm^{-1} K^{-1}).
10	1181	Ratnalingam, R.	1970	L	0.5–4.0	Gd 2	The above specimen cold-worked; electrical resistivity 144.7 μohm cm at 295 K; residual electrical resistivity 7.31 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0 = 19.8$; thermal conductivity values calculated from the formula $k = 3.46\ T + 0.270\ T^2$ (mW cm^{-1} K^{-1}).
11	1181	Ratnalingam, R.	1970	L	0.5–4.0	Gd 2	The above specimen further cold-worked; electrical resistivity 147.8 μohm cm at 295 K; electrical resistivity ratio $\rho(295K)/\rho_0 = 15.1$; residual electrical resistivity 9.79 μohm cm; thermal conductivity values calculated from the formula $k = 2.56\ T + 0.152\ T^2$ (mW cm^{-1} K^{-1}).

Gallium

Gallium was first found by Powell [1112, 1113] to possess unusually anisotropic conducting properties. Many determinations of the thermal conductivity of gallium single crystals have since been made at low temperatures for the three principal crystal directions. The main interest has been centered in and near the superconducting range and only the measurements of Powell, Woodman, and Tye [1147] (curves 77–79) have been reported for the range 83 to 293 K.

The measurements made at low temperatures for the three main crystal directions of gallium afford a clear insight into the manner in which each increase in sample purity increases the height of the maximum and displaces it to lower temperatures. It is also clearly seen that for each crystal direction the maxima, when plotted against temperature on a logarithmic scale, conform approximately to different straight lines. These lines are roughly parallel to each other, and an m-value of 2.78 has been used for each crystal direction.

Boughton and Yaqub [185] (curves 87–92) have apparently been responsible for thermal conductivity measurements on gallium single crystals of the highest purity (99.9999%). On these samples which gave $\rho_{297\ K}/\rho_{4.2\ K} = 4 \times 10^5$ they made measurements at temperatures ranging from about 1.51 to 4.12 K and their maximum values of thermal conductivity for the a, b, and c-axis are 300, 845, and 76 W cm^{1-} K^{-1} at 1.84, 1.77, and 1.98 K, respectively. The curves for which recommended thermal conductivity values at low temperatures for the normal state in the three principal directions are tabulated were derived to fit their data by using equation (7) and using $\beta = 0.00409$, 0.00140, and 0.0174 for k_a, k_b, and k_c, respectively, although it was in the course of this work that Boughton and Yaqub found evidence of a dependence of the thermal conductivity on the size of the sample below about 3.6 K. The true course of these curves for the bulk metal must therefore await the outcome of further investigation and analysis.

Below 1.091 K gallium becomes a superconductor. For information regarding the thermal conductivity of gallium in the superconducting state the work of Zavaritskii [1600] (curves 62–69) should be studied. He has reported values for each crystal direction and for samples of high purity ($\rho_{293\ K}/\rho_{0\ K}$ of 20800, 23300, and 13500 for the a, b, and c directions respectively) over the approximate temperature range of 0.115 to 0.850 K.

At higher temperatures the curves decrease to merge at about 80 K with those of Powell, Woodman, and Tye and to follow these curves to the melting point.

Gallium forms single crystals so readily that polycrystalline samples are not normally produced, and in Section 2 of this work the difficulty is discussed of attempting to derive the polycrystalline thermal conductivity of such a markedly anisotropic metal from single crystal data. For the time being it seems appropriate to regard the values for the a-axial direction as approximating that for the polycrystalline form.

Thermal conductivity determinations have been made on molten gallium by five groups of workers. These values are in fair agreement near the melting point but at 600 K the extreme values differ by 136 percent. The tentatively recommended curve derived from the electrical resistivity on the basis of a theoretical value for the Lorenz function yields a value at 600 K about 15 percent below the mean of these two extreme values and some 10 percent above the latest determinations by Duggin [374] (curve 96). The two most recent, Yurchak and Smirnov [1593] (curve 94) and Duggin [374] (curve 96), have obtained values which yield Lorenz functions that were stated to be some 0 to 23 percent and 10 to 13 percent below the theoretical value over the respective temperature ranges of 333 to 661 K and 350 to 550 K.

The recommended values are thought to be accurate to within ±20 percent at temperatures below 10 K due to the additional uncertainty in the location of the maxima, ±10 percent from 10 K to 100 K, and ±5 percent from 100 K to the melting point. For liquid gallium the uncertainty of the values is probably ±10 percent near the melting point and increases to ±20 percent at the highest temperatures. Those values above 500 K are provisional. At temperatures below 60 K the values for k_a, k_b, and k_c are applicable only to specimens having $\rho_0 = 0.000100$, 0.0000342, and 0.000425 $\mu\Omega$ cm, respectively. The values for k_a are also good for polycrystalline gallium.

TABLE 59. Recommended thermal conductivity of gallium†

(Temperature, T, K; Thermal Conductivity, W cm^{-1} K^{-1})

Solid				Liquid	
T	‖ to a-axis‡ k	‖ to b-axis k	‖ to c-axis k	T	k
0	0	0	0	302.93	0.281
1	226	657	54.1	323.2	0.294
2	298	832	76.0	373.2	0.328
3	194	524	58.2	400	0.345
4	99.3	272	31.1	473.2	0.389
5	59.2	163	18.2	500	0.406
6	38.8	107	11.8	573.2	0.447
7	27.2	74.0	8.15	600	0.462
8	19.9	54.2	5.93	673.2	0.503*
9	15.2	41.4	4.47	700	0.519*
10	11.9	32.5	3.49		
15	4.48	13.2	1.44		
20	2.65	17.3	0.835		
25	1.71	4.54	0.588		
30	1.23	3.22	0.462		
35	0.952	2.46	0.385		
40	0.795	1.98	0.333		
50	0.634	1.42	0.269		
60	0.555	1.15	0.233		
70	0.516	1.02	0.210		
80	0.494	0.983	0.196		
90	0.483	0.960	0.187		
100	0.474	0.951	0.181		
123.2	0.457	0.933	0.172		
150	0.443	0.918	0.167		
173.2	0.433	0.906	0.165		
200	0.424	0.896	0.163		
223.2	0.418	0.890	0.162		
250	0.414	0.885	0.160		
273.2	0.410	0.884	0.160		
298.2	0.408	0.883	0.159		
300	0.406	0.883	0.159		
302.93	0.406	0.883	0.159		

†The values are for high-purity gallium, and those below 60 K for k_a, k_b, and k_c are applicable only to specimens having $\rho_o = 0.000100$, 0.0000342, and 0.000425 μΩ cm, respectively. The values above 500 K are provisional.

‡The values recommended for gallium single crystal in the direction parallel to the a-axis are also good for polycrystalline gallium.

*Extrapolated.

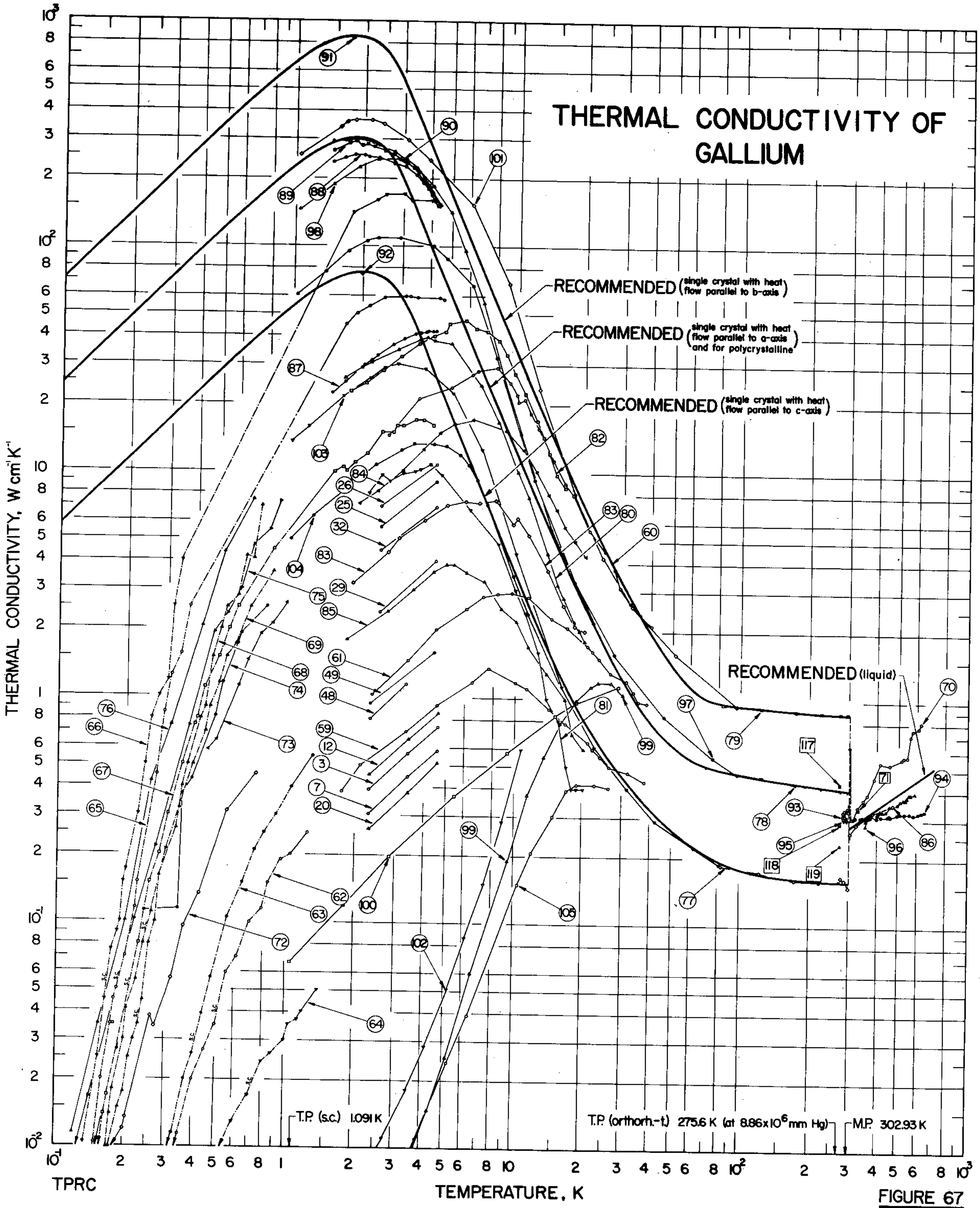

THERMAL CONDUCTIVITY OF GALLIUM
RECOMMENDED (single crystal with heat flow parallel to b-axis)
RECOMMENDED (single crystal with heat flow parallel to a-axis and for polycrystalline)
RECOMMENDED (single crystal with heat flow parallel to c-axis)
RECOMMENDED (liquid)
T.P. (s.c.) 1.091 K
T.P. (orthorh.-t.) 275.6 K (at 8.86x10^6 mm Hg)
M.P. 302.93 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC
FIGURE 67

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.4, 4.6	Ga 42-1	Single crystal; 2.92 cm long, 0.223 cm dia; supplied by National Physical Lab; rod axis parallel to the high electrical resistance direction of the crystal; measured in a longitudinal field of 0.36 kOe (kilooersted).
2*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a longitudinal field of 0.73 kOe.
3	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a longitudinal field of 1.08 kOe.
4*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a longitudinal field of 1.47 kOe.
5*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a longitudinal field of 1.81 kOe.
6*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a longitudinal field of 2.15 kOe.
7	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a longitudinal field of 2.51 kOe.
8*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a longitudinal field of 2.98 kOe.
9*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a longitudinal field of 3.24 kOe.
10*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.4	Ga 42-1	The above specimen measured in a longitudinal field of 3.62 kOe.
11*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 4.6	Ga 42-1	The above specimen measured in a longitudinal field of 3.65 kOe.
12	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a longitudinal field of 0.36 kOe.
13*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 0.73 kOe.
14*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a transverse field of 1.10 kOe.
15*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 1.42 kOe.
16*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a transverse field of 1.78 kOe.
17*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 2.17 kOe.
18*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a transverse field of 2.53 kOe.
19*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 2.90 kOe.
20	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.6	Ga 42-1	The above specimen measured in a transverse field of 3.26 kOe.
21*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3	Ga 42-1	The above specimen measured in a transverse field of 3.54 kOe.
22*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 3.62 kOe.
23*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.4	Ga 42-1	The above specimen measured in a transverse field of 3.66 kOe.
24*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Ga 42-1	The above specimen measured in a transverse field of 3.88 kOe.
25	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	Single crystal; 2.45 cm long, 0.218 cm dia; supplied by National Physical Lab; rod axis parallel to the low electrical resistance direction; measured in a transverse field of 0.35 kOe.
26	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a longitudinal field of 0.35 kOe.
27*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a transverse field of 1.05 kOe.

* Not shown in figure.

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
28*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a longitudinal field of 1.05 kOe.
29	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a transverse field of 1.80 kOe.
30*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a longitudinal field of 1.80 kOe.
31*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-2	The above specimen measured in a transverse field of 2.55 kOe.
32	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a longitudinal field of 2.55 kOe.
33*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-2	The above specimen measured in a transverse field of 3.24 kOe.
34*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5, 4.4	Ga 42-2	The above specimen measured in a longitudinal field of 3.24 kOe.
35*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5	Ga 42-2	The above specimen measured in a longitudinal field of 3.76 kOe.
36*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-2	The above specimen measured in a longitudinal field of 3.91 kOe.
37*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-2	The above specimen measured in a transverse field of 3.98 kOe.
38*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	Single crystal; supplied by National Physical Lab; rod axis parallel to the intermediate electrical resistance direction; measured in a transverse field of 0.2 kOe.
39*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 4.4	Ga 42-3	The above specimen measured in a transverse field of 0.38 kOe.
40*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.4	Ga 42-3	The above specimen measured in a longitudinal field of 0.38 kOe.
41*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 0.75 kOe.
42*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 3.3	Ga 42-3	The above specimen measured in a transverse field of 1.17 kOe.
43*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.4	Ga 42-3	The above specimen measured in a longitudinal field of 1.17 kOe.
44*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 1.43 kOe.
45*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 3.3	Ga 42-3	The above specimen measured in a transverse field of 1.80 kOe.
46*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 4.4	Ga 42-3	The above specimen measured in a longitudinal field of 1.80 kOe.
47*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 2.16 kOe.
48	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 3.3	Ga 42-3	The above specimen measured in a transverse field of 2.53 kOe.
49	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3-4.4	Ga 42-3	The above specimen measured in a longitudinal field of 2.53 kOe.
50*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 2.90 kOe.
51*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 3.3	Ga 42-3	The above specimen measured in a transverse field of 3.22 kOe.
52*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 4.4	Ga 42-3	The above specimen measured in a longitudinal field of 3.22 kOe.
53*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 3.60 kOe.
54*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3, 3.3	Ga 42-3	The above specimen measured in a transverse field of 3.72 kOe.
55*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3	Ga 42-3	The above specimen measured in a longitudinal field of 3.72 kOe.
56*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a longitudinal field of 3.84 kOe.

* Not shown in figure.

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
57*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.3	Ga 42-3	The above specimen measured in a longitudinal field of 3.86 kOe.
58*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Ga 42-3	The above specimen measured in a transverse field of 4.09 kOe.
59	1220	Rosenberg, H.M.	1955	L	1.8-38	Ga 42-1	Single crystal; 2.92 cm long, 0.223 cm in dia; supplied by National Physical Lab; rod axis parallel to the high electrical resistance direction of the crystal; electrical resisitivity ratio $\rho(293\ K)/\rho(20\ K) = 92.1$.
60	1220	Rosenberg, H.M.	1955	L	2.7-40	Ga 42-2	Single crystal; 2.45 cm long, 0.218 cm in dia; supplied by National Physical Lab; rod axis parallel to the low electrical resistance direction of the crystal; electrical resistivity ratio $\rho(293\ K)/\rho(20\ K) = 111$.
61	1220	Rosenberg, H.M.	1955	L	2.3-39	Ga 42-3	Single crystal; supplied by National Physical Lab; rod axis parallel to the intermediate electrical resistance direction of the crystal; electrical resistivity ratio $\rho(293\ K)/\rho(20\ K) = 106.5$.
62	1600	Zavaritskii, N. V.	1959	L	0.16-1.3	3 Da	0.1 impurities (mainly Si, P, K, Ca, Al, Ti, and V); single crystalline rod; 3 mm dia; rod axis parallel to the crystallographic a-direction (a = 4.5258 Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 1.28 \times 10^2$; in superconducting state.
63	1600	Zavaritskii, N. V.	1959	L	0.12-1.3	3 Db	0.1 impurities (mainly Si, P, K, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic b-direction (b = 4.5198 Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 1.18 \times 10^2$; in superconducting state.
64	1600	Zavaritskii, N. V.	1959	L	0.12-1.4	3 Dc	0.1 impurities (mainly Si, P, K, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic c-direction (c = 7.6602 Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 0.67 \times 10^2$; in superconducting state.
65	1600	Zavaritskii, N. V.	1959	L	0.13-4.6	2 Pa	0.001 impurities (mainly Si, P, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic a-direction (a = 4.5258Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 2.08 \times 10^4$; in normal and superconducting state.
66	1600	Zavaritskii, N. V.	1959	L	0.12-4.0	2 Pb	0.001 impurities (mainly Si, P, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic b-direction (b = 4.5198 Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 2.33 \times 10^4$; in normal and superconducting state.
67	1600	Zavaritskii, N. V.	1959	L	0.13-4.2	2 Pc	0.001 impurities (mainly Si, P, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic c-direction (c = 7.6602 Å); electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 1.35 \times 10^4$; in normal and superconducting state.
68	1600	Zavaritskii, N. V.	1959	L	0.16-0.75	b-3P	0.001 impurities (mainly Si, P, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic b-direction (b = 4.5198 Å); specimen 1.7 mm in dia; electrical resistivity ratio $\rho(293\ K)/\rho(0\ K) = 2.44 \times 10^3$; in superconducting state.
69	1600	Zavaritskii, N. V.	1959	L	0.15-0.85	c-4P	0.001 impurities (mainly Si, P, Ca, Al, Ti, and V); single crystalline rod; rod axis parallel to the crystallographic c-direction (c = 7.6602 Å); dia 0.7 mm; electrical resistivity ratio $\rho(293\ K)/\rho_0 = 10^4$; in superconducting state.
70	1066, 1067	Pashaev, B.P.	1961	L	283-621		99.999 pure; measured in solid state and liquid state; 3 mm dia, 64 mm long; melting point 30 C.

* Not shown in figure.

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
71	211	Briggs, L. J.	1957	C	333		99.95 pure liquid gallium; supplied by Aluminum Co. of America; mercury of 0.0001 impurity used as comparative material.
72	1603	Zavaritskii, N. V.	1960	L	0.3-0.7	C-6	0.0077 total impurity; single crystalline; specimen 0.12 cm in dia and approx 50 cm long; electrical resistivity ratio $\rho(293K)/\rho_0 = 1.85 \times 10^3$; in superconducting state.
73	1603	Zavaritskii, N. V.	1960	L	0.5-1.0	C-7	0.0023 total impurity; 0.083 cm in dia and ~50 cm long; $\rho(293K)/\rho_0 = 6.25 \times 10^3$; in superconducting state.
74	1603	Zavaritskii, N. V.	1960	L	0.1-0.8	C-8	0.0017 total impurity; 0.16 cm in dia and ~50 cm long; $\rho(293K)/\rho_0 = 8.33 \times 10^3$; in superconducting state.
75	1603	Zavaritskii, N. V.	1960	L	0.1-0.9	C-9	0.00086 total impurity; 0.115 cm in dia and ~50 cm long; $\rho(293K)/\rho_0 = 1.67 \times 10^4$; in superconducting state.
76	1603	Zavaritskii, N. V.	1960	L	0.1-0.7	C-10	0.0005 total impurity; 0.11 cm in dia and ~50 cm long; $\rho(293K)/\rho_0 = 2.78 \times 10^4$; in superconducting state.
77	1147	Powell, R. W., Woodman, M. J., and Tye, R. P.	1963	L	83-293	Ga 14.2	Single crystalline rod approx 4 mm in dia; supplied by National Chemical Laboratory; electrical resistivity reported as 12.0, 20.3, 30.8, 40.6, 50.3, and 54.3 μohm cm at 83, 123, 173, 223, 273, and 293 K, respectively; electrical resistivity ratio $\rho(293K)/\rho(20.4K) = 136$; heat flow parallel to the c-axis.
78	1147	Powell, R. W., et al.	1963	L	83-293	Ga 14.5	Similar to the above specimen except electrical resistivity reported as 3.52, 6.18, 9.42, 12.7, 16.05, and 17.40 μohm cm at 83, 123, 173, 223, 273, and 293 K, respectively, and electrical resistivity ratio $\rho(293K)/\rho(20.4K) = 159$; heat flow parallel to the a-axis.
79	1147	Powell, R. W., et al.	1963	L	83-293	Ga 14.4	Similar to the above except electrical resistivity reported as 1.72, 2.92, 4.44, 5.96, 7.48, and 8.10 μohm cm at 83, 123, 173, 223, 273, and 293 K, respectively, and electrical resistivity ratio $\rho(293K)/\rho(20.4K) = 155$; heat flow parallel to the b-axis.
80	1094	Plumb, H. H.	1954	L	1.7-20	a_1	Impurities: 0.01 Hg, 0.001 Ca, 0.001 Fe, 0.001 Si, 0.0001-0.001 Pb, 0.0001 Mg, and 0.00001 Cu; single crystal; supplied by Aluminum Co. of America; electrical resistivity $\rho(273K) = 16.1$ μohm cm; electrical resistivity ratio $\rho(273K)/\rho(14K) = 588$; heat flow parallel to a-axis.
81	1094	Plumb, H. H.	1954	L	2.2-20	c_1	Impurities: 0.01 Hg, 0.001 Ca, 0.001 Fe, 0.0001-0.001 Cu, 0.0001 Mg, and trace of Pb; $\rho(273K) = 52.0$ μohm cm; $\rho(273K)/\rho(14K) = 455$; heat flow parallel to c-axis.
82	1094	Plumb, H. H.	1954	L	1.8-16	b_3	Impurities: 0.01 Hg, 0.001 Ca, 0.001 Fe, 0.0001-0.001 Cu, 0.0001 Mg, and trace of Pb; single crystal; supplied by Aluminum Co. of America; $\rho(273K) = 7.6$ μohm cm; $\rho(273K)/\rho(14K) = 625$; heat flow parallel to b-axis.
83	1094	Plumb, H. H.	1954	L	1.9-20	a_2	Impurities: 0.05-0.5 Hg, 0.001 Ca, 0.001 Fe, 0.001 Si, 0.0003-0.003 Pb, 0.0001-0.001 Cu, and 0.0001 Mg; single crystal; supplied by Aluminum Co. of America; $\rho(273K) = 19.8$ μohm cm; $\rho(273K)/\rho(14K) = 455$; heat flow parallel to a-axis.

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
84	1094	Plumb, H.H.	1954	L	2.0–20	b_2	Impurities: 0.01–0.1 Hg, 0.001 Ca, 0.001 Fe, 0.0001–0.001 Cu, 0.0001–0.001 Pb, and 0.0001 Mg; ρ(273 K) = 7.5 μohm cm; ρ(273 K)/ρ(14 K) = 476; heat flow parallel to b-axis.
85	1094	Plumb, H.H.	1954	L	1.8–20	c_2	Impurities: 0.02–0.2 Hg, 0.001 Ca, 0.001 Fe, 0.0001–0.001 Cu, 0.0001 Mg, and trace of Pb, ρ(273 K) = 52.8 μohm cm; ρ(273 K)/ρ(14 K) = 370; heat flow parallel to c-axis.
86	383	Dutchak, Ya.S. and Panasyuk, P.V.	1966	C	278–473		The molten metal placed in a hole 21 mm in dia drilled in an asbestos cement cylinder of 30 mm height; steel 1Kh18N9T used as comparative material.
87	185	Boughton, R.I. and Yaqub, M.	1968	L	1.5–4.3		99.99 pure; single crystal; specimen 3.175 mm in dia; heat flow parallel to a-axis.
88	185	Boughton, R.I. and Yaqub, M.	1968	L	1.5–4.3		99.9999 pure; single crystal; specimen 2.69 mm in dia; supplied by Alcoa, Pittsburgh, Pa.; electrical resistivity ratio ρ(273K)/ρ(0K) ~400,000; heat flow parallel to a-axis. (Additional information obtained from a private communication with the author.)
89	185	Boughton, R.I. and Yaqub, M.	1968	L	1.5–4.3		Similar to the above except specimen 3.18 mm in dia.
90	185	Boughton, R.I. and Yaqub, M.	1968	L	1.5–4.3		Similar to the above except specimen 3.97 mm in dia.
91	185	Boughton, R.I. and Yaqub, M.	1968	L	1.77		Similar to the above except specimen 3.175 mm in dia and heat flow parallel to b-axis.
92	185	Boughton, R.I. and Yaqub, M.	1968	L	1.98		Similar to the above except heat flow parallel to c-axis.
93	1593	Yurchak, R.P. and Smirnov, B.P.	1968	E	285–294	Grade Ga-2	Lorenz function reported as 2.63, 2.55, 2.47, 2.41, 2.36, 2.32, 2.28, 2.25, 2.21, 2.16, 2.12, 2.08, 2.05, 2.02, 2.00, 1.97, 1.96, 1.91, 1.89, and 1.86 x 10^8 $V^2 K^{-2}$ at 303, 317, 330, 342, 355, 367, 381, 394, 408, 429, 453, 471, 488, 505, 523, 542, 583, 625, 664, and 704 K, respectively.
94	1593	Yurchak, R.P. and Smirnov, B.P.	1968	E	304–661		Liquid specimen contained in an aperture made of ceramic about 0.2 mm in dia.
95	1593	Yurchak, R.P. and Smirnov, B.P.	1968	E	287–296		Super cooled specimen.
96	374	Duggin, M.J.	1969	L	358–589		Liquid specimen contained in a rectangular cell with internal cross-section 0.849 cm^2 and about 5.5 cm long; electrical resistivity 26.73, 27.70, 28.68, 29.65, and 30.63 μohm cm at 350, 400, 450, 500, and 550 K, respectively; Lorenz function, as estimated for electron transport only, 2.057, 2.081, 2.084, 2.076, and 2.071 x 10^{-8} $V^2 K^{-2}$ at 350, 400, 450, 500, and 550 K, respectively.
97	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0–96	a56 I	Single crystal; rectangular bar specimen 2 x 2 mm in cross section grown in plexiglass mould from 99.9999 pure material supplied by Alusuisse; electrical resistivity ratio $\rho(r.t.)/\rho_0 = 10^5$; electrical resistivity 0.000141, 0.00160, 0.0147, 0.107, 0.510, 2.29, 4.43, and 20.3 μohm cm at 4.06, 7.21, 12.0, 19.0, 34.5, 58.9, 78.7, and 284 K, respectively; heat flow parallel to a-axis; data taken from smooth curve.
98	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0–96	a56 II	Single crystal; rectangular bar specimen 2 x 2 mm in cross section grown in plexiglass mould from 99.9999 pure material supplied by Alusuisse; electrical resistivity ratio $\rho(r.t.)/\rho_0 = 4.4 \times 10^4$; heat flow parallel to a-axis; data taken from smooth curve.

TABLE 60. THERMAL CONDUCTIVITY OF GALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
99	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.7-30	a56 I	The specimen a56 I for curve No. 97 measured in a magnetic field of 15 kG.
100	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0-29	GaZn	0.02 Zn; prepared from 99.9999 pure gallium supplied by Alusuisse; heat flow along a-axis; data taken from smooth curve.
101	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0-96	b56 I	Single crystal; rectangular bar specimen 2 x 2 mm in cross section grown in plexiglass mould from 99.9999 pure material supplied by Alusuisse; electrical resistivity ratio $\rho(r.t.)/\rho_0 = 8 \times 10^4$; electrical resistivity 0.0000589, 0.000302, 0.00195, 0.00951, 0.0547, 0.305, 1.99, and 9.46 μohm cm at 4.13, 5.83, 9.20, 13.6, 20.2, 38.4, 76.9, and 284 K, respectively; heat flow parallel to b-axis; data taken from smooth curve.
102	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0-11	b56 I	The above specimen measured in a magnetic field of 14 kG.
103	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0-81	c56 II	Single crystal; rectangular bar specimen 2 x 2 mm in cross section grown in plexiglass mould from 99.9999 pure material supplied by Alusuisse; electrical resistivity ratio $\rho(r.t.)/\rho_0 = 3.2 \times 10^4$; heat flow parallel to c-axis; data taken from smooth curve; residual electrical resistivity ~0.0005 μohm cm.
104	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.0-81	c56 I	Single crystal; rectangular bar specimen 2 x 2 mm in cross section grown in plexiglass mould from 99.9999 pure material supplied by Alusuisse; electrical resistivity ratio $\rho(r.t.)/\rho_0 = 1.13 \times 10^4$; electrical resistivity 0.0000233, 0.000318, 0.00485, 0.0483, 0.428, 2.69, 13.4, and 58.3 μohm cm at 1.13, 3.78, 7.14, 11.9, 19.5, 41.1, 77.3, and 284 K, respectively; heat flow parallel to c-axis; data taken from smooth curve.
105	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.4-26	c56 I	The above specimen measured in a magnetic field of 15 kG.
106*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.395	c56 I	The above specimen measured in magnetic fields ranging from 0.509 to 15.0 kG.
107*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.760	c56 I	The above specimen measured in magnetic fields ranging from 0.540 to 15.0 kG.
108*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	1.800	c56 I	The above specimen measured in magnetic fields ranging from 0.662 to 15.0 kG.
109*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	2.244	c56 I	The above specimen measured in magnetic fields ranging from 0.438 to 15.7 kG.
110*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	2.877	c56 I	The above specimen measured in magnetic fields ranging from 0.540 to 15.0 kG.
111*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	3.415	c56 I	The above specimen measured in magnetic fields ranging from 0.607 to 15.0 kG.
112*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	3.899	c56 I	The above specimen measured in magnetic fields ranging from 0.706 to 13.9 kG.
113*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	4.395	c56 I	The above specimen measured in magnetic fields ranging from 1.12 to 15.0 kG.
114*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	5.254	c56 I	The above specimen measured in magnetic fields ranging from 1.13 to 15.0 kG.
115*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	6.376	c56 I	The above specimen measured in magnetic fields ranging from 1.39 to 14.7 kG.
116*	518	Gorter, F.W. and Noordermeer, L.J.	1970	L	7.99	c56 I	The above specimen measured in magnetic fields ranging from 2.03 to 15.0 kG.
117	636	Horner, P.	1961		273.2		Heat flow parallel to b-axis.
118	636	Horner, P.	1961		273.2		Heat flow parallel to a-axis.
119	636	Horner, P.	1961		273.2		Heat flow parallel to c-axis.

* Not shown in figure.

Germanium

Many determinations of the thermal conductivity of germanium have been reported which together cover the temperature range 0.2 to 1194 K. Both *n*-type and *p*-type single crystal samples have been included and studies have also been made to determine the effects of a marked change in the isotopic composition and of neutron irradiation.

The measurements of Geballe and Hull [480] for an *n*-type crystal (curve 49) containing 95.78 percent ^{74}Ge, 1.54 percent ^{73}Ge, 1.11 percent ^{72}Ge, 0.84 percent ^{76}Ge, and 0.728 percent ^{78}Ge differ appreciably from the general pattern. Not only is the thermal conductivity much higher, due presumably to reduced isotope scattering, but the maximum occurs at a higher temperature and therefore departs from the general trend. Irradiation, as might be expected, is found by Goff and Pearlman [506] (curves 36 and 37) and by Nguyen, Vandevyer, and Pham [1031] (curves 84–86) to decrease the thermal conductivity of germanium, the magnitude of the change being greater at low temperatures.

The temperature at which the maximum thermal conductivity occurs decreases reasonably steadily with increase in thermal conductivity, from about 70 K for a conductivity of 0.6 W cm^{-1} K^{-1} (curve 107) to 12.5 K where the thermal conductivity has the maximum value of 18 W cm^{-1} K^{-1}, the value reported by Slack and Glassbrenner [1322] (curve 52). This ignores the above mentioned measurement of Geballe and Hull for a sample highly enriched with isotope ^{74}Ge.

The determinations by Slack and Glassbrenner were made over the range 3.2 to 300 K by a longitudinal heat flow method and from 300 to 1020 K by a radial heat flow method. The radial heat flow method was chosen as it enabled radiation losses at high temperature to be minimized. Radiation heat transfer had been considered to account for the much higher values reported above about 350 K by Kettel [744] (curves 20, 21). From 3 to 10 K Slack and Glassbrenner considered that the form of their curve could be explained by boundary and isotope scattering, and they considered their higher values to be consistent with the larger dimensions of their sample.

A typical curve for the thermal conductivity of well-annealed high-purity germanium has been drawn to fit the data of Slack and Glassbrenner (curve 52) over the full temperature range. From room temperature to a temperature of 940 K an inverse temperature relationship is obeyed and the heat is believed to be conducted solely by phonons. Above 940 K the curve commences to deviate to higher values, due, it is thought, to additional heat transfer that is associated with the bipolar diffusion of electron-hole pairs. This mechanism is stated to be of the order of magnitude required to account for the increased heat conduction, but the agreement with the experimental data is only qualitative.

No measurements on the thermal conductivity of molten germanium have been reported, and the large proportion of phonon conduction in the solid at the melting point would seem, if it persists into the liquid phase, to make uncertain any derivation from electrical resistivity even if the electrical data were available.

An accuracy of the order of ±10 percent is thought probable for the recommended values for well-annealed high-purity germanium at and above room temperature. Below room temperature the thermal conductivity of any particular specimen depends strongly on purity and several other factors, and the tabulated values represent only a typical curve for well-annealed high-purity germanium.

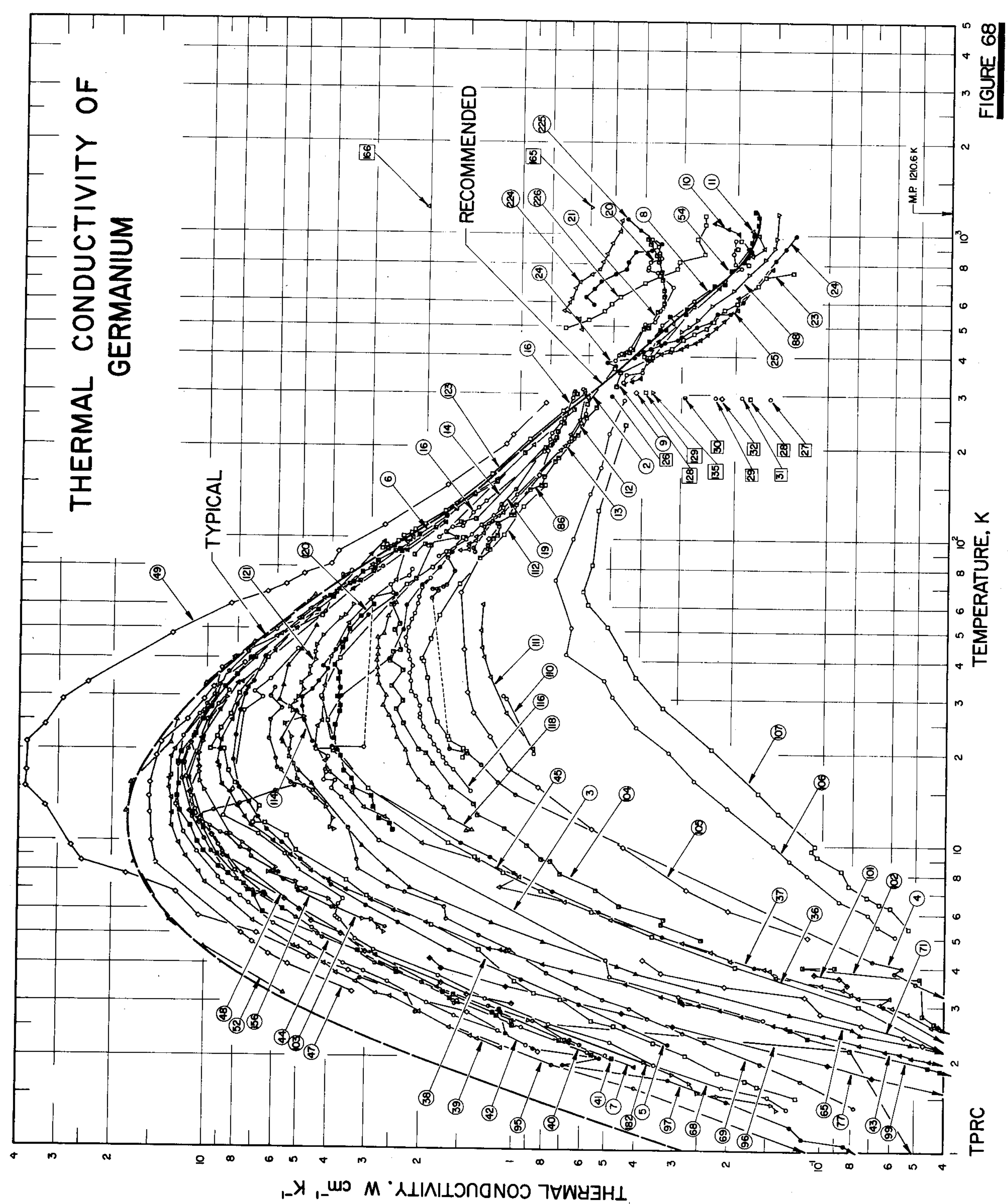
TABLE 61. Recommended thermal conductivity of germanium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1} K^{-1})

Solid

T	*k*	*T*	*k*
0	0	123.2	1.68
1	0.274	150	1.32
2	2.06	173.2	1.13
3	5.35	200	0.968
4	8.77	223.2	0.859
5	11.6	250	0.749
6	13.9	273.2	0.667
7	15.5	298.2	0.602
8	16.6	300	0.599
9	17.3	323.2	0.548
10	17.7	350	0.495
11	17.9	373.2	0.465
12	18.0	400	0.432
13	17.9	473.2	0.359
14	17.7	500	0.338
15	17.3	573.2	0.288
16	16.9	600	0.273
18	15.9	673.2	0.237
20	14.9	700	0.227
25	12.7	773.2	0.204
30	10.8	800	0.198
35	9.20	873.2	0.185
40	7.98	900	0.182
45	6.95	973.2	0.176
50	6.15	1000	0.174
60	4.87	1073.2	0.171
70	3.93	1100	0.170
80	3.25	1173.2	0.172
90	2.70	1200	0.174
100	2.32		

†The values are for well-annealed high-purity germanium, and those below room temperature are merely typical values.


THERMAL CONDUCTIVITY OF GERMANIUM
TYPICAL
RECOMMENDED
M.P. 1210.6 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 68

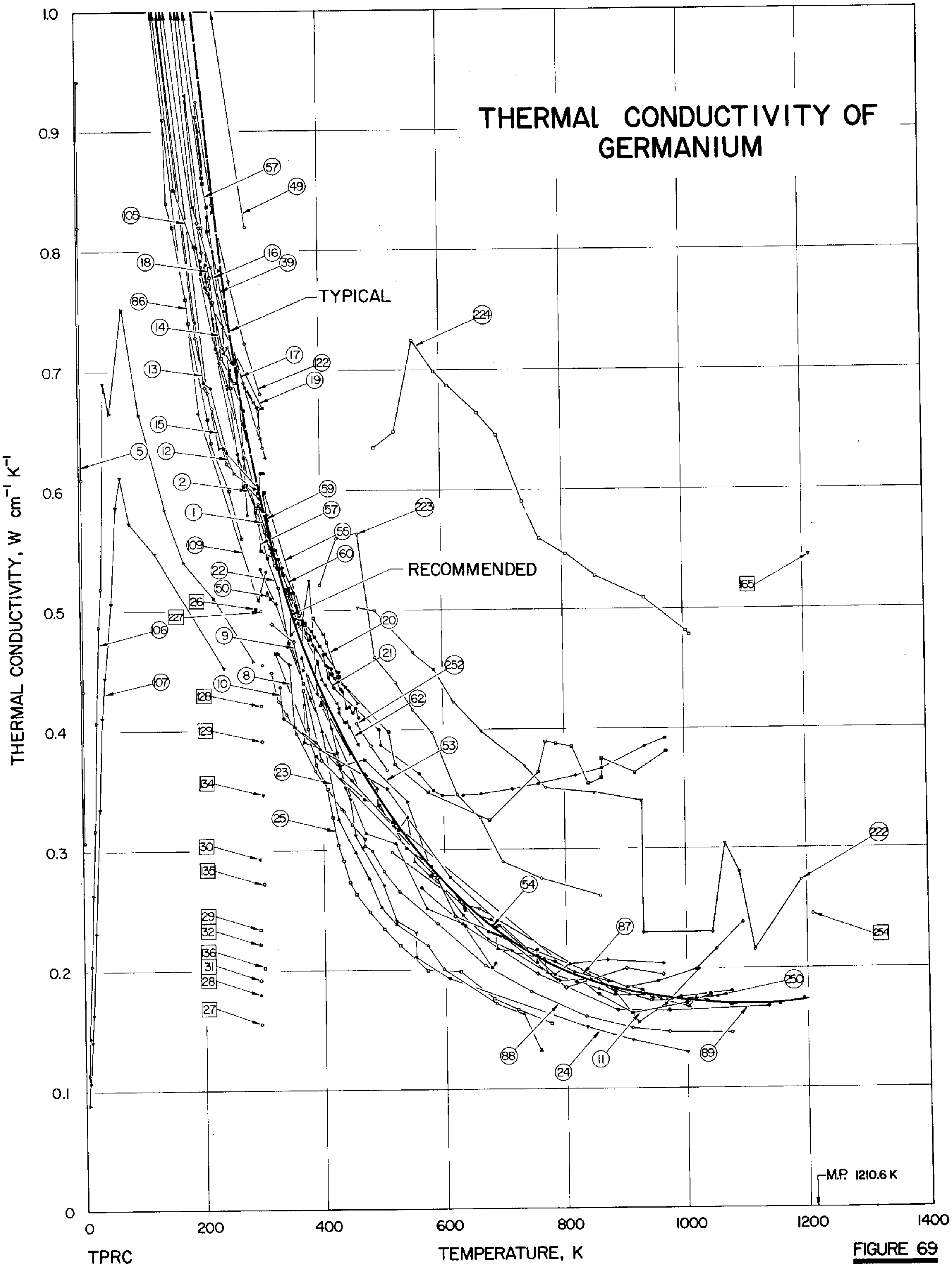

THERMAL CONDUCTIVITY OF GERMANIUM
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TYPICAL
RECOMMENDED
M.P. 1210.6 K
TPRC

FIGURE 69

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	539	Grieco, A. and Montgomery, H. C.	1952	C	298, 373		High-purity; n-type single crystal; 0.313 x 0.313 x 0.75 in.; heat flow parallel to [100] crystal direction; Ni and Zn used as comparative materials.
2	906	McCarthy, K. A. and Ballard, S. S.	1955	C	278-365		High-purity; n-type single crystal; supplied by Westinghouse Research Lab; heat flow parallel to the [100] crystal direction; cast Zn and cast Ni used as comparative materials.
3	1613	Zimmerman, J. E.	1951	L	2.7-79		High-purity; single crystal; 0.25 in. in dia and ~1.5 in. long; prepared by melting in a graphite crucible, solidified slowly by lowering the crucible through the furnace at a rate of 3 in. hr^{-1}; electrical resistivity 0.30 ohm cm at room temp.
4	1613	Zimmerman, J. E.	1951	L	2.7-86		0.0022 Al; single crystal; 0.125 in. in dia and ~1.5 in. long; same preparation method as above; electrical resistivity 0.0021 ohm cm at room temp.
5	1218	Rosenberg, H. M.	1954	L	2.2-95	Ge 1	High-purity; single crystal; 1 cm long and 1.2 x 0.6 mm cross section; electrical resistivity at room temp 60 ohm cm.
6	1544	White, G. K. and Woods, S. B.	1956	L	2.8-137	Ge 3a	High-purity; p-type; polycrystalline.
7	1544	White, G. K. and Woods, S. B.	1956	L	1.9-111	Ge 3b	The above specimen cleaned, annealed at 550 C for 3 hrs in helium, then cooled slowly.
8	11	Abeles, B.	1959	L	330-962	1	n-type single crystal; 0.4 cm^2 in cross-sectional area and 0.3 cm long; electrical resistivity 3 ohm cm at 293 K.
9	11	Abeles, B.	1959	L	319-962	2	Similar to the above specimen except electrical resistivity 0.05 ohm cm at 293 K.
10	11	Abeles, B.	1959	L	331-1094	3	Similar to the above specimen except 0.8 cm long and electrical resistivity 0.03 ohm cm at 293 K.
11	11	Abeles, B.	1959	L	324-1040	4	Similar to the above specimen except 0.3 cm long and electrical resistivity 0.001 ohm cm at 293 K.
12	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	87-293	1	Sb-doped; n-type single crystal; 2.035 x 0.231 x 0.417 cm; electrical resistivity 2.84 ohm cm at room temp.
13	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	91-307	2	Sb-doped; n-type single crystal; 1.800 x 0.228 x 0.294 cm; electrical resistivity 6×10^{-3} ohm cm at room temp.
14	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	88-300	8	Sb-doped; p-type single crystal; thermally converted from the above specimen 2; 1.675 x 0.212 x 0.250 cm; electrical resistivity 1.6 ohm cm at room temp.
15	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	89-311	3	Sb-doped; n-type single crystal; dimensions 1.875 x 0.262 x 0.329 cm; electrical resistivity 40 ohm cm at room temp.
16	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	94-311	4	Ga-doped; p-type single crystal; dimensions 2.000 x 0.336 x 0.285 cm; electrical resistivity 68 ohm cm at room temp.
17	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	96-305	5	Ga-doped; p-type single crystal; dimensions 1.450 x 0.215 x 0.330 cm; electrical resistivity 51 ohm cm at room temp.
18	356	Devyatkova, E. D. and Smirnov, I. A.	1957	L	208-260	6	Ga-doped; p-type single crystal; dimensions 2.205 x 0.295 x 0.503 cm; electrical resistivity 5 ohm cm at room temp.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
19	356	Devyatkova, E.D. and Smirnov, I.A.	1957	L	90–306	7	Ga-doped; p-type single crystal; 2.13 cm long, 0.062 cm^2 cross-sectional area; electrical resistivity 3×10^{-3} ohm cm at room temp.
20	744	Kettel, F.	1959	L	388–971		Single crystal; intrinsic; 18 mm dia x 20 mm long.
21	744	Kettel, F.	1959	L	405–971		p-type; single crystal; 18 mm in dia x 20 mm long; impurity concentration 1.1×10^{18} cm^{-3}.
22	114	Baranskii, P.I. and Konoplyasova, N.S.	1958		76–370		p-type; single crystal; crystallographic orientation [111]; heat treated at 500 C for 32 hrs.
23	1062	Pankove, J.I.	1959	C	368–758		n-type; single crystal; oriented in the [100] direction; 30 mils dia x 100 mils long; measured in He atm; Ni used as comparative material (data from Honda, Simidu, 1917).
24	1062	Pankove, J.I.	1959	C	354–1000		Similar to the above specimen but oriented in the [110] direction.
25	1062	Pankove, J.I.	1959	C	370–775		Similar to the above specimen.
26	4	Abdullaev, G.B., Aliev, G.M., and Chetverikov, N.I.	1958	L	293		Single crystal; impurity concentration 1.4×10^{15} cm^{-3}; approx 15 mm long and 16 mm in dia.
27	4	Abdullaev, G.B., Aliev, G.M., and Chetverikov, N.I.	1958	L	293		Ga-doped p-type single crystal; impurity concentration 7.4×10^{17} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
28	4	Abdullaev, G.B., et al.	1958	L	293		Fe-doped n-type single crystal; impurity concentration 4.1×10^{17} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
29	4	Abdullaev, G.B., et al.	1958	L	293		Ga-doped p-type single crystal; impurity concentration 4.1×10^{16} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
30	4	Abdullaev, G.B., et al.	1958	L	293		Fe-doped n-type single crystal; impurity concentration 2.2×10^{16} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
31	4	Abdullaev, G.B., et al.	1958	L	293		Ga-doped p-type single crystal; impurity concentration 8.8×10^{16} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
32	4	Abdullaev, G.B., et al.	1958	L	293		Fe-doped n-type single crystal; impurity concentration 7.5×10^{16} atom cm^{-3}; approx 15 mm long and 16 mm in dia.
33*	503	Goff, J.F.	1953	L	56–81	A18-4-1	Al-doped p-type single crystal; cut transverse to the axis of crystal growth; electrical resistivity 0.2 ohm cm at room temp.
34*	503	Goff, J.F.	1953	L	65–81	Sb-7	Sb-doped n-type single crystal; specimen parallel to the [110] direction; cut transverse to the axis of crystal growth; electrical resistivity 0.013 ohm cm at room temp.
35*	658	Ioffe, A.V. and Ioffe, A.F.	1954		283		Pure crystal.
36	506	Goff, J.F. and Pearlman, N.	1957	L	2.0–100	Ga-2	Ga-doped p-type single crystal; 3.2 x 3.6 x 25 mm; cut transverse to the crystal growth axis; electrical resistivity 6.9 and 7.84 milliohm cm at 10 K and room temp, respectively.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
37	506	Goff, J.F. and Pearlman, N.	1957	L	2.0-100	Ga-2	The above specimen irradiated in Argonne CP-5 reactor with fast neutrons (total flux 5×10^{17} neutrons cm^{-2}) then kept at room temp for about 5 months; electrical resistivity 6.4 and 7.657 milliohm cm at room temp, respectively.
38	507	Goff, J.F. and Pearlman, N.	1958	L	1.5-120	PN-3E	Ga-Sb-doped p-type single crystal; data derived from the measurement of three specimens.
39	241	Carruthers, J.A., Geballe, T.H., Rosenberg, H.M. and Ziman, J.M.	1957	L	2.2-280	Ge 2	n-type single crystal; specimen cross section 2.53 x 2.68 mm; zone grown; electrical resistivity at room temperature approx 39 ohm cm; heat flow parallel to the [100] direction.
40	241	Carruthers, J.A., et al.	1957	L	2.1-31	Ge 3	In-doped p-type single crystal; carrier concentration 10^{14} cm^{-3}; specimen cross section 2.56 x 2.65 mm; grown by zone melting; electrical resistivity 37 ohm cm at room temp; heat flow parallel to [111] direction.
41	241	Carruthers, J.A., et al.	1957	L	2.0-84	Ge 4	In-doped p-type single crystal; carrier concentration 1.9×10^{14} cm^{-3}; specimen cross section 2.65 x 2.66 mm; grown by zone melting; electrical resistivity ~21 ohm cm at room temp; heat flow parallel to [111] direction.
42	241	Carruthers, J.A., et al.	1957	L	2.2-78	Ge 5	n-type single crystal; carrier concentration 10^{12} cm^{-3}; specimen cross section 2.19 x 2.10 mm; pulled from melt, cut parallel to crystal growth direction; electrical resistivity approx 41 ohm cm at room temp; heat flow parallel to [100] direction.
43	241	Carruthers, J.A., et al.	1957	L	2.0-97	Ge 7	In-doped p-type single crystal; carrier concentration 2.3×10^{16} cm^{-3} cross section 2.70 x 2.69 mm; grown by zone melting; electrical resistivity approx 0.19 ohm cm at room temp; heat flow parallel to the [111] direction.
44	241	Carruthers, J.A., et al.	1957	L	2.2-80	Ge 10	In-doped p-type single crystal; carrier concentration 10^{15} cm^{-3}; specimen cross section 2.56 x 2.60 mm; grown by zone melting; electrical resistivity approx 2.75 ohm cm at room temp; heat flow parallel to the [111] direction.
45	241	Carruthers, J.A., et al.	1957	L	2.0-100	Ge 11	Ga-doped p-type single crystal; carrier concentration 2×10^{18} cm^{-3}; specimen cross section 2.13 x 1.86 mm; pulled from melt, cut parallel to crystal growth direction; electrical resistivity approx 0.009 ohm cm at room temp; heat flow parallel to the [100] direction.
46*	241	Carruther, J.A., et al.	1957	L	2.2-96	Ge 12	Ga-doped p-type single crystal; carrier concentration 10^{19} cm^{-3}; specimen cross section 2.06 x 1.95 mm; pulled from melt, cut parallel to crystal growth direction; electrical resistivity approx 0.0027 ohm cm at room temp; heat flow parallel to the [100] direction.
47	1543	White, G.K. and Woods, S.B.	1955	L	3.3-155	Ge 1	p-type single crystal; specimen 2 x 4 mm cross section, 5 mm long; electrical resistivity 31 ohm cm at 22 C.
48	480	Geballe, T.H. and Hull, G.W.	1958	L	3.0-25	Normal Ge	n-type single crystal.
49	480	Geballe, T.H. and Hull, G.W.	1958	L	2.1-280	Enriched Ge^{74}	Specimen composed of the following isotopes: 95.78 Ge^{74}, 0.728 Ge^{78}, 1.10 Ge^{72}, 1.54 Ge^{73} and 0.840 Ge^{76}; supplied by Union Carbide Nuclear Co.; 1.2×10^{13} excess donor atoms cm^{-3}; 2.54 cm long, 0.13 x 0.157 cm cross section; zone refined, grown using a modified Teal Little crystal puller; heat flow parallel to the [100] direction.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
50	1373	Stuckes, A. D.	1960	C	311-683		n-type; electrical resistivity approx 5 ohm cm (inhomogeneous electrical resistivity, especially high at center); F.H. stainless steel used as the reference (data on F.H. stainless steel from R. W. Powell 1936).
51*	1361	Steele, M.C. and Rosi, F.D.	1958	L	300	T-1007	Sb-doped n-type; polycrystalline; specimen dimensions 5 x 5 x 15 mm; electrical resistivity 10.0 ohm cm at 300 K; measured in a vacuum of approx 10^{-6} mm Hg.
52	1322, 497	Slack, G.A. and Glassbrenner, C.	1960	L	3.2-300		Cu-doped p-type crystal; (approx 10^{14} carriers cm^{-3}); dimensions 0.94 x 0.94 x 3.2 cm; dislocation density 3 x 10^{3} cm^{-3}.
53	1322	Slack, G.A. and Glassbrenner, C.	1960	R	300-1020		Very pure; n-type polycrystalline; crystal size approx 0.2 cm; specimen 1.27 cm in dia 6.1 cm long; zone refined, ground and cut to desired size; electrical resistivity 30 ohm cm at 300 K.
54	496, 497	Glassbrenner, C.J.	1963	R	398-1194		Intrinsic Ge; carrier concentration 2 x 10^{12} cm^{-3}; doped by copper during measurement to give 8 x 10^{15} acceptors cm^{-3}; cylindrical specimen approx 2.6 cm dia x 13 cm long made from single crystal grown by Czochralskii's method from zone refined germanium of the G.E. Co.; specimen aligned in the [100] crystalline direction; electrical resistivity before thermal conductivity measurement 46.6 ohm cm at room temp changed to 4.6 ohm cm after the measurement.
55	13	Abeles, B., Beers, D., Cody, G., Novak, R., and Rosi, F.	1960	P	308-1073		As-doped n-type single crystal; 2 in. long, cross section 0.3 x 0.3 in., heat flow and rod axis parallel to [111] direction; electrical resistivity at room temp 0.3 ohm cm; thermal conductivity values calculated from measured thermal diffusivity data and the specific heat value of 1.83 J cm^{-3} K^{-1} (derived from Dulong-Petit' law).
56*	283	Cohen, A.F.	1957		16		Very pure; single crystal; 14.80 mm^2 cross section; polished.
57	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	112-429	Sample 1	p-type; crystal obtained by Czochralskii method; cross sectional area, 0.53 x 0.32 cm^2; sand blasted; electrical resistivity ρ at room temp 60 ohm cm; data corrected for radiation.
58*	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	83-455	Sample 1A	Similar to the above specimen except cross sectional area 0.45 x 0.25 cm^2, produced from specimen 1 by grinding away a side.
59	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	108-460	Sample 2	Similar to the above specimen except cross sectional area 0.74 x 0.55 cm^2, ρ = 21 ohm cm at room temp.
60	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	109-461	Sample 3	n-type; crystal obtained by Czochralskii method; cross sectional area 0.39 x 0.63 cm^2; sand blasted ρ = 2 ohm cm at room temp.
61*	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	106-451	Sample 4	Ga-doped p-type; obtained from zone melting; cross sectional area 0.72 x 0.87 cm^2, ρ = 0.049 ohm cm at room temp.
62	357	Devyatkova, E.D. and Smirnov, I.A.	1960	L	107-460	Sample 5	Sb-doped n-type; obtained from zone melting; cross sectional area 0.82 x 0.53 cm^2, ρ = 0.043 ohm cm at room temp.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
63*	504	Goff, J.F.	1962	L	1.2-98	Sb 30	Sb-doped single crystal; 12.217 x 3.211 x 1.5055 mm; from ingot grown by the Czochralskii technique with the growth axis in [110] direction; cut transversely to the ingot axis, ground to size with specimen axis approx in [100] direction; carrier concentration n = 2.5 x 10^8 cm^{-3}; electrical resistivity reported as 2.691, 2.70, 2.67, 2.65, 2.6, 2.846, 2.855, 2.870, 2.891, 2.904, 2.919, 3.319, 3.386, 3.413, 3.441, 3.443, and 3.524 milliohm cm at 1.234, 1.664, 2.004, 2.658, 4.128, 14.00, 14.78, 16.11, 17.98, 19.07, 20.22, 55.60, 68.44, 74.14, 84.93, 90.46, and 296 K, respectively.
64*	504	Goff, J.F.	1962	L	1.3-87	Sb 172	Sb-doped single crystal; 15.918 x 3.8221 x 3.7129 mm; same fabrication method as above; specimen axis approx in [111] direction; n = 6.1 x 10^{15} cm^{-3}; electrical resistivity reported as 2.15 x 10^6, 3.20 x 10^4, 3.22 x 10^3, 5.66 x 10^2, 63.22, 21.46, 4.311, 2.277, 2.058, 1.608, 1.115, 0.9610, 0.6570, 0.5448, 0.4587, 0.3685, 0.3099, 0.2300, 0.1557, 0.1075, 0.09557, 0.09040, 0.09343, 0.09512, 0.09708, 0.09931, 0.1052, 0.1252, 0.1812, 0.248, and 0.3988 ohm cm at 4.214, 5.139, 5.947, 6.763, 8.422, 9.690, 12.54, 14.22, 14.64, 15.45, 17.03, 17.82, 20.22, 21.76, 23.39, 26.02, 28.65, 34.06, 39.98, 47.13, 52.74, 62.13, 77.22, 81.32, 82.93, 97.20, 120.2, 166.6, 211.1, and 297.5 K, respectively.
65	504	Goff, J.F.	1962	L	1.3-145	Sb 187	Sb-doped single crystal; 16.422 x 3.8906 x 4.0601 mm; same fabrication method as above; specimen axis approx in [100] direction; n = 1.2 x 10^{17} cm^{-3}; electrical resistivity reported as 182.4, 178.3, 172.8, 168.7, 163.6, 158.8, 155.8, 154.2, 152.8, 153.3, 154.1, 155.2, 151.0, 141.8, 132.4, 113.5, 98.69, 87.6, 79.16, 68.39, 55.54, 43.86, 37.13, 31.25, 24.55, 23.36, 22.51, 20.32, 18.81, 18.51, and 24.4 milliohm cm at 1.314, 1.436, 1.639, 1.835, 2.157, 2.582, 3.042, 3.451, 4.209, 5.881, 6.587, 8.208, 12.16, 14.12, 16.84, 20.23, 23.39, 25.71, 28.32, 31.46, 37.49, 45.16, 51.71, 60.13, 77.24, 82.12, 86.62, 102.6, 126.2, 141.5, and 296.9 K, respectively.
66*	504	Goff, J.F.	1962	L	1.2-98	Sb 207	Sb-doped single crystal; 14.73 x 3.8975 x 3.9068 mm; same fabrication method and specimen axis orientation as above; n = 2.4 x 10^{16} cm^{-3}; electrical resistivity reported as 5.72 x 10^5, 1.63 x 10^5, 7.15 x 10^4, 3.40 x 10^4, 9.072 x 10^3, 1.331 x 10^3, 451, 179.2, 35.9, 12.49, 2.847, 1.331, 0.7778, 0.4811, 0.3191, 0.2570, 0.2143, 0.1702, 0.1400, 0.1049, 0.07895, 0.06426, 0.05369, 0.04743, 0.04187, 0.04091, 0.04066, 0.04180, 0.04372, 0.04692, and 0.09460 ohm cm at 2.140, 2.594, 3.016, 3.467, 4.214, 5.222, 5.935, 6.609, 8.194, 9.563, 12.21, 14.04, 15.84, 17.91, 20.21, 21.78, 23.28, 25.48, 27.72, 32.01, 38.06, 44.33, 52.17, 60.21, 77.36, 84.40, 99.69, 115.1, 128.9, 146.1, and 296.4 K, respectively.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
67*	504	Goff, J.F.	1962	L	1.5-137	Sb 222	Sb-doped single crystal; 18.128 x 4.0751 x 4.0667 mm; same fabrication method and specimen axis orientation as above; n = 1.1 x 10^{18} cm^{-3}; electrical resistivity reported as 4.364, 4.372, 4.385, 4.404, 4.418, 4.430, 4.447, 4.466, 4.496, 4.523, 4.583, 4.642, 4.728, 4.786, 4.849, 4.891, 4.936, 5.020, 5.141, 5.268, 5.373, 5.453, 5.517, 5.479, 5.436, 5.375, 5.262, 5.075, 4.940, and 4.951 milliohm cm at 1.320, 1.579, 1.925, 2.587, 3.032, 3.422, 4.667, 5.624, 6.971, 8.256, 10.87, 13.14, 15.90, 17.97, 20.20, 21.75, 23.34, 26.15, 30.76, 36.27, 42.04, 48.21, 58.11, 77.28, 83.58, 92.17, 105.7, 128.9, 149.7, and 299.8 K, respectively.
68	504	Goff, J.F.	1962	L	1.4-137	As 223 I	As-doped single crystal; 16.682 x 4.0939 x 4.0645 mm; same fabrication method and specimen axis orientation as above; n = 2.1 x 10^{16} cm^{-3}; electrical resistivity reported as 7.8 x 10^{6}, 2.7 x 10^{6}, 1.99 x 10^{3}, 343.1, 28.28, 6.263, 3.467, 1.567, 0.8056, 0.4880, 0.3821, 0.2927, 0.2079, 0.1640, 0.1160, 0.0943, 0.07229, 0.06290, 0.05490, 0.04620, 0.04479, 0.04337, 0.04363, 0.04550, 0.04893, and 0.09847 ohm cm at 4.208, 5.059, 7.378, 8.443, 10.77, 12.95, 13.96, 15.71, 18.04, 20.20, 21.59, 23.25, 25.93, 28.34, 32.92, 36.80, 43.40, 48.46, 55.44, 71.09, 77.17, 91.16, 104.7, 122.3, 142.0, and 293.9 K, respectively.
69	504	Goff, J.F.	1962	L	1.5-125	As 223 II	As-doped single crystal; 15.938 x 3.8803 x 4.0645 mm; same fabrication method and specimen axis orientation as above; n = 6.3 x 10^{16} cm^{-3}; electrical resistivity 0.04178 ohm cm at room temp.
70*	504	Goff, J.F.	1962	L	1.4-134	As 226	As-doped single crystal; 17.482 x 4.0012 x 3.8648 mm; same fabrication method and specimen axis orientation as above; n = 8.8 x 10^{17} cm^{-3}; electrical resistivity reported as 8.570, 8.577, 8.584, 8.592, 8.617, 8.642, 8.691, 8.800, 8.798, 8.764, 8.700, 8.582, 8.625, 8.749, 8.943, 9.120, 9.394, 9.606, 9.730, 9.872, 9.889, 9.730, 9.252, 9.014, 8.675, 8.228, 7.907, 7.590, and 6.568 milliohm cm at 1.346, 1.564, 1.751, 1.946, 2.584, 3.020, 3.507, 4.191, 4.927, 5.394, 5.855, 7.016, 7.996, 10.68, 14.32, 17.81, 23.29, 28.20, 32.11, 38.92, 49.48, 59.49, 77.15, 85.36, 95.98, 111.2, 123.5, 138.4, and 295.5 K, respectively.
71	504	Goff, J.F.	1962	L	1.4-4.2	As 232	As-doped single crystal; 19.812 x 3.8479, 4.034 mm; same fabrication method and specimen axis orientation as above; n = 3.1 x 10^{17} cm^{-3}; electrical resistivity reported as 0.8594, 0.7764, 0.7216, 0.6667, 0.6181, 0.5307, 0.4573, 0.3341, 0.2739, 0.02043, and 0.01467 ohm cm at 1.389, 1.533, 1.635, 1.764, 1.893, 2.205, 2.526, 3.451, 4.198, 77.2, and 296.5 K, respectively.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
72*	504	Goff, J. F.	1962	L	1.3-139	As 233 I	As-doped single crystal; 17.308 x 4.0731 x 3.9978 mm; same fabrication method and specimen axis orientation as above; n = 1.1 x 10^{17} cm^{-3}; electrical resistivity reported as 1.92 x 10^6, 4.60 x 10^5, 1.69 x 10^5, 7.08 x 10^4, 2.238 x 10^4, 2.222 x 10^4, 2.189 x 10^4, 3408, 315.3, 104.2, 44.19, 16.65, 5.344, 2.647, 1.246, 0.7792, 0.4984, 0.3371, 0.2784, 0.2309, 0.1823, 0.1471, 0.1213, 0.08625, 0.06402, 0.05244, 0.04378, 0.03024, 0.02782, 0.02584, 0.02424, 0.02318, 0.02277, and 0.03129 ohm cm at 2.118, 2.598, 3.046, 3.513, 4.204, 4.206, 4.188, 5.132, 6.487, 7.315, 8.088, 9.144, 10.80, 12.18, 14.30, 15.93, 17.90, 20.24, 21.64, 23.12, 25.31, 27.69, 30.22, 35.90, 42.60, 48.56, 55.08, 76.52, 84.12, 94.16, 106.1, 122.9, 141.4, and 295.4 K, respectively.
73*	504	Goff, J. F.	1962	L	1.3-129	As 233 II	As-doped single crystal; 17.053 x 3.9504 x 4.0951 mm; same fabrication method and specimen axis orientation as above; n = 1.7 x 10^{17} cm^{-3}; electrical resistivity reported as 2.83 x 10^4, 1.856 x 10^4, 9742, 2845, 1045, 373.7, 154.4, 36.90, 14.15, 5.802, 1.966, 1.188, 0.8640, 0.5392, 0.3085, 0.2690, 0.2149, 0.1757, 0.1483, 0.1347, 0.1216, 0.1040, 0.09275, 0.06963, 0.05547, 0.04247, 0.03696, 0.03077, 0.02318, 0.02172, 0.02090, 0.01982, 0.01838, 0.01778, 0.01706, 0.01618, and 0.01977 ohm cm at 1.445, 1.578, 1.786, 2.171, 2.526, 2.946, 3.358, 4.202, 5.001, 5.914, 7.468, 8.479, 9.291, 10.84, 13.57, 14.34, 16.14, 18.16, 20.22, 21.61, 23.16, 25.74, 27.78, 33.47, 38.80, 46.49, 51.32, 59.03, 77.25, 82.08, 86.98, 93.10, 103.8, 109.3, 118.6, 132.7, and 297.0 K, respectively.
74*	504	Goff, J. F.	1962	L	1.3-76	SbGa 170	Doped with antimony and gallium; single crystal; 19.413 x 4.2278 x 3.7717 mm; same fabrication method and specimen axis orientation as above; n = 5.4 x 10^{16} cm^{-3}; electrical resistivity reported as 2.13 x 10^3, 1.65 x 10^3, 1.29 x 10^3, 1.03 x 10^3, 891, 685, 421, 346, 191.4, 124.0, 86.78, 56.26, 55.66, 41.60, 34.63, 29.32, 20.81, 15.59, 10.58, 8.182, 6.502, 4.978, 4.420, 4.125, 3.534, 3.095, 2.425, 1.884, 1.599, 1.162, 0.8203, 0.5025, and 0.1304 ohm cm at 1.303, 1.389, 1.486, 1.569, 1.637, 1.756, 2.017, 2.141, 2.589, 3.023, 3.475, 4.210, 4.229, 4.884, 5.358, 5.844, 7.091, 8.538, 11.23, 13.66, 16.44, 20.41, 22.42, 23.64, 26.52, 29.17, 34.26, 39.97, 43.96, 52.48, 63.04, 81.42, and 296.4 K, respectively.
75*	504	Goff, J. F.	1962	L	1.3-148	SbGa 183	Doped with antimony and gallium; single crystal; 15.65 x 3.7364 x 3.6070 mm; same fabrication method and specimen axis orientation as above; n = 1.5 x 10^{17} cm^{-3}; electrical resistivity reported as 25.7, 21.24, 17.78, 14.54, 12.14, 9.619, 6.192, 4.578, 3.638, 2.835, 2.149, 1.750, 1.537, 1.245, 1.038, 0.9525, 0.866, 0.7876, 0.7180, 0.6489, 0.6039, 0.5136, 0.4304, 0.3877, 0.3183, 0.2497, 0.2110, 0.1684, 0.1597, 0.1291, 0.1177, and 0.06187 ohm cm at 1.269, 1.368, 1.487, 1.634, 1.781, 2.022, 2.596, 3.511, 4.206, 5.212, 6.792, 8.398, 9.787, 12.55, 15.94, 17.90, 20.32, 23.16, 26.21, 29.83, 32.83, 39.78, 47.47, 52.55, 62.58, 77.18, 87.21, 108.8, 123.9, 141.9, 161.6, and 296.2 K, respectively.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
76*	504	Goff, J.F.	1962	L	1.4-151	SbGa 204	Doped with antimony and gallium; single crystal; 16.822 x 3.913 x 3.924 mm; same fabrication method and specimen axis orientation as above; n = 2.6 x 10^{16} cm^{-3}; electrical resistivity reported as 1.19 x 10^5, 1.04 x 10^5, 6.82 x 10^4, 2.66 x 10^4, 1.27 x 10^4, 7.33 x 10^3, 3857, 3695, 2229, 1712, 1204, 682.2, 457, 241, 171, 120, 80.00, 70.41, 61.69, 51.53, 40.24, 31.79, 21.69, 15.13, 11.37, 7.597, 4.137, 3.777, 3.374, 2.822, 2.260, 1.853, 1.428, 1.161, 0.9402, and 0.4279 ohm cm at 1.934, 1.986, 2.141, 2.589, 3.062, 3.509, 4.201, 4.254, 4.939, 5.365, 6.039, 7.404, 8.655, 11.51, 13.67, 16.27, 20.24, 21.74, 23.32, 25.60, 28.94, 32.41, 38.52, 45.12, 50.76, 59.74, 77.08, 78.86, 84.13, 90.66, 99.63, 108.7, 122.7, 135.9, 152.1, and 293.8 K, respectively.
77	753	Keyes, R.W. and Sladek, R.J.	1962	L	1.3-4.2	1 N	Sb-doped n-type single crystal; dimensions approx 1 x 2 x 25 mm; specimen axis in [110] direction; lapped and etched; impurity concentration, n = 2 x 16^6 cm^{-3}; electrical resistivity 0.13 ohm cm at 300 K.
78*	753	Keyes, R.W. and Sladek, R.J.	1962	L	1.7-3.9	2 N	Similar to the above specimen except specimen axis in [111] direction and electrical resistivity 0.12 ohm cm at 300 K.
79*	753	Keyes, R.W. and Sladek, R.J.	1962	L	1.7-4.1	3 N	Similar to the above specimen except specimen axis in [100] direction, n = 1 x 10^{16} cm^{-3}, and electrical resistivity 0.20 ohm cm at 300 K.
80*	753	Keyes, R.W. and Sladek, R.J.	1962	L	2.0-4.0	4 N	As-doped single crystal; dimensions approx 1 x 2 x 25 mm; specimen axis in [110] direction; lapped and etched; n = 2 x 10^{16} cm^{-3}, electrical resistivity 0.12 ohm cm at 300 K.
81*	753	Keyes, R.W. and Sladek, R.J.	1962	L	2.1-4.0	5 N	Pure; dimensions approx 1 x 2 x 25 mm; specimen axis in [111] direction; lapped and etched; electrical resistivity 31 ohm cm at 300 K.
82*	753	Keyes, R.W. and Sladek, R.J.	1962	L	2.1-3.9	1 P	p-type; similar to the above specimen except specimen axis in [110] direction and electrical resistivity 47 ohm cm at 300 K.
83*	1423	Toxen, A.M.	1958	L	2.1-87		Pure germanium crystal; size approx 0.125 x 0.125 x 0.625 in.; provided by the Radio Corp. of America.
84*	1030, 1031	Nguyen, V.D., Vandevyver, M., and Pham, N.T.	1963		90-300		Germanium crystal; before neutron bombardment.
85*	1030, 1031	Nguyen, V.D., Vandevyver, M., and Pham, N.T.	1963		90-300		The above specimen after a bombardment of 6 x 10^{17} neutron cm^{-2}.
86	1030, 1031	Nguyen, V.D. et al.	1963		86-270		The above specimen after a bombardment of 1.2 x 10^{18} neutron cm^{-2}.
87	125	Beers, D.S., Cody, G.P., and Abeles, B.	1962	P	300-1075	Ge-1810	As-doped n-type single crystal; carrier concentration 5 x 10^{15} atoms cm^{-3}.
88	125	Beers, D.S., et al.	1962	P	317-1075	Ge-1796	Similar to the above specimen except carrier concentration 3 x 10^{19} atoms cm^{-3}.
89	125	Beers, D.S., et al.	1962	P	562-1136	Ge-5	Ga-doped p-type single crystal; carrier concentration 2.4 x 10^{19} atoms cm^{-3}.
90*	396	Erdmann, J. Schultz, H., and Appel, J.	1957	L	18-94		n-type single crystal; specimen dimensions 1.5 x 1.8 x 15 mm; electron concentration approx 10^{14} cm^{-3}; heat flow parallel to [100] direction.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
91*	1001	Moss, M.	1963	L	1.3–82	CS	Sb-doped single crystal; supplied by Bell Telephone Lab; cut into an "L" shape; dimensions of legs approx 6 mm long, 1.2 x 1.2 mm cross section; one leg connected to heat sink (S leg), another leg connected to heater (H leg); S leg perpendicular to H leg; S leg axis aligned in the $[\bar{1}\bar{1}2]$ direction; measurements made on S leg.
92*	1001	Moss, M.	1963	L	1.3–85	CH	Data from measurements made on H leg of the above specimen.
93*	1001	Moss, M.	1963	L	1.4–84	DS	Similar to the above specimen but with the H leg bent to a circular curvature of radius 3.35 cm; measurements made on the S leg.
94*	1001	Moss, M.	1963	L	1.4–88	DH	Data frommeasurements made on the H leg.
95	240	Carruthers, J.A., Cochran, J.F., and Mendelssohn, K.	1962	L	0.2–3.6	Ge 2	Same specimen as the one for curve 39.
96	240	Carruthers, J.A., et al.	1962	L	0.2–3.2	Ge 3	Same specimen as the one for curve 40.
97	240	Carruthers, J.A., et al.	1962	L	0.3–2.9	Ge 4	Same specimen as the one for curve 41.
98*	240	Carruthers, J.A., et al.	1962	L	0.2–0.7	Ge 5	Same specimen as the one for curve 42.
99	240	Carruthers, J.A., et al.	1962	L	0.3–3.1	Ge 7	Same specimen as the one for curve 43.
100*	240	Carruthers, J.A., et al.	1962	L	0.3–0.8	Ge 10	Same specimen as the one for curve 44.
101	240	Carruthers, J.A., et al.	1962	L	0.2–3.8	Ge 11	Same specimen as the one for curve 45.
102	240	Carruthers, J.A., et al.	1962	L	0.3–4.0	Ge 12	Same specimen as the one for curve 46.
103	1460, 32	Vandevyver, M. and Albany, H.J.	1965	L	5.1–281		Sb-doped n-type single crystal, 2 x 4 x 15 mm; long dimension in the <111> direction; obtained by Czochralskii technique; electrical resistivity 0.10 ohm cm at 300K.
104	1460, 32	Vandevyver, M., Roubeau, P., and Albany, H.J.	1965	L	4.9–268		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux of 1.1×10^{17} n cm^{-2}.
105	1460, 32	Vandevyver, M. and Albany, H.J.	1965	L	5.0–275		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux of 2.5×10^{17} n cm^{-2}.
106	32	Albany, H.J. and Vandevyver, M.	1967	L	5.1–287		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux of 1.7×10^{18} n cm^{-2}.
107	32	Albany, H.J. and Vandevyver, M.	1967	L	5.4–500		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux of 3.4×10^{20} n cm^{-2}.
108*	1491	Vook, F. L.	1965	L	47–136	Ge II	High purity n-type single crystal; obtained from Eagle-Picher Co.; bar shaped, 0.153 cm wide, 0.048 cm thick; 1.0 cm long dimension in the <$\bar{1}$10> direction; irradiated (base temperature near 47 K, tip temperature <70 K) for a length of 1 cm in <111> direction with a total electron flux of 1.01×10^{18} 2-Mev e cm^{-2}; annealed for 15 min at 175 K; electrical resistivity 50 ohm cm, carrier concentration approx 10^{14} cm^{-3}; measured on warming in the dark from 47 K after the electron traps were filled by a white-light illumination at 47 K.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
109	1491	Vook, F. L.	1965	L	18-310	Ge I	High purity n-type single crystal; obtained from Eagle-Picher Co.; bar shaped, 0.159 cm wide, 0.043 cm thick; 1.0 cm long dimension in the $\langle 1\bar{1}0\rangle$ direction; electrical resistivity 50 ohm cm; carrier concentration approx 10^{14} cm^{-3}.
110	1491	Vook, F. L.	1965	L	20-31	Ge I	Same specimen as above; irradiated (base temperature near 20 K, tip temperature <50 K) for a length of 1 cm in $\langle 111\rangle$ direction with a total electron flux of 3.4 x 10^{18} 2-Mev e cm^{-2}; annealed at 30 K for 15 min.
111	1491	Vook, F. L.	1965	L	20-61	Ge I	The above specimen annealed for the second time at 70 K for 15 min.
112	1491	Vook, F. L	1965	L	19-150	Ge I	The above specimen annealed for the third time at 175 K for 15 min.
113*	1491	Vook, F. L.	1965	L	18-65	Ge I	The above specimen annealed for the fourth time at 325 K for 15 min.
114	1491	Vook, F. L.	1965	L	20-290	Ge I	The above specimen annealed for the fifth time at 405 K for 15 min.
115*	1491	Vook, F. L.	1965	L	11-298	Ge II	High purity n-type single crystal; obtained from Eagle-Picher Co.; bar shaped, 0.153 cm wide, 0.048 cm thick; long dimension in the $\langle 1\bar{1}0\rangle$ direction; electrical resistivity 50 ohm cm; carrier concentration approx 10^{14} cm^{-3}.
116	1491	Vook, F. L.	1965	L	11-74	Ge II	Same specimen as above; irradiated (base temp near 47 K, tip temp <70 K) for a length of 1 cm in $\langle 111\rangle$ direction with a total electron flux of 1.01 x 10^{18} 2-Mev e cm^{-2}; annealed at 77 K for 15 min.
117*	1491	Vook, F. L.	1965	L	11-118	Ge II	The above specimen annealed for the second time at 125 K for 15 min.
118	1491	Vook, F. L.	1965	L	11-131	Ge II	The above specimen annealed for the third time at 140 K for 15 min.
119*	1491	Vook, F. L.	1965	L	11-171	Ge II	The above specimen annealed for the fourth time at 175 K for 15 min.
120	1491	Vook, F. L.	1965	L	11-150	Ge II	The above specimen annealed for the fifth time at 200 K for 15 min.
121	1491	Vook, F. L.	1965	L	11-202	Ge II	The above specimen annealed for the sixth time at 230 K for 15 min.
122	1491	Vook, F. L.	1965	L	10-303	Ge II	The above specimen annealed for the seventh time at 405 K for 15 min.
123	30	Albany, H.J. and Vandevyver, M.	1964		92-300	A	Single crystal.
124*	30	Albany, H.J. and Vandevyver, M.	1964		89-301	B	Single crystal; irradiated at 70 C for a fast neutron flux of 6 x 10^{17} n cm^{-2}.
125*	30	Albany, H.J. and Vandevyver, M.	1964		90-271	C	Similar to the above specimen except irradiated at 70 C by a fast neutron flux of 1.2 x 10^{18} n cm^{-2}.
126*	43	Aliev, M.I., Fistul', V.I., and Arasly, D.G.	1964		300		Ga-doped p-type single crystal; carrier concentration 1.29 x 10^{14} cm^{-3}.
127*	43	Aliev, M.I., et al.	1964		300		Ga-doped p-type single crystal; carrier concentration 1.70 x 10^{19} cm^{-3}.
128	43	Aliev, M.I., et al.	1964		300		Ga-doped p-type single crystal; carrier concentration 7.76 x 10^{19} cm^{-3}.
129	43	Aliev, M.I., et al.	1964		300		Ga-doped p-type single crystal; carrier concentration 1.12 x 10^{20} cm^{-3}.
130*	43	Aliev, M.I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 4.07 x 10^{15} cm^{-3}.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
131*	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 4.37×10^{16} cm^{-3}.
132*	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 9.77×10^{16} cm^{-3}.
133*	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 3.24×10^{17} cm^{-3}.
134	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 1.02×10^{19} cm^{-3}.
135	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 1.51×10^{19} cm^{-3}.
136	43	Aliev, M. I., et al.	1964		300		As-doped n-type single crystal; carrier concentration 6.03×10^{19} cm^{-3}.
137*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	110-317	I 1	Sb-doped n-type single crystal; electrical resistivity 0.0205-0.0227 ohm cm at 300 K.
138*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	108-304	I 2	Similar to the above specimen.
139*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	142-308	I 3	Similar to the above specimen.
140*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	121-306	I 4	Ga-doped p-type single crystal; electrical resistivity 0.154-0.155 ohm cm at 300 K.
141*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	98-316	I 5	Similar to the above specimen.
142*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	122-312	I 6	Similar to the above specimen.
143*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	109-307	II 1	Sb-doped n-type single crystal; electrical resistivity 13.9-15.1 ohm cm at 300 K.
144*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	118-302	II 2	Similar to the above specimen.
145*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	114-304	II 3	Ga-doped p-type single crystal; electrical resistivity 25.4-26.0 ohm cm at 300 K.
146*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	131-310	II 4	Similar to the above specimen.
147*	358	Devyatkova, E. D. and Smirnov, I. A.	1962	L	128-306	II 5	Similar to the above specimen.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
148*	656	Ioffe, A. V.	1963	P	290		Density 5.66 g cm^{-3}; melting point 958 C; measured by a transient method.
149*	1374	Stuckes, A. D. and Chasmar, R. P.	1956	C	313.2		Disk specimen; electrical resistivity 4.9 ohm cm at 20 C; Firth Brown FH steel used as comparative material. (Preliminary result.)
150*	395	Erdmann, J.	1958	L	13-82	1	Sb-doped n-type single crystal; 14 x 2.02 x 2.01 mm; specimen axis in [100] direction; carrier concentration 1.4 x 10^{14} cm^{-3}; electrical resistivity 12.4 ohm cm at 300 K.
151*	395	Erdmann, J.	1958	L	15-87	2	Sb-doped n-type single crystal; 14 x 2.10 x 2.09 mm; specimen axis in [100] direction; carrier concentration 7.4 x 10^{14} cm^{-3}; electrical resistivity 2.6 ohm cm at 300 K.
152*	395	Erdmann, J.	1958	L	16-81	4	Sb-doped n-type single crystal; 15 x 2.17 x 2.11 mm; specimen axis in [100] direction; carrier concentration 3.6 x 10^{16} cm^{-3}; electrical resistivity 0.067 ohm cm at 300 K.
153*	395	Erdmann, J.	1958	L	17-100	5	Sb-doped n-type single crystal; 15 x 2.05 x 2.04 mm; specimen axis in [100] direction; carrier concentration 1.0 x 10^{17} cm^{-3}; electrical resistivity 0.02 ohm cm at 300 K.
154*	395	Erdmann, J.	1958	L	15-77	6	Ga-doped p-type single crystal; 15 x 2.00 x 1.95 mm; specimen axis in [100] direction; carrier concentration 1.7 x 10^{14} cm^{-3}; electrical resistivity 18.0 ohm cm at 300 K.
155*	395	Erdmann, J.	1958	L	16-82	7	Ga-doped p-type single crystal; 13 x 2.06 x 2.03 mm; specimen axis in [100] direction; carrier concentration 7.2 x 10^{15} cm^{-3}; electrical resistivity 0.123 ohm cm at 300 K.
156	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.3-66	1	Sb-doped n-type single crystal; specimen 2 x 4 mm^2 in cross section and 15 mm long; obtained by Czochralski technique; specimen axis in [111] direction; electrical resistivity 0.10 ohm cm.
157*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.2-37	2	Similar to the above specimen; irradiated at about 40 C with an electron flux of 1.3 x 10^{17} electrons cm^{-2} at 4 MeV.
158*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.2-37	3	Similar to the above specimen except irradiated with an electron flux of 5.2 x 10^{17} electrons cm^{-2}.
159*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.2-23	4	Similar to the above specimen except irradiated with an electron flux of 1.6 x 10^{18} electrons cm^{-2}.
160*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.1-65		In-doped p-type single crystal; specimen 2 x 4 mm^2 in cross section and 15 mm long; obtained by Czochralski technique; specimen axis in [111] direction; electrical resistivity 1.2 ohm cm.
161*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.5-23		Similar to the above specimen; irradiated at about 40 C with an electron flux of 1.3 x 10^{17} electrons cm^{-2} at 4 MeV.
162*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.3-24		Similar to the above specimen except irradiated with an electron flux of 2.6 x 10^{17} electrons cm^{-2}.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
163*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.5-25		Similar to the above specimen except irradiated with an electron flux of 6.5 x 10^{17} electrons cm^{-2}.
164*	33, 1459	Albany, H. J. and Vandevyver, M.	1967	L	5.0-21		Similar to the above specimen except irradiated with an electron flux of 1.7 x 10^{18} electrons cm^{-2}.
165	974	Mil'vidskii, M. G. and Evemeev, V. V.	1964	→	<1211		Thermal conductivity determination for solid near melting point based on utilization of the equation of heat balance at phase separation boundary; measuring temp assumed 1210.6 K as the melting point taken by TPRC.
166	974	Mil'vidskii, M. G. and Evemeev, V. V.	1964	→	>1211		The above specimen and method used for determination in liquid state.
167*	460	Frederikse, H. P. R.	1953		20-80	B	Sb-doped; n-type single crystal; specimen ~1 x 2.5 mm in cross section; prepared by Roth, L. of physics dept. of Purdue Univ.; ground; electrical resistivity 1.0 ohm cm at room temp.
168*	460	Frederikse, H. P. R.	1953		20-80	C	Similar to the above specimen except electrical resistivity 0.46 ohm cm at room temp.
169*	460	Frederikse, H. P. R.	1953		20-80	D	Similar to the above specimen except electrical resistivity 0.13 ohm cm at room temp.
170*	460	Frederikse, H. P. R.	1953		20-80	F	Similar to the above specimen except electrical resistivity 0.005 ohm cm at room temp.
171*	166	Bird, B. L. and Pearlman, N.	1968	L	0.38-4.1	Ge-422A	n-type; impurity concentration 5.4 x 10^{13} cm^{-3}; 4 x 4 x 24 mm; specimen axis in (100) direction perpendicular to the growth axis of the crystal.
172*	166	Bird, B. L. and Pearlman, N.	1968	L	0.35-3.6	Ge(Sb)-172AI	Sb-doped; n-type; impurity concentration 3.6 x 10^{15} cm^{-3}; 4 x 4 x 25 mm; specimen axis in (100) direction perpendicular to the growth axis of the crystal.
173*	166	Bird, B. L. and Pearlman, N.	1968	L	0.44-0.98	Ge(Sb)-172AI	The above specimen; second run.
174*	166	Bird, B. L. and Pearlman, N.	1968	L	0.37-4.2	Ge(As)-200A	As-doped; n-type; impurity concentration 5.3 x 10^{15} cm^{-3}; 4 x 4 x 25 mm; specimen axis in (100) direction perpendicular to the growth axis of the crystal.
175*	1027	Nguyen, V. D.	1963		94-298		Irradiated by a dose of 1.2 x 10^{18} neutrons cm^{-2}.
176*	1027	Nguyen, V. D.	1963		97-278		The above specimen annealed at 260 C for 2 hrs.
177*	1027	Nguyen, V. D.	1964	L	16-98		n-type; 15 x 3.3 x 3 mm.
178*	1027	Nguyen, V. D.	1964	L	20-93		The above specimen irradiated with 5 x 10^{17} n cm^{-2}.
179*	1246	Sawin, F.	1962	L	12-95	631	Sb-doped; obtained from Geballe, T. H.; form factor 12.3 cm^{-1}; nickel-plated; electrical resistivity 3.6 ohm cm; measured in a vacuum of 5 x 10^{-6} mm Hg.
180*	1246	Sawin, F.	1962	L	6.8-194	732	Similar to above but form factor 24.4 cm^{-1}.
181*	901	Mathur, M. P.	1966	L	2.5-4.0	P-1	P-doped single crystal; 17.65 x 4.1005 x 3.282 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 0.13 x 10^{17} cm^{-3}.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
182	901	Mathur, M. P.	1966	L	1.4-2.6	P-1	The above specimen.
183*	901	Mathur, M. P.	1966	L	1.3-3.9	P-2	P-doped single crystal; 16.44 x 4.891 x 4.528 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 0.263 x 10^{17} cm^{-3}; electrical resistivity 9.9 x 10^{4}, 0.0276, and 0.0608 ohm cm at 4.2, 78, and 300 K, respectively.
184*	901	Mathur, M. P.	1966	L	1.4-3.1	P-3	P-doped single crystal; 14.135 x 3.853 x 3.773 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 0.3 x 10^{17} cm^{-3}.
185*	901	Mathur, M. P.	1966	L	1.4-4.3	P-4	P-doped single crystal; 10.48 x 4.365 x 4.214 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 0.63 x 10^{17} cm^{-3}; electrical resistivity 4.5 x 10^{3}, 0.0207, and 0.0303 ohm cm at 4.2, 78, and 300 K, respectively.
186*	901	Mathur, M. P.	1966	L	1.4-3.9	P-4	Similar to above but specimen length 12.54 mm.
187*	901	Mathur, M. P.	1966	L	1.4-2.9	P-5	P-doped single crystal; 13.72 x 3.759 x 3.641 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.2 x 10^{17} cm^{-3}; electrical resistivity 8.0 x 10^{3}, 0.0387, and 0.0504 ohm cm at 4.2, 78, and 300 K, respectively.
188*	901	Mathur, M. P.	1966	L	2.4-4.5	P-5	The above specimen.
189*	901	Mathur, M. P.	1966	L	1.4-3.7	P-6	P-doped single crystal; 15.91 x 3.911 x 3.850 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.7 x 10^{17} cm^{-3}; electrical resistivity 0.221, 0.0199, and 0.0166 ohm cm at 4.2, 78, and 300 K, respectively.
190*	901	Mathur, M. P.	1966	L	1.4-3.8	P-6	Similar to above but specimen length 16.97 mm.
191*	901	Mathur, M. P.	1966	L	1.3-4.2	P-7	P-doped single crystal; 13.36 x 3.974 x 3.797 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 2.35 x 10^{17} cm^{-3}; electrical resistivity 0.126, 0.0211, and 0.0168 ohm cm at 4.2, 78, and 300 K, respectively.
192*	901	Mathur, M. P.	1966	L	1.3-2.7	P-8	P-doped single crystal; 13.86 x 4.116 x 4.034 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 5.6 x 10^{17} cm^{-3}; electrical resistivity 0.0125, 0.0104, and 0.0729 ohm cm at 4.2, 78, and 300 K, respectively.
193*	901	Mathur, M. P.	1966	L	2.3-4.0	P-8	The above specimen.
194*	901	Mathur, M. P.	1966	L	2.3-3.9	P-9	P-doped single crystal; 14.32 x 4.116 x 3.703 mm; grown in Purdue laboratory with growth axis along the <110> direction; donor concentration 1.1 x 10^{18} cm^{-3}; electrical resistivity 3.71, 4.86, and 3.99 milliohm cm at 4.2, 78, and 300 K, respectively.
195*	901	Mathur, M. P.	1966	L	1.4-3.1	P-9	Similar to above but specimen length 13.16 mm.

*Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
196*	901	Mathur, M.P.	1966	L	1.4-3.8	Bi-1	Bi-doped single crystal; 15.96 x 4.600 x 4.451 mm; grown in Purdue Laboratory with growth axis in the <110> direction; donor concentration 0.14 x 10^{17} cm^{-3}.
197*	901	Mathur, M.P.	1966	L	1.4-3.4	Bi-1	Similar to above.
198*	901	Mathur, M.P.	1966	L	1.5-4.0	PGa-1	Ga- and P-doped; single crystal; 14.21 x 4.418 x 4.167 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 0.465 x 10^{17} cm^{-3}; acceptor concentration 0.348 x 10^{17} cm^{-3}; electrical resistivity 10.9, 5.88, 4.00, 2.67, 1.92, 1.43, and 1.11 x 10^4ohm cm at 2.3450, 2.7188, 2.9929, 3.2752, 3.6220, 3.9230, and 4.2069 K, respectively, and 0.205, 0.178, 0.172, 0.203, 0.246, 0.291, 0.308, and 0.338 ohm cm at 77.4, 90.2, 194.5, 245, 295, 336, 355, and 383 K, respectively.
199*	901	Mathur, M.P.	1966	L	1.4-3.7	PGa-2	Ga- and P-doped; single crystal; 15.71 x 3.603, x 3.492 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.02 x 10^{17} cm^{-3}; acceptor concentration 0.78 x 10^{17} cm^{-3}; electrical resistivity 59500, 30700, 19200, 10200, 4650, 2640, 1850, 1270, 944, 717, 569, 0.146, 0.114, 0.105, 0.0957, 0.1247, 0.1246, 0.141, 0.148, and 1.157 ohm cm at 1.2854, 1.4524, 1.6135, 1.8227, 2.3450, 2.7188, 2.9929, 3.2752, 3.6220, 3.9230, 4.2069, 77.4, 97.5, 114, 155, 295, 296, 330, 330, 347, and 366 K, respectively.
200*	901	Mathur, M.P.	1966	L	1.6-3.0	PGa-2	Similar to above.
201*	901	Mathur, M.P.	1966	L	1.4-4.2	PGa-3	Ga- and P-doped; single crystal; 16.28 x 3.999 x 3.667 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 2.65 x 10^{19} cm^{-3}; acceptor concentration 2.60 x 10^{19} cm^{-3}; electrical resistivity 0.316, 6.99, 1.89, 0.623, 0.605, 0.491, 0.477, 0.453, 0.426, and 0.402 ohm cm at 4.2, 77.2, 157, 289, 295, 333, 340, 358, 380, and 400 K, respectively.
202*	901	Mathur, M.P.	1966	L	1.5-3.5	PGa-3	Similar to above.
203*	901	Mathur, M.P.	1966	L	1.5-3.7	PGa-4	Ga- and P-doped; single crystal; 15.16 x 3.965 x 3.707 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 5.0 x 10^{17} cm^{-3}; acceptor concentration 2.12 x 10^{17} cm^{-3}; electrical resistivity 0.211, 0.207, 0.200, 0.184, 0.184, 0.177, 0.169, 0.161, 0.154, 0.154, 0.146, 0.0189, 0.0171, 0.0128, 0.0135, 0.0150, 0.0180, 0.0176, and 0.0180 ohm cm at 1.2854, 1.4524, 1.6135, 1.8227, 2.3450, 2.7188, 2.9929, 3.2752, 3.6220, 3.9230, 4.2069, 77.4, 90.2, 194.5, 245, 295, 335, 355, and 384 K, respectively.
204*	901	Mathur, M.P.	1966	L	1.4-4.0	PGa-5	Ga- and P-doped; single crystal; 12.29 x 4.098 x 3.925 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 7.5 x 10^{17} cm^{-3}; acceptor concentration 3.2 x 10^{17} cm^{-3}; electrical resistivity 0.0394, 0.0394, 0.0424, 0.0424, 0.0165, 0.0149, 0.0107, 0.0108, 0.0120, 0.0127, 0.0132, and 0.0144 ohm cm at 1.2854, 1.8227, 2.3450, 4.2069, 77.4, 90.2, 194.5, 245, 295, 334, 356, and 383 K, respectively.
205*	901	Mathur, M.P.	1966	L	1.5-3.9	AsGa-1	As- and Ga-doped; single crystal; 14.29 x 4.398 x 4.337 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration ~1 x 10^{17} cm^{-3}; acceptor concentration ~1 x 10^{17} cm^{-3}.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
206*	901	Mathur, M. P.	1966	L	1.4-3.8	AsGa-3	As- and Ga-doped; single crystal; 15.83 x 3.983 x 3.880 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 2.37 x 10^{18} cm^{-3}; acceptor concentration 2.27 x 10^{18} cm^{-3}; electrical resistivity 2680, 1380, 902, 620, 393, 254, 197, 135, 108, 84.6, 68.2, 56.3, 0.637, 0.453, 0.145, 0.118, 0.0953, 0.101, 0.100, and 0.100 ohm cm at 1.2562, 1.4390, 1.6173, 1.7943, 2.0365, 2.3638, 2.5979, 2.9543. 3.2080, 3.5408, 3.8592, 4.1988, 77.4, 90.2, 194.5, 245, 295, 332, 358, and 388 K, respectively.
207*	901	Mathur, M. P.	1966	L	1.4-4.1	AsGa-2	As- and Ga-doped; single crystal; 14.44 x 4.410 x 4.145 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.20 x 10^{19} cm^{-3}; acceptor concentration 1.20 x 10^{19} cm^{-3}; electrical resistivity 223000, 5.12, 3.47, 0.711, 0.549, 0.504, 0.472, 0.468, and 0.459 ohm cm at 4.2, 77.4, 90.2, 194.5, 245, 295, 333, 355, and 382 K, respectively.
208*	901	Mathur, M. P.	1966	L	1.5-3.4	AsGa-2	The above specimen measured after apparatus brought to room temp; data considered by author as not representative.
209*	901	Mathur, M. P.	1966	L	1.4-4.0	AsGa-4	As- and Ga-doped; single crystal; 12.41 x 4.705 x 4.164 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 3.87 x 10^{18} cm^{-3}; acceptor concentration 3.67 x 10^{18} cm^{-3}; electrical resistivity 58.9, 41.8, 31.7, 25.4, 17.1, 11.9, 10.3, 8.57, 7.61, 7.01, 6.34, 6.11, 0.272, 0.232, 0.0943, 0.0760, 0.0668, 0.0637, 0.0626, and 0.0625 ohm cm at 1.2562, 1.4390, 1.6173, 1.7943, 2.0365, 2.3638, 2.5979, 2.9543, 3.2080, 3.5408, 3.8592, 4.1988, 77.4, 90.2, 194.5, 245, 295, 333, 357, and 387 K, respectively.
210*	901	Mathur, M. P.	1966	L	1.5-3.8	AsGa-5	As- and Ga-doped; single crystal; 14.18 x 4.909 x 4.139 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 6.3 x 10^{18} cm^{-3}; acceptor concentration 6.3 x 10^{18} cm^{-3}; electrical resistivity 0.0816, 0.0723, 0.0704, 0.0634, 0.0634, 0.0624, 0.0624, 0.0614, 0.0370, 0.0354, 0.0241, 0.0211, 0.0194, 0.0187, and 0.0190 ohm cm at 1.94, 2.37, 2.79, 3.58, 3.79, 3.96, 4.12, 4.21, 77.2, 90.2, 194.5, 245, 295, 337, and 383 K, respectively.
211*	901	Mathur, M. P.	1966	L	1.4-3.7	SbIn-1'	Sb- and In-doped; single crystal; 14.13 x 4.485 x 4.284 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.61 x 10^{17} cm^{-3}; acceptor concentration 1.30 x 10^{17} cm^{-3}; electrical resistivity 16500, 6600, 4190, 2860, 1760, 1500, 1030, 692, 519, 394, 303, 244, 0.294, 0.231, 0.130, 0.134, 0.146, 0.152, 0.164, and 0.172 ohm cm at 1.2469, 1.4792, 1.6404, 1.8037, 2.0419, 2.3196, 2.5873, 2.9305, 3.2160, 3.5336, 3.8883, 4.2077, 77.2, 90.4, 194.5, 245, 295, 336, 360, and 384 K, respectively.
212*	901	Mathur, M. P.	1966	L	1.4-3.4	SbIn-2'	Sb- and In-doped; single crystal; 13.96 x 4.642 x 4.287 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 2.08 x 10^{17} cm^{-3}; acceptor concentration 1.54 x 10^{17} cm^{-3}; electrical resistivity 333, 177, 128, 98.6, 70.7, 55.3, 43.5, 33.5, 27.7, 23.2, 19.6, 17.1, 0.159, 0.128, 0.0715, 0.0723, 0.0781, 0.0846, 0.0889, and 0.0945 ohm cm at 1.2469, 1.4792, 1.6404, 1.8037, 2.0419, 2.3196, 2.5873, 2.9305, 3.2160, 3.5336, 3.8883, 4.2077, 77.4, 90.2, 194.5, 245, 295, 337, 356, and 385 K, respectively.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
213*	901	Mathur, M. P.	1966	L	1.4-3.6	SbIn-3'	Sb- and In-doped; single crystal; 15.175 x 4.414 x 4.256 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 3.6 x 10^{17} cm^{-3}; acceptor concentration 2.9 x 10^{17} cm^{-3}; electrical resistivity 359, 188, 137, 108, 77.2, 61.5, 48.6, 37.4, 31.1, 26.1, 22.0, 19.2, 0.183, 0.142, 0.0775, 0.768, 0.0816, 0.0864, 0.0907, and 0.0977 ohm cm at 1.2469, 1.4792, 1.6404, 1.8037, 2.0419, 2.3196, 2.5873, 2.9305, 3.2160, 3.5336, 3.8883, 4.2077, 77.2, 90.2, 194.5, 245, 295, 331, 356, and 386 K, respectively.
214*	901	Mathur, M. P.	1966	L	1.4-4.2	SbIn-4'	Sb- and In-doped; single crystal; 14.225 x 4.260 x 4.108 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 1.45 x 10^{19} cm^{-3}; acceptor concentration 1.45 x 10^{19} cm^{-3}; electrical resistivity 8.42, 7.23, 6.63, 6.20, 5.60, 5.12, 4.73, 4.32, 4.04, 3.80, 3.59, 3.44, 0.536, 0.456, 0.234, 0.212, 0.205, 0.209, 0.210, and 0.209 ohm cm at 1.2469, 1.4792, 1.6404, 1.8037, 2.0419, 2.3196, 2.5873, 2.9305, 3.2160, 3.5336, 3.8883, 4.2077, 77.4, 90.4, 194.5, 245, 295, 332, 360, and 381 K, respectively.
215*	901	Mathur, M. P.	1966	L	1.5-4.0	SbGa-4	Sb- and Ga-doped; single crystal; 14.73 x 3.287 x 2.928 mm; grown in Purdue laboratory with growth axis in the <110> direction; donor concentration 2.35 x 10^{18} cm^{-3}; acceptor concentration 1.71 x 10^{18} cm^{-3}; electrical resistivity 0.0172, 0.0162, 0.0112, 0.0107, 0.0104, 0.0112, 0.0114, and 0.0120 ohm cm at 77.4, 90.2, 194.5, 245, 295, 334, 354, and 383 K, respectively.
216*	1029	Nguyen, V. D.	1966	L	18-80		n-type; 12 x 3.3 x 3 mm.
217*	1029	Nguyen, V. D.	1966	L	18-85		The above specimen irradiated by a flux of fast neutron of 5 x 10^{17} n cm^{-2}.
218*	1029	Nguyen, V. D.	1966	L	19-84		The above specimen annealed at 100 C for 80 hrs.
219*	1139	Powell, R. W., Tye, R. P., and Jolliffe, B. W.	1962	C	298.2		Measured by a thermal comparator.
220*	1528	Weill, G.	1962	L	298.2		Small specimen.
221*	1080	Perron, J. C.	1961	P	300		3 cm long; measured by Angström's method.
222	944	Mette, H., Gärtner, W. W., and Loscoe, C.	1959	→	461-1190		p-type; 2 x 0.7 x 0.1 cm; electrical resistivity 30 ohm cm; thermal conductivity values calculated from measured Nernst coefficient and Ettingshausen coefficient using the Bridgman relation.
223	944	Mette, H., et al.	1959	→	398-855		Similar to above but electrical resistivity 4.5 ohm cm.
224	944	Mette, H., et al.	1959	→	490-1111		Similar to above but electrical resistivity 0.46 ohm cm.
225	944	Mette, H., et al.	1959	→	585-1124		Similar to above but electrical resistivity 0.38 ohm cm.
226	944	Mette, H., et al.	1959	→	490-1149		Similar to above but specimen n-type and electrical resistivity 1.9 ohm cm.
227	364	Dismukes, J. P., Ekstrom, L., Steigmeier, E. F., Kudman, I., and Beers, D. S.	1964	L	300		1 cm cubic specimen; carrier concentration ≤2 x 10^{18} cm^{-3}.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
228*	1459	Vandevyver, M.	1968	L	5.9-54		The specimen for curve No. 107 annealed at 100 C for 1 hr.
229*	1459	Vandevyver, M.	1968	L	5.1-103		The above specimen annealed again at 130 C for 1 hr.
230*	1459	Vandevyver, M.	1968	L	5.5-220		The above specimen annealed again at 160 C for 1 hr.
231*	1459	Vandevyver, M.	1968	L	5.2-82		The above specimen annealed again at 190 C for 1 hr.
232*	1459	Vandevyver, M.	1968	L	5.5-91		The above specimen annealed again at 220 C for 1 hr.
233*	1459	Vandevyver, M.	1968	L	6.0-93		The above specimen annealed again at 250 C for 1 hr.
234*	1459	Vandevyver, M.	1968	L	6.0-89		The above specimen annealed again at 280 C for 1 hr.
235*	1459	Vandevyver, M.	1968	L	5.5-87		The above specimen annealed again at 310 C for 1 hr.
236*	1459	Vandevyver, M.	1968	L	5.7-85		The above specimen annealed again at 340 C for 1 hr.
237*	1459	Vandevyver, M.	1968	L	5.0-80		The above specimen annealed again at 370 C for 1 hr.
238*	1459	Vandevyver, M.	1968	L	5.2-84		The above specimen annealed again at 400 C for 1 hr.
239*	1459	Vandevyver, M.	1968	L	5.1-53		The above specimen annealed again at 430 C for 1 hr.
240*	1459	Vandevyver, M.	1968	L	5.6-12		The above specimen annealed again at 460 C for 1 hr.
241*	1459	Vandevyver, M.	1968	L	5.2-29		The above specimen annealed again at 490 C for 1 hr.
242*	1459	Vandevyver, M.	1968	L	5.6-18		Similar to the above specimen with all the heat treatements but without irradiation.
243*	1459	Vandevyver, M.	1968	L	5.2-37		Cut from the same ingot as the specimen for curve No. 103.
244*	1459	Vandevyver, M.	1968	L	5.0-26		The above specimen irradiated by electrons with a dose 1.56×10^{18} e cm^{-2}.
245*	1459	Vandevyver, M.	1968	L	4.9-216		Cut from the same ingot as the specimen for curve No. 103.
246*	1459	Vandevyver, M.	1968	L	5.9-36		The above specimen irradiated by an electron flux of 1.3×10^{17} e cm^{-2}.
247*	1459	Vandevyver, M.	1968	L	4.9-61		Similar to the above specimen but irradiated by an electron flux of 5.2×10^{17} e cm^{-2}.
248*	1459	Vandevyver, M.	1968	L	5.2-30		Similar to the above specimen but irradiated by an electron flux of 1×10^{18} e cm^{-2}.
249*	1459	Vandevyver, M.	1968	L	5.0-24		Similar to the above specimen but irradiated by an electron flux of 1.4×10^{18} e cm^{-2}.
250	917	Meddins. H.R. and Parrott, J.E.	1969	P	290-1051		Polycrystalline; specimen 6 cm x 0.3 cm x 0.6 cm; electrical resistivity reported as 55.0, 1.63, 0.313, 0.139, 0.0738, 0.0492, 0.0331, 0.0277, 0.0242, 0.0132, 0.00863, 0.00348, 0.00238, 0.00218, and 0.00177 ohm cm at 300, 392, 463, 503, 543, 581, 617, 625, 654, 694, 781, 917, 1000, 1031, and 1075 K, respectively; thermal conductivity values calculated from the measurements of thermal diffusivity (measured by Angström method), specific heat and density.
251*	917	Meddins, H.R. and Parrott, J.E.	1969	P	371-1062		Similar to the above.

* Not shown in figure.

TABLE 62. THERMAL CONDUCTIVITY OF GERMANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
252	87	Arasly, D.G. and Aliev, M.I.	1966		114-507		As-doped; carrier concentration 3.58×10^{15} cm^{-3}.
253*	87	Arasly, D.G. and Aliev, M.I.	1966		123-495		As-doped; carrier concentration 5.45×10^{19} cm^{-3}.
254	206	Brice, J.C. and Whiffen, P.A.C.	1964	→	1210.6		Single crystal; thermal conductivity value deduced from measured latent heat and temperature gradients at solid-liquid interface.
255*	206	Brice, J.C. and Whiffen, P.A.C.	1964	→	1210.6		The above specimen in liquid state.

*Not shown in figure.

Gold

Gold is a metal of much theoretical interest, because, due to its low Debye temperature (θ about 170 K), measurements for the solid phase can be made to the relatively high temperature of nearly 8 θ. Determinations have been made recently by Laubitz [818] (curve 45) for thermal conductivity of 7 θ and by Shanks, Burns, and Danielson [1295] (curves 37–40) for thermal diffusivity to 7.4 θ, but for the molten state the estimations by Grosse [546] (curve 50) provide the only information available at present.

At cryogenic temperatures the determinations by Andersen and Nielsen [65] (curve 26) include the maximum and yield the highest values so far obtained. The low-temperature curve for which recommended values are tabulated is based on their data and has the following coefficients: $m = 2.46$, $n = 2.00$, $\alpha'' = 4.6 \times 10^{-5}$, and the parameter $\beta = 0.225$. These recommended conductivity values are applicable only to a sample having $\rho_0 = 0.00550$ $\mu\Omega$ cm. Above about 14 K this curve has been extrapolated to merge with that of White [1536] (curve 7), which it follows to about 80 K.

While at low temperatures a particular set of recommended thermal conductivity values applies only to a sample of a particular purity and perfection, at moderate and high temperatures one set of recommended values can be given for well-annealed high-purity gold. The recommended curve for moderate and high temperatures follows the recent measurements of Cook and Van der Meer [295] (curve 49) from 80 K to room temperature and then follows that of Laubitz [818] (curve 45) to 1200 K, and is extrapolated to the melting point. In the over-lap region around room temperature, Cook and Van der Meer's data agree well with those of Laubitz. In the 1000–1250 K region most of the data derived by Shanks, et al. [1295] (curves 37–40) from thermal diffusivity observations on several samples lie within ± 5 percent of the curve.

No thermal conductivity measurements for molten gold have been published, but Gross [546] (curve 50) has estimated thermal conductivity values from derived values for the electrical conductivity and assuming the theoretical Lorenz number to hold throughout the range from the melting point to the critical point.

The probable uncertainty of the recommended values is about ± 2 percent near room temperature, increasing to ± 5 percent at 1200 K and below 80 K. At temperatures below 80 K the tabulated values are only for gold having $\rho_0 = 0.00550$ $\mu\Omega$ cm. The provisional values for molten gold are probably good to ± 20 percent from melting point to 2000 K.

TABLE 63. Recommended thermal conductivity of gold†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	k	T	k	T	k	T	k
0	0	123.2	3.26	1337.58	1.04*	3600	1.21*
1	5.46	150	3.25	1373.2	1.06*	3673	1.21*
2	10.9	173.2	3.24	1400	1.06*	3800	1.19*
3	16.1	200	3.23	1473.2	1.09*	3873	1.18*
4	20.9	223.2	3.22	1500	1.08*	4000	1.17*
5	25.2	250	3.21	1573.2	1.10*	4073	1.17*
6	28.5	273.2	3.19	1673.2	1.14*	4273	1.14*
7	30.9	298.2	3.18	1700	1.13*	4500	1.11*
8	32.3	300	3.17	1773.2	1.15*	4773	1.06*
9	32.7	323.2	3.16	1800	1.16*	5000	1.02*
10	32.4	350	3.14	1873.2	1.17*	5273	0.974*
11	31.5	373.2	3.13	1900	1.17*	5500	0.933*
12	30.0	400	3.11	1973.2	1.18*	5773	0.884*
13	28.4	473.2	3.06	2000	1.19*	6000	0.839*
14	26.6	500	3.04	2073.2	1.20*	6273	0.781*
15	24.6	573.2	2.99	2173.2	1.21*	6500	0.731*
16	22.7	600	2.98	2200	1.22*	6773	0.761*
18	18.9	673.2	2.93	2273.2	1.22*	7000	0.620*
20	15.8	700	2.91	2400	1.23*	7273	0.557*
25	10.3	773.2	2.86	2473.2	1.24*	7500	0.540*
30	7.55	800	2.84	2600	1.25*	7773	0.439*
35	6.00	873.2	2.79	2673.2	1.25*	8000	0.384*
40	5.15	900	2.77	2800	1.25*	8273	0.316*
45	4.59	973.2	2.72	2873.2	1.25*	8500	0.259*
50	4.21	1000	2.70	3000	1.25*	8773	0.189*
60	3.74	1073.2	2.64	3073	1.24*	9000	0.131*
70	3.48	1100	2.62	3200	1.24*	9273	0.0601*
80	3.32	1173.2	2.57	3273	1.23*		
90	3.28	1200	2.55	3400	1.23*		
100	3.27	1273.2	2.49*	3473	1.22*		
		1300	2.47*				
		1337.58	2.44*				

†The values are for well-annealed high-purity gold, and those below 80 K are applicable only to a specimen having $\rho_0 = 0.00550$ $\mu\Omega$ cm. The values for molten gold are provisional.

*Extrapolated or estimated.

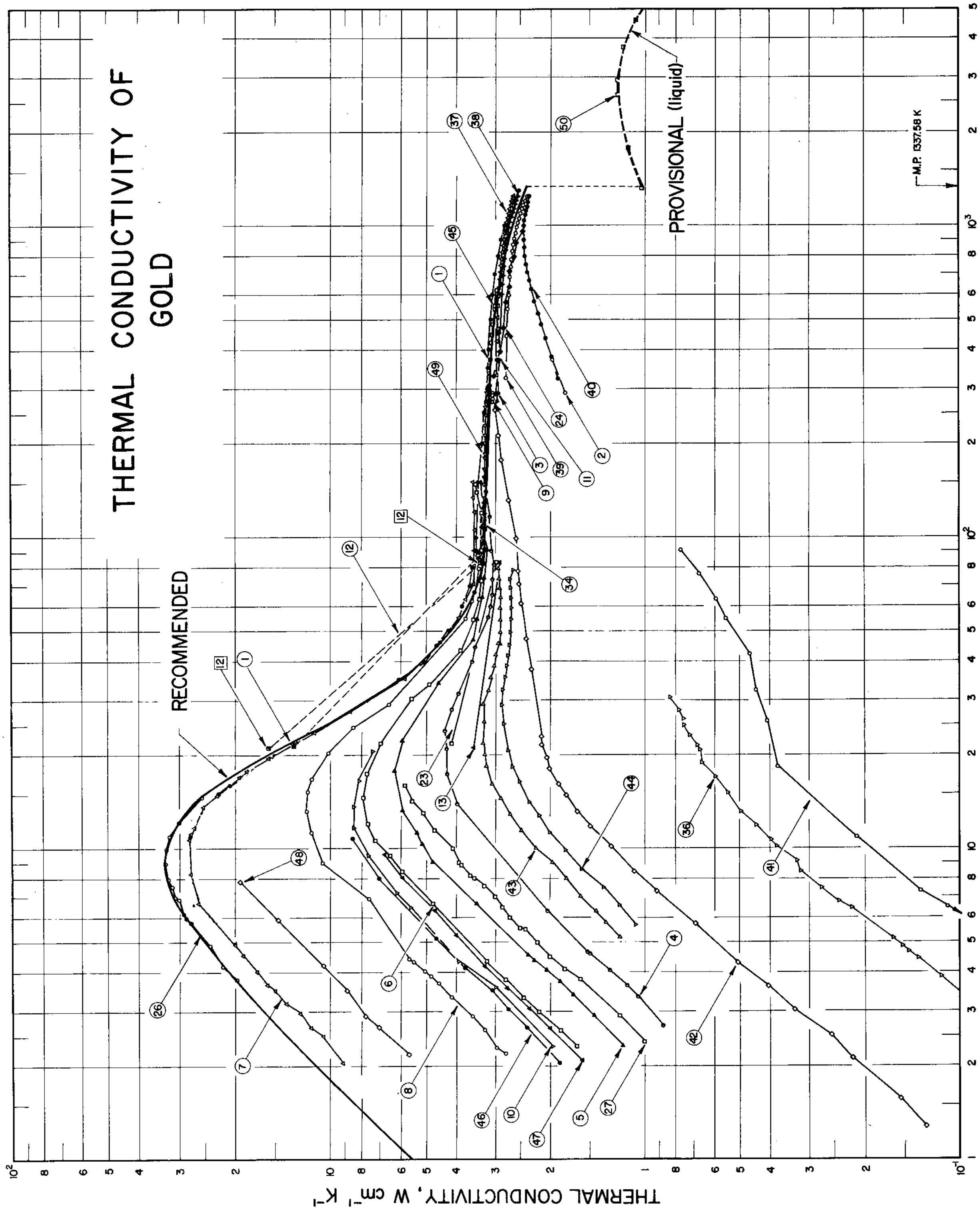

THERMAL CONDUCTIVITY OF GOLD
RECOMMENDED
PROVISIONAL (liquid)
M.P. 1337.58 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 70

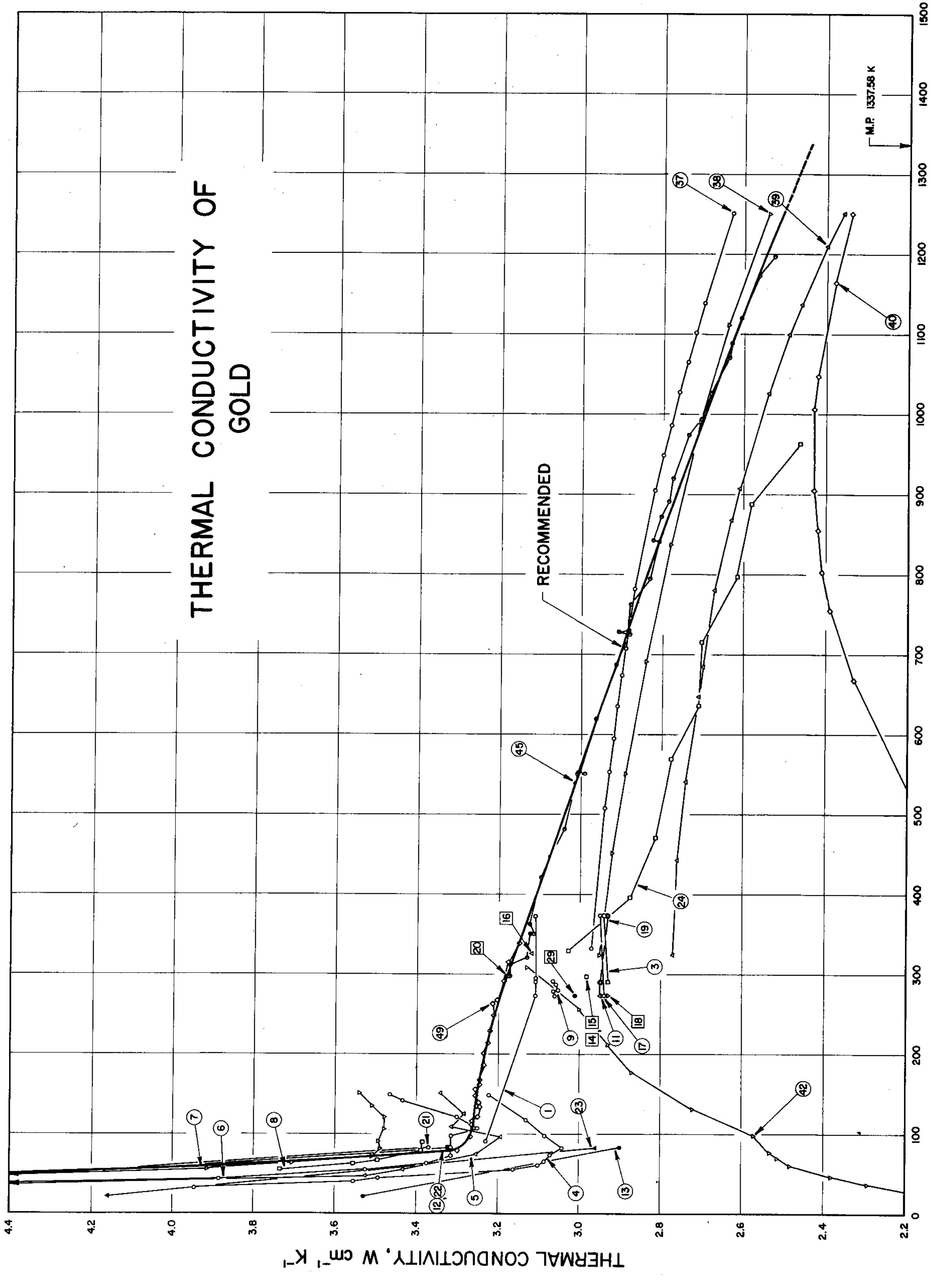

THERMAL CONDUCTIVITY OF
GOLD
RECOMMENDED
M.P. 1337.58 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 71

TABLE 64. THERMAL CONDUCTIVITY OF GOLD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	920	Meissner, W.	1915	E	22-374		99.999 pure; electrical conductivity 7118, 48.4, 45.1, and 34.6 x $10^4 ohm^{-1} cm^{-1}$ at 20.3, 273.1, 291, and 373.1 K, respectively.
2	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373	Au 1	99.8 Au, 0.1 Fe, 0.1 Cu, and trace Ag; 1.2078 cm dia x 27.7 cm long; density 19.22 g cm^{-3} at 18 C; electrical conductivity 24.7 and 21.2 x $10^4 ohm^{-1} cm^{-1}$ at 18 and 100 C, respectively.
3	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373	Au II	High purity; 1.1545 cm dia x 27.7 cm long; density 19.21 g cm^{-3} at 18 C; electrical conductivity 41.3 and 32.1 x $10^4 ohm^{-1} cm^{-1}$ at 18 and 100 C, respectively.
4	1536	White, G.K.	1953	L	2.7-141	Au 1	99.9 pure; major impurity Ag, trace Pt, faint traces of Fe, Cu, and Sn; specimen 2 mm in dia obtained from Garrett, Davidson and Matthey of Sydney.
5	1536	White, G.K.	1953	L	2.3-150	Au 2	The above specimen annealed at 700 C in vacuo and slowly cooled.
6	1536	White, G.K.	1953	L	2.3-148	Au 3	99.999$^+$ pure; spectral analysis showed lines of Ag and Cu and faint lines of Cd, Fe, Mg, and Na, and very faint lines of Ca and Zn; specimen 1.5 mm dia rod; obtained from Garrett, Davidson and Matthey of Sydney.
7	1536	White, G.K.	1953	L	2.1-151	Au 4	The above specimen annealed at 700 C in vacuo for about 3 hrs and slowly cooled to 200 C in 6 hrs.
8	1536	White, G.K.	1953	L	2.2-90	Au 5	The above annealed specimen cold drawn to 1.3 mm dia.
9	702	Kannuluik, W.G.	1931	E	273-292		99.99 pure; specimen 0.07960 cm in dia and 20.12 cm long; electrical conductivity 47.0 x $10^4 ohm^{-1} cm^{-1}$ at 273 K.
10	1937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-21	Au 1	99.999 pure; polycrystalline wire; obtained from Johnson, Matthey and Co., Ltd.; form factor = 497; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 51.8.
11	116	Barratt, T. and Winter, R.M.	1914	L	273-373		Specimen 0.1014 cm in dia; specific gravity 19.49; electrical resistivity 2.268 and 3.075 μohm cm at 273 and 373 K, respectively.
12	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Au 12	High purity; single crystal; unstrained; electrical resistivity 0.0142, 0.488, and 2.04 μohm cm at -252, -190, and 0 C, respectively.
13	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Au II	Commercially pure; cold-worked and annealed; electrical resistivity 0.1174, 0.599, and 2.16 μohm cm at -252, -190, and 0 C, respectively.
14	898	Masumoto, H.	1927	E	297.2	1a	Specimen 4 mm in dia and 20 cm long; made from forged material and machined to shape; electrical resistivity 2.44 μohm cm at 24 C.
15	898	Masumoto, H.	1927	E	297.2	1b	The above specimen measured after being annealed at 600 C for 1 hr; electrical resistivity 2.44 μohm cm at 24 C.
16	525	Gray, J.H.	1894	L	326.2		Specimen 2.0 mm dia.
17	1282	Sedstrom, E.	1919	T	273,373		Rolled and drawn; heated 0.5 hr close to melting point.
18	1282	Sedstrom, E.	1924	T	273.2		Pure; rolled and drawn to a wire, specimen 3 cm long and 1 mm^2 cross section, and then heated close to melting point.
19	117	Barratt, T. and Winter, R.M.	1925	L	290,373		Pure.

TABLE 64. THERMAL CONDUCTIVITY OF GOLD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	1280	Schulze, F.A.	1911	E	298.2		Pure.
21	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Au 14	High purity; single crystal; unstrained; electrical resistivity 0.0160, 0.490 and 2.04 μohm cm at -252, -190, and 0 C, respectively.
22	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Au 13	Originally single crystal, hammered to 2 mm dia; annealed 5.5 hrs at 380 C; electrical resistivity 0.0147, 0.489 and 2.04 μohm cm at -250, -190 and 0 C, respectively.
23	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Au IIa	Commercially pure; remelted and hammered to 2 mm dia; annealed; tempered 3 hrs at 390 C; electrical resistivity 0.0941, 0.575 and 2.14 μohm cm at -250, -190 and 0 C, respectively.
24	964, 966	Mikryukov, V.E.	1957	E	331-964		99.99 pure; polycrystal; electrical resistivity 2.61, 3.31, 4.10, 5.03, 5.78, 6.54, 7.53, 8.55 and 9.72 μohm cm at 57.5, 123.0, 198.3, 296.3, 363.3, 443.3, 524.6, 615.6, and 690.6 C, respectively.
25*	318	Davey, G. and Mendelssohn, K.	1963	L	0.418-0.94		99.99 pure, polycrystalline wire; electrical resistivity measured by Mendelssohn, K. et al. (Bull. Inst. Intern. Froid, Annexe, (2), 49-56, 1965) as 0.716 μohm cm in the range 0.62 to 1.22 K.
26	65	Andersen, H.H. and Nielsen, M.	1964	L	3.8-15	Oxidized	40 μ thick foils rolled from spec-pure Johnson-Matthey material; annealed at 1223 K for 24 hrs in air; electrical resistance ratio $(R_{273} - R_{4.2})/(R_{4.2}) = 610$; electrical resistance 25.369, 25.379, 25.390, 25.408, 25.442, 25.496, and 25.529 μohm cm at 2.29, 2.79, 3.20, 3.61, 4.11, 4.68, and 4.90 K, respectively; $L_0 = (2.46 \pm 0.02) \times 10^{-8}$ watt ohm K^{-2}.
27	65	Andersen, H.H. and Nielsen, M.	1964	L	2.4-16	Vacuum annealed	40 μ thick foils rolled from spec-pure Johnson-Matthey material, annealed at 1223 K for 24 hrs in vacuum (pressure $<10^{-5}$ mm Hg); electrical resistance ratio $(R_{273} - R_{4.2})/(R_{4.2}) = 32.2$; electrical resistance 467.9, 463.8, 461.2, 458.7, 456.9, 455.0, 453.3, 451.9, 450.7, 449.8, 449.0, 448.0, 447.7, and 448.2 μohm cm at 2.32, 2.79, 3.20, 3.62, 4.0, 4.40, 4.90, 5.38, 5.88, 6.33, 6.80, 7.45, 8.03, and 8.68 K, respectively.
28*	939	Mendelssohn, K., Sharma, J.K.N., and Yoshida, I.	1965	L	0.39-0.92		Very pure (higher purity than the specimen used by Davey and Mendelssohn 1963); polycrystalline; electrical resistivity data plotted for the range ~0.6-1.2 K are constant and show no anomaly.
29	216	Brown, H.M.	1927	E	273.2		99.9 pure; specimen 0.125 in. in dia and 10 cm long; obtained from Baker and Co.; electrical resistivity 2.214 μohm cm at 0 C.
30*	1299	Sharma, J.K.N.	1967	L	0.51-0.93		99.999 pure; polycrystalline wire specimen supplied by Johnson, Matthey and Co., Ltd., Lab. No. 34418; form factor $(\ell/a) = 7.89 \times 10^3$ cm^{-1}; electrical resistivity 1.66×10^{-8} ohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 146$; anomalous peak occurred in between 0.35 and 0.50 K; run No. 3.
31*	1299	Sharma, J.K.N.	1967	L	0.56-0.81		The above specimen run number 5.
32*	1299	Sharma, J.K.N.	1967	L	0.39-0.92		The above specimen run number 12.
33*	1299	Sharma, J.K.N.	1967	L	0.42-0.92		The above specimen run number 13.

* Not shown in figure.

TABLE 64. THERMAL CONDUCTIVITY OF GOLD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
34	1467	Van Witzenburg, W. and Laubitz, M. J.	1968	L	80-130		99.9999 pure; 1.6 mm dia wire supplied by Cominco; annealed in a vacuum of 10^{-6} mm Hg at 890 K for 14 hrs; electrical resistivity ratio $\rho(273K)/\rho 4.2K) = 870$; residual electrical resistivity 0.0023 μohm cm; reported thermal conductivity values calculated from the measurements of the two (electrical and thermal) relative magneto resistances and the two normal resistances.
35*	217	Brown, H. M.	1928	E	281.6		10 cm x 0.0779 cm^2; electrical resistivity 2.219 μohm cm at 8.47 C; no changes in thermal conductivity and electrical resistivity observed during the application of magnetic fields of 1000 gauss in longitudinal, and 4000 and 8000 gauss in transverse direction.
36	369	Dreyfus, B., Lacaze, A., Thomas, P., and Weil, L.	1963	L	3.29-31.0		0.10 Co (0.34 at. %); supplied by Johnson, Matthey and Co., Ltd.; prepared by melting the material in hydrogen at 1200 C for 1 hr then drawn into 3 mm dia wire; residual electrical resistivity 1.72 μohm cm.
37	1295	Shanks, H.R., Burns, M.M., and Danielson, G.C.	1968	P	333-1252	Au 1	99.999 pure; specimen 0.35 cm in dia and 30 cm long; supplied by Johnson, Matthey and Co., Ltd.; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 600$; electrical resistivity reported as 2.33, 2.72, 3.04, 3.77, 4.13, 4.55, 5.07, 5.60, 6.24, 6.72, 7.20, 7.77, 8.28, 8.79, 9.34, 10.1, 10.6, 11.3, and 11.7 μohm cm at 302, 349, 395, 476, 521, 562, 625, 684, 746, 796, 845, 902, 946, 995, 1044, 1100, 1145, 1195, and 1222 K, respectively; thermal conductivity values extracted from smooth curve derived from the measured data of thermal diffusivity, specific heat data obtained from Jaeger, F. M., Rosenbohm, E., and Bottema, J. A., (Pro. Acad. Sci., 35, p. 772, 1932, Amsterdam), and density 19.30 g cm^{-3}; Lorenz function reported as 2.24, 2.28, 2.32, 2.34, 2.37, 2.41, 2.43, 2.47, 2.50, and 2.52 x 10^{-8} V^2 K^{-2} at 325, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.
38	1295	Shanks, H.R., et al.	1968	P	325-1252	Au 2	99.99 pure; specimen 0.35 cm in dia and 30 cm long; supplied by Sigmund Cohn; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 310$; electrical resistivity reported as 2.26, 2.70, 3.32, 3.88, 4.74, 5.54, 6.48, 7.64, 9.17, 9.78, and 11.06 μohm cm at 300, 356, 426, 497, 594, 679, 782, 893, 1031, 1081, and 1179 K, respectively; thermal conductivity values extracted from smooth curve derived by the same method as the above specimen; Lorenz function reported as 2.23, 2.26, 2.29, 2.31, 2.33, 2.36, 2.37, 2.40, 2.43, and 2.46 x 10^{-8} V^2 K^{-2} at 325, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.
39	1295	Shanks, H.R., et al.	1968	P	325-1252	Au 3	99.9999 pure; specimen 0.35 cm in dia and 30 cm long; supplied by Aremco; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 110$; electrical resistivity reported as 2.34, 3.05, 3.50, 3.93, 4.23, 4.76, 5.23, 5.75, 6.26, 6.73, 7.18, 7.69, 8.28, 8.88, 9.36, 10.0, 10.7, and 11.4 μohm cm at 296, 385, 433, 482, 521, 578, 630, 679, 729, 780, 831, 881, 929, 979, 1029, 1080, 1130, and 1178 K, respectively; thermal conductivity values extracted from smooth curve derived by the same method as the above specimen; Lorenz function reported as 2.15, 2.21, 2.24, 2.26, 2.29, 2.31, 2.31, 2.33, 2.33, and 2.33 x 10^{-8} V^2 K^{-2} at 323, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.

* Not shown in figure.

TABLE 64. THERMAL CONDUCTIVITY OF GOLD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
40	1295	Shanks, H.R., Burns, M.M., and Danielson, G.C.	1968	P	325-1252	Au 4	Specimen 0.35 cm in dia and 30 cm long; supplied by Mint Gold; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 3$; electrical resistivity reported as 3.72, 4.16, 4.81, 5.61, 6.28, 7.06, 7.81, 8.97, 9.97, 11.1, 12.1, and 12.7 μohm cm at 300, 352, 433, 534, 607, 697, 793, 884, 983, 1080, 1182, and 1229 K, respectively; thermal conductivity values extracted from smooth curve derived by the same method as the above specimen; Lorenz function reported as 2.29, 2.28, 2.31, 2.35, 2.39, 2.43, 2.44, 2.45, 2.46, and 2.45×10^{-8} V^2 K^{-2} at 325, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively.
41	164	Birch, J.A., Kemp, W.R.G., Klemens, P.G., and Tainish, R.J.	1959	L	3.1-91		0.182 Cr; annealed in vacuo at 1050 C for 4 hrs cumulatively.
42	142	Berman, R., Brock, J.C.F., and Huntley, D.J.	1964	L	1.28-309		0.0085 Fe (0.03 at. %); 2.0 mm dia rod; electrical resistivity 0.280, 0.276, 0.273, 0.270, 0.268, 0.266, 0.265, 0.265, 0.266, 0.269, 0.275, 0.285, 0.294, 0.764, and 2.622 μohm cm at 1.22, 2.06, 3.06, 4.34, 5.66, 7.43, 9.02, 10.9, 13.2, 15.8, 18.4, 21.3, 23.9, 79.4, and 300.6 K, respectively.
43	1453	Van Baarle, C. and Huebener, R.P.	1968	L	5.2-78	SA 9	0.109 Pt (0.11 at. %); polycrystalline; 0.010 in. wire specimen; prepared from 99.999 pure Au and 99.999 pure Pt; annealed in air at 750 C for 24 hrs, gradually cooled to room temp.
44	1453	Van Baarle, C. and Huebener, R.P.	1968	L	5.7-78	SA 9	The above specimen quenched from 1000 C to ice-water temp within 0.03 sec; electrical resistivity 0.154 μohm cm at 4.2 K.
45	818	Laubitz, M.J.	1969	L	299-1200		0.0003-0.0005 Fe, ND ~0.0002 Ca, 0.0001-0.0002 Si, >0.0001 Mg, 0.0001 Ag, and <0.0001 Cu; obtained from Cominco; annealed in oxygen at 1100 K for 7 weeks; density 19.28 g cm^{-3} at 20 C; electrical resistivity ratio $\rho(273K)/\rho_0 = 150$; electrical resistivity 2.2716, 3.1080, 3.9656, 4.8535, 5.7804, 6.7553, 7.7161, 8.8845, 10.0565, and 11.3120 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, 1100, and 1200 K, respectively; data obtained from the author in tabular form in a private communication.
46	424	Fenton, E.W.	1962	L	2.1-11	Specimen No. 3	Specimen 3 mm in dia and 8 cm long; obtained from Engelhard Industries (Toronto); annealed; electrical resistivity ratio $\rho_0/\rho(298.2K) = 40$; electrical resistivity reported as 2.81, 2.81, 2.81, 2.81, 2.81, 2.81, 2.84, and 2.90×10^{-2} μohm cm at 2.03, 2.49, 2.97, 3.43, 4.13, 5.31, 7.93, and 10.75 K, respectively; Lorenz function 2.51×10^{-8} V^2 deg^{-2}; measured in a vacuum of $<5 \times 10^{-6}$ mm Hg.
47	424	Fenton, E.W.	1962		2.1-10	Specimen No. 4	Similar to the above specimen except electrical resistivity reported as 3.28, 3.28, 3.28, 3.28, 3.27, 3.29, 3.30, 3.33, and 3.37×10^{-2} μohm cm at 2.04, 2.58, 2.99, 3.50, 4.13, 5.21, 6.24, 7.94, and 9.48 K, respectively; Lorenz function 2.50×10^{-2} V^2 deg^{-2}.
48	424	Fenton, E.W.	1962	L	2.2-7.9	Specimen No. 5	Similar to the above specimen except electrical resistivity reported as 9.50, 9.51, 9.58, 9.63, 9.64, 9.77, and 9.95×10^{-3} μohm cm at 2.00, 2.54, 2.95, 3.45, 4.14, 6.06, and 7.88 K, respectively; Lorenz function $2.47 \pm 0.4 \times 10^{-8}$ V^2 deg^{-2}.

TABLE 64. THERMAL CONDUCTIVITY OF GOLD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
49	295	Cook, J. G. and Van der Meer, M. P.	1970	L	79-339		Specimen taken from the larger sample of Van Witzenburg, W. and Laubitz, M. J. (see curve No. 34); machined to 1 cm in dia and 9.5 cm long; annealed in air at 600 C for 2 hrs; electrical resistivity 0.0222, 0.036, 0.073, 0.141, 0.222, 0.309, 0.396, 0.4824, 0.6521, 0.8185, 0.9809, 1.143, 1.304, 1.464, 1.624, 1.784, 1.946, 2.053, 2.109, 2.271, 2.434, and 2.597 μohm cm at 4, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 273.15, 280, 300, 320, and 340 K, respectively.
50	546	Grosse, A. V.	1964	→	1336-9500		Thermal conductivity values calculated from electrical resistivity using the Wiedemann-Franz-Lorenz law.
51*	1096	Poltz, H.	1970		303-773		99.999 pure; cylindrical specimen 50 mm in diameter and 90 mm long; recrystallized at 220 C; density 19.281 g cm^{-3}.

* Not shown in figure.

Hafnium

No thermal conductivity determinations are known to have been made on high-purity hafnium. White and Woods [1548] (curve 6) measured a sample with up to 1 percent impurity over the range 2.7 to 91 K, Deem [326] (curve 5) measured a sample containing 2 percent of zirconium and small amounts of other impurities from 323 to 823 K, Fieldhouse and Lang [431] (curve 3) measured a sample having 1 percent of zirconium and small amounts of other impurities from 401 to 1878 K, and it is possible to fit all these data with a reasonably smooth curve. The only other determinations of note are those of Timrot, Peletskii, and Voskresenskii [1412] (curve 4) for the range 1301 to 1908 K, which, over their common range lie from 23 to 47 percent above the values of Fieldhouse and Lang. Timrot, et al. do not state the purity of their sample, which had been prepared from iodine hafnium and had a density of 13.06 g cm^{-3}. This low density was attributed to an open structure between the grain boundaries. They remark that this may mean that the conductivity, which is for the direction parallel to the axis of the rod and perpendicular to the growth direction of the crystals, is less than the value for a single crystal or for vacuum-melted hafnium. It is possible that the higher values of Timrot, et al. could result from a high degree of preferred orientation in their sample.

The recommended curve for moderate and high temperatures is the aforementioned curve as drawn through most of the other data, but in view of the positive temperature coefficient and higher values indicated by the measurements of Timrot, et al. it deviates toward these values from about 900 K upward. This curve is of course for a sample of only about 99 percent purity. At low temperatures, a particular curve applies only to a sample of a particular purity and perfection, and the present curve below 150 K is only for a sample having $\rho_0 = 4.23\ \mu\Omega$ cm and ρ (295 K)$/\rho_0 = 8.58$.

No information is available for the molten state.

From room temperature to 900 K the recommended curve probably represents the thermal conductivity of pure hafnium to an accuracy of within about 10 percent. At higher temperatures the uncertainty could be 20 percent. The low-temperature values, which apply only to a particular sample mentioned above, are probably good to within ±10 percent.

TABLE 65. Recommended thermal conductivity of hafnium†

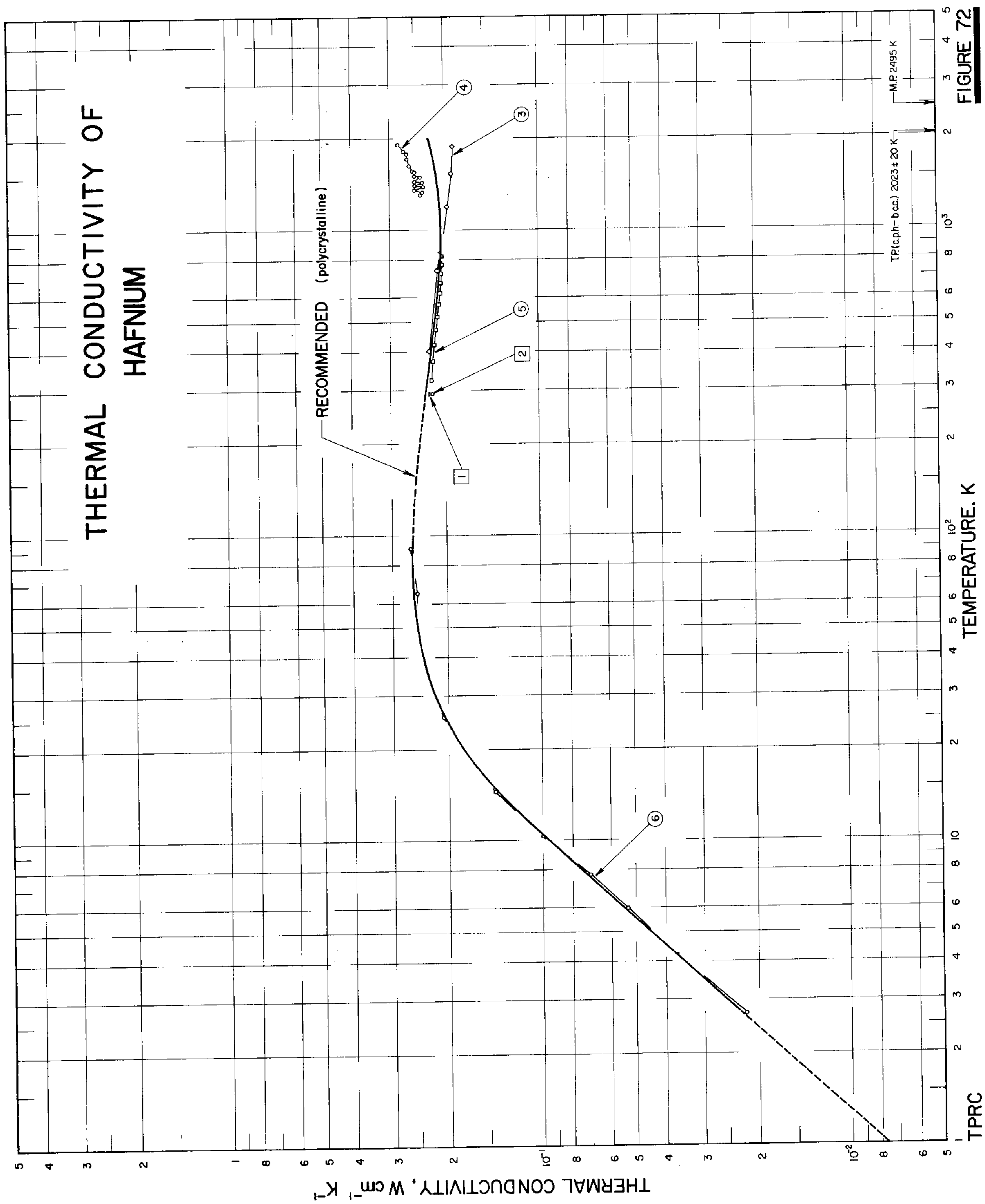
(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1} K^{-1})

Solid
Polycrystalline

T	*k*	*T*	*k*
0	0	350	0.226
1	0.00764*	373.2	0.224
2	0.0163*	400	0.223
3	0.0255	473.2	0.219
4	0.0349	500	0.217
5	0.0445	573.2	0.214
6	0.0544	600	0.213
7	0.0645	673.2	0.211
8	0.0746	700	0.210
9	0.0848	773.2	0.209
10	0.0952	800	0.208
11	0.106	873.2	0.207
12	0.116	900	0.207
13	0.126	973.2	0.207
14	0.135	1000	0.207
15	0.144	1073.2	0.207
16	0.152	1100	0.207
18	0.167	1173.2	0.208
20	0.180	1200	0.208
25	0.205	1273.2	0.209
30	0.222	1300	0.209
35	0.233	1373.2	0.211
40	0.241	1400	0.211
45	0.247	1473.2	0.212
50	0.251	1500	0.213
60	0.256	1573.2	0.215
70	0.259	1600	0.215
80	0.260	1673.2	0.217
90	0.260	1700	0.218
100	0.260*	1773.2	0.220
123.2	0.256*	1800	0.220
150	0.251*	1873.2	0.222
173.2	0.248*	1900	0.223
200	0.244*	1973.2	0.225*
223.2	0.240*	2000	0.226*
250	0.236*		
273.2	0.233*		
298.2	0.230		
300	0.230		
323.2	0.228		

†The recommended values are for well-annealed high-purity hafnium, and those below 150 K are applicable only to a specimen having $\rho_0 = 4.23\ \mu\Omega$ cm, and electrical resistivity ratio $\rho_{(295K)}/\rho_0 = 8.58$.

*Extrapolated or interpolated.



THERMAL CONDUCTIVITY OF HAFNIUM
RECOMMENDED (polycrystalline)
M.P. 2495 K
T.P.(c.p.h.–b.c.c.) 2023 ± 20 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TPRC

FIGURE 72

TABLE 66. THERMAL CONDUCTIVITY OF HAFNIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	667	Jaffee, R.I.	1959		293.2		Density 13.36 g cm^{-3}; electrical resistivity 30 μohm cm at 20 C; data probably not original.
2	234	Campbell, J.E., Goodwin, H.B., Wagner, H.J., Douglass, R.W., and Allen, B.C.	1961		293.2		Hexagonal close packed; density 13.1 g cm^{-3}; electrical resistivity 35.1 μohm cm at ~20 C.
3	431	Fieldhouse, I.B. and Lang, J.I.	1961	R	401-1878		99 Hafnium, 1.0 max Zr, 0.1 max Ti and Si each, 0.01 max Fe, V, and Zn each, 0.001 max Mn, Ni and Cu each, 0.0001 max Mg.
4	1412	Timrot, D.L., Peletskii, V.E., and Voskresenskii, V.Yu.	1966	T	1301-1908	Iodide Hf	12 mm dia x 65 mm long; density 13.06 g cm^{-3}; measured in a vacuum of 5 x 10^{-5} mm Hg.
5	326	Deem, H.W.	1953	C	323-823		~97.96 Hf, 2.0 Zr, 0.008 Pb, 0.007 Al, 0.006 W, 0.005 Fe, 0.004 Cu, < 0.003 Zn, 0.002 each of Si, Ti, and Mo, trace Sn, U, Co, Ni, Mg, Cr, and Mn; specimen 2 cm in dia and 15 cm long; supplied by Westinghouse Atomic Power Division; electrical resistivity 34.1, 40.6, 47.1, 53.6, 60.1 and 66.6 μohm cm at 0, 50, 100, 150, 200 and 250 C, respectively; measured in vacuum of ~1 x 10^{-5} mm Hg; Armco iron used as comparative material.
6	1548	White, G.K. and Woods, S.B.	1957	L	2.7-91	Hf 1	99.5-99 Hf, 0.5-1.0 Zr; specimen 5 x 1.52 mm and ~6 cm long; supplied by Foote Mineral Co.; as received; ρ_0 = 4.23 μ ohm cm; electrical resistivity ratio ρ (295 K)/ρ_0 = 8.58.

Helium

No information is available for the thermal conductivity of saturated vapor. The thermal conductivities of other physical states are discussed separately below.

Solid

At the time of our earlier compilation [608] relatively few studies had been made. The works there considered included those of Agrawal [25] which, for a molar volume of 20.2 cm^3 mol^{-1}, considered ^4He to exist as close-packed hexagonal (cph) and ^3He as body-centered cubic (bcc) structures. For a volume of 19.5 cm^3 mol^{-1}, ^3He was considered cph.The Bertman [150] values were selected as the basis for the recommended values, with note being made that the Mezhov-Deglin [952] values were, in general, larger, this being claimed as due to the influence of crystal purity, container size, etc.

In the present re-examination, various works were consulted [139, 141, 140, 146, 149, 151, 153, 152, 953, 954, 955, 304, 616, 1406, 570, 132, 1290, 543, 1158, 417] which include the results of groups of work by Berman, et al. [139, 141, 140, 146], Bertman, et al. [149, 151, 153, 152], Mezhov-Deglin [953, 954, 955], and others [304, 616, 1406, 570, 132, 1290, 543, 1158, 417]. Most of these works considered ^4He. Those considering ^3He were [141, 149, 153, 304, 1406, 543]. The most detailed publications appear to be the works of [616, 1290] for ^4He and [149, 151] for ^3He.

The impression gained from examining the entire set of newer works [139, 141, 140, 146, 149, 151, 153, 152, 953, 954, 955, 304, 616, 1406, 507, 132, 1290, 543, 1158, 417] is that an order of magnitude variation of thermal conductivity for a given temperature may occur although such variations are more usually of fifty percent or less. Factors producing such changes include the structure of the solid, the crystal orientation (if single crystal material) or the sample size, effect of annealing, Poiseuille flow and, connected with these, the solid density, the pressure imposed during the formation of the solid, and even the rate of formation of the solid. For an indication of the order of magnitude of the thermal conductivity only, the values recommended here are based upon the Bertman 20.2 cm^3 mol^{-1} data [1530, 853]. The reader is referred to any of the sources listed above for further information and especially to the four publications listed as being most detailed. In considering such additional study, the reader should have knowledge of the sample volume of interest, whether the material is single or polycrystal and possibly other information may be needed (depending upon temperature in some cases) before a meaningful value can be obtained for a specific set of conditions.

Saturated Liquid

A number of experimental works have been reported on the thermal conductivity of liquid helium from the standpoint of the interest in low temperature physics. As is well known, a thermodynamic transition in the liquid phase of helium takes place at a temperature near 2.18 K, referred to as the "lambda point." At temperatures above the lambda point, the liquid is called helium-I and below this point it is called helium-II. Helium-I is not particularly remarkable, but helium-II has a number of interesting properties, especially flow and conduction properties, due to the quantum nature of this liquid. However, due to the different mechanism of the heat transport in helium-II from that for other liquids, no evaluation for this state is attempted here.

The thermal conductivity of liquid helium-I was first measured by Keesom and Keesom [728], and it was found that the value is of the same order of magnitude as that of gases at ordinary temperatures. Grenier [536, 535, 537] made measurements in a parallel-plate apparatus within the uncertainty of ten percent, covering the temperature range from 2.2 to 4.2 K, and found that the thermal conductivity of helium-I decreases with decreasing temperature and exhibits a minimum near 2.4 K. He concluded that helium-I behaves more like a gas than a normal liquid. Bowers [187, 188] also measured it in a longitudinal capillary apparatus. Although his measurements were not a precise absolute evaluation of the thermal conductivity, he obtained a linear relation down to the lambda point with considerable scattering. More recently, Fairbank and Lee [418] obtained more accurate values at temperatures from 2.3 to 3.9 K under saturated vapor pressures, using a capillary method. As their results are considered to be the most reliable to date, all their reported points are given equal weight in this analysis and are fitted to a quadratic equation, represented by

$$k(\text{mW cm}^{-1}\,\text{K}^{-1}) = 0.41657 - 0.18365\,T + 0.03744\,T^2.$$

This equation should be valid at temperatures above 2.2 K. The above equation is found to fit the data of Fairbank and Lee with a mean deviation of 1.7 percent and a maximum of 3.7 percent. The recommended values are generated from this equation, and the values should be substantially correct within two percent.

Gas

The original [843, 1420, 608, 844] tables at high temperatures relied largely on the Blais and Mann values [167]. Since their publication, additional measurements have been made. The principal difficulty at the time of preparation of the earlier tables was the difference in trend of the values of Johnston and Grilly [689] and Kannuluik and Carman [705] as opposed to those of Zaitseva [1597]. The former sets were chosen in the earlier work. Subsequent experiments by LeNeindre, et al. [838], Vargaftik and Zimina [1480] and the citation by Petersen [1083] of Haarmans measurements [571], also cited by Kestin [743], tend to show that the previous tables were too low from 260 to 820 K and too high above 870 K. The reconciliation with viscosity data by Kestin [743] also supports this conclusion. The present tables were therefore constructed above 250 K by analysis of the tables of Kestin [743], Petersen [1083] and the Russian [1430] book on helium. From 1000 to 2000 K, the variation with temperature could be expressed by a 2/3rds power of absolute temperature function. The departure plot shows that this is adequate to fit the [743, 1474, 1083, 1430] tabular values, as well as the [1084, 1597, 1448, 1417, 286] data to within five percent in this temperature range. The result of adopting this choice is to increase the deviation of the Blais and Mann [167] data and to reduce the deviation of other [1381, 1303, 387, 652] estimates in this temperature range. The power function was used to generate the recommended values above 1000 K. From 250 to 1000 K the values were based on the [743, 1083, 1430] tables and minor adjustments made to provide smooth mergings into the tables below 250 and above 1000 K.

Values below 250 K are those cited previously [843, 1420, 608, 844] and are based on a curve drawn through both calculated and experimental values. No experimental data were located below 2 K and gaps existed from 4–14 K and 21–73 K. The usual increment of 10 K for the tabulation of recommended values is inadequate for helium at low temperatures and appropriate increments have been chosen in preparing the tables.

Due to the gaps in experimental data below 100 K the recommended values may be uncertain to five percent. From 100 to 700 K the accuracy should be two percent, from 700 to 1500 K five percent, and above 1500 K, ten percent.

TABLE 67. Recommended thermal conductivity of helium

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	$k(^3He)$	$k(^4He)$
0.6	0.250	
0.7	0.104	
0.8	0.055	
0.9	0.033	0.650
1.0	0.020	0.245
1.1	0.0144	0.097
1.2	0.0108	0.045
1.3	0.0089	0.027
1.4	0.0073	0.016
1.5	0.0057	0.0105
1.6	0.0046	0.0069
1.7	0.0038	0.0049
1.8	0.0030	0.0034
1.9	0.0025	0.0025
2.0	0.0021	0.0018

Saturated liquid
(Helium-I)

T	$k \times 10^3$
2.5	0.191
3.0	0.203
3.5	0.232
4.0	0.281
4.5	0.348
5.0	0.434

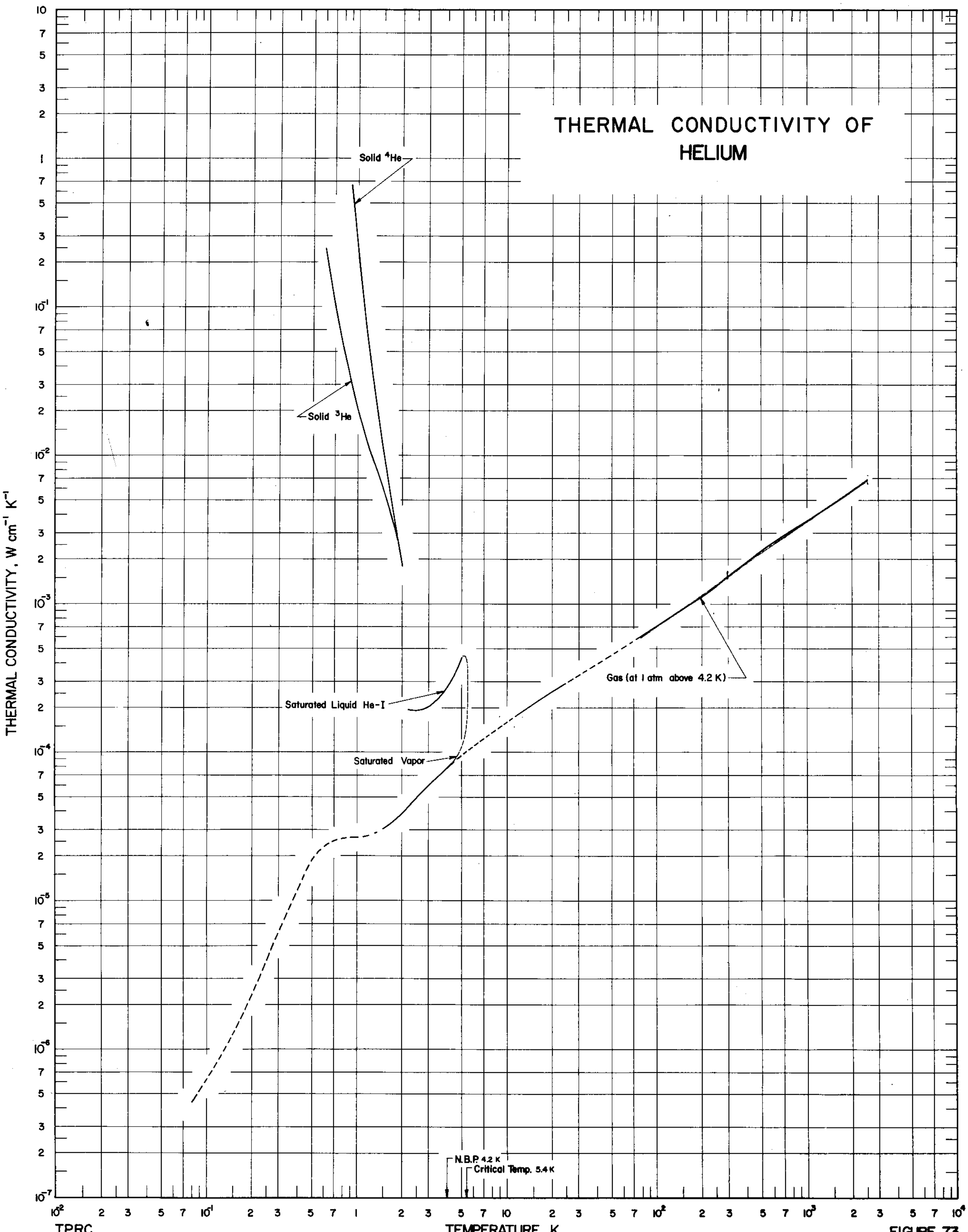
TABLE 67. Recommended thermal conductivity of helium—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas
(At 1 atm above 4.2 K)

T	$k \times 10^3$	T	$k \times 10^3$	T	$k \times 10^3$	T	$k \times 10^3$
0.08	0.00044*	50	0.4623*	450	2.038	850	3.20
0.09	0.00053*	60	0.521*	460	2.071	860	3.23
0.10	0.00064*	70	0.578*	470	2.104	870	3.25
0.15	0.00130*	80	0.631	480	2.136	880	3.28
0.20	0.00231*	90	0.679	490	2.169	890	3.30
0.25	0.0039*	100	0.730	500	2.202	900	3.32
0.30	0.0062*	110	0.776	510	2.234	910	3.35
0.35	0.0089*	120	0.819	520	2.266	920	3.37
0.40	0.0120*	130	0.863	530	2.297	930	3.40
0.45	0.0154*	140	0.907	540	2.329	940	3.43
0.5	0.0187*	150	0.950	550	2.361	950	3.45
0.6	0.0231*	160	0.992	560	2.392	960	3.47
0.7	0.0252*	170	1.033	570	2.423	970	3.50
0.8	0.0262*	180	1.072	580	2.453	980	3.52
0.9	0.0266*	190	1.112	590	2.484	990	3.54
1.0	0.0269*	200	1.151	600	2.515	1000	3.57
1.25	0.0281*	210	1.190	610	2.55	1050	3.69
1.5	0.0306	220	1.228	620	2.58	1100	3.80
2.0	0.0393	230	1.266	630	2.60	1150	3.91
2.5	0.0502	240	1.304	640	2.63	1200	4.03
3.0	0.0607	250	1.338	650	2.66	1250	4.14
3.5	0.0710	260	1.374	660	2.69	1300	4.25
4.0	0.0803	270	1.411	670	2.72	1350	4.36
4.5	0.0879*	280	1.447	680	2.75	1400	4.47
5.0	0.0962*	290	1.484	690	2.78	1450	4.57
6	0.1113*	300	1.520	700	2.81	1500	4.68
7	0.1247*	310	1.555	710	2.83	1550	4.78
8	0.1393*	320	1.591	720	2.86	1600	4.88
9	0.1523*	330	1.626	730	2.89	1650	4.98
10	0.1640*	340	1.662	740	2.91	1700	5.08
12	0.1866*	350	1.697	750	2.94	1750	5.18
14	0.2067*	360	1.732	760	2.97	1800	5.28
16	0.2259	370	1.766	770	3.00	1850	5.38
18	0.2435	380	1.801	780	3.02	1900	5.47
20	0.2582	390	1.835	790	3.05	1950	5.57
25	0.2962*	400	1.870	800	3.08	2000	5.66
30	0.3330*	410	1.904	810	3.10	2100	5.85
35	0.3669*	420	1.937	820	3.13	2200	6.03
40	0.4000*	430	1.971	830	3.15	2300	6.22
45	0.4314*	440	2.004	840	3.18	2400	6.40
						2500	6.57

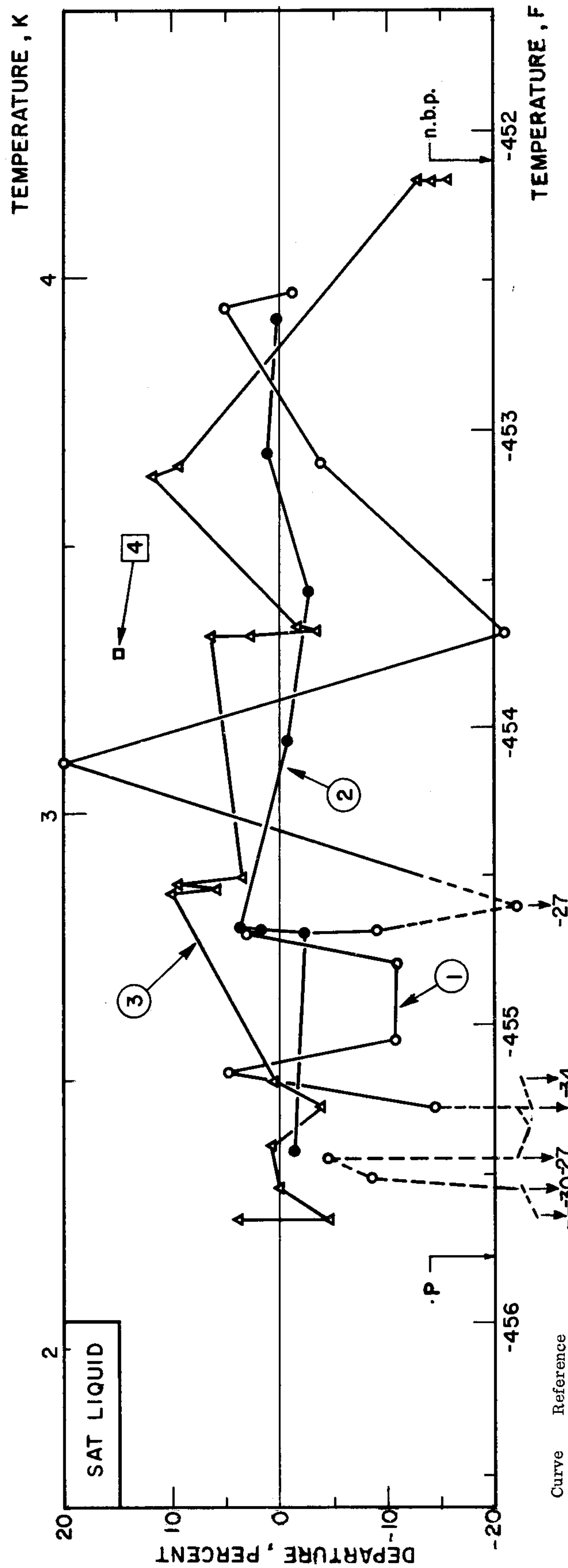
*Extrapolated or estimated.



TPRC

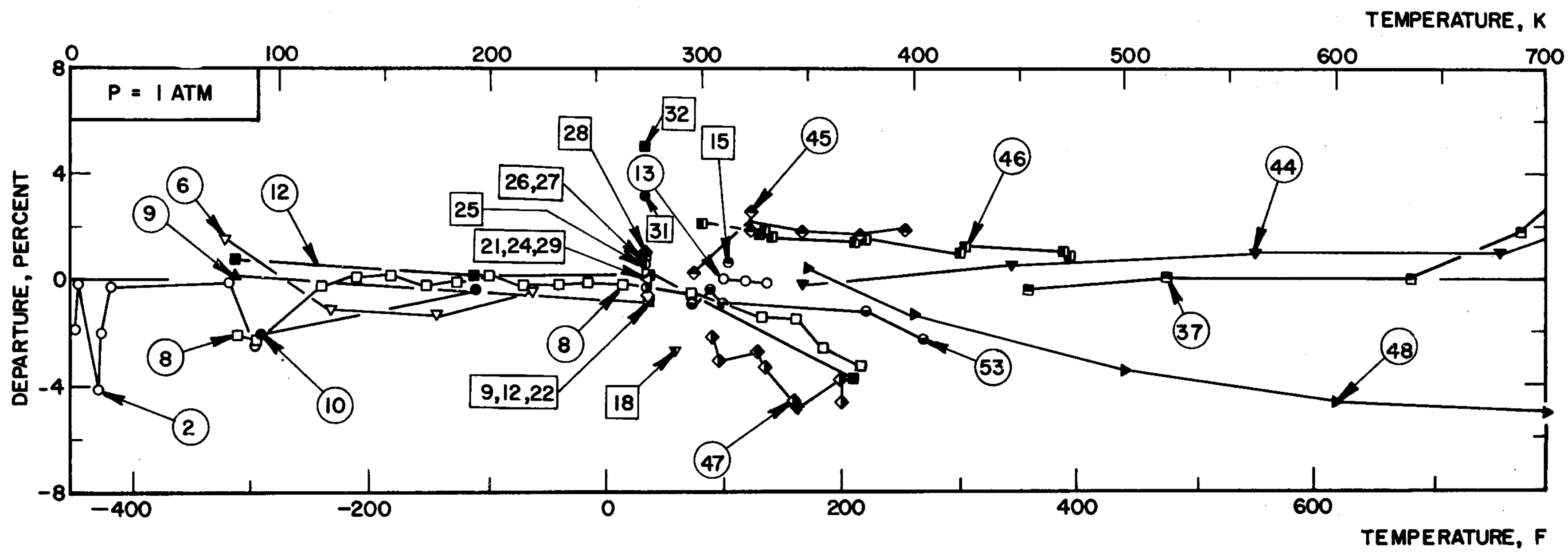
FIGURE 73

FIGURE 74. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID HELIUM



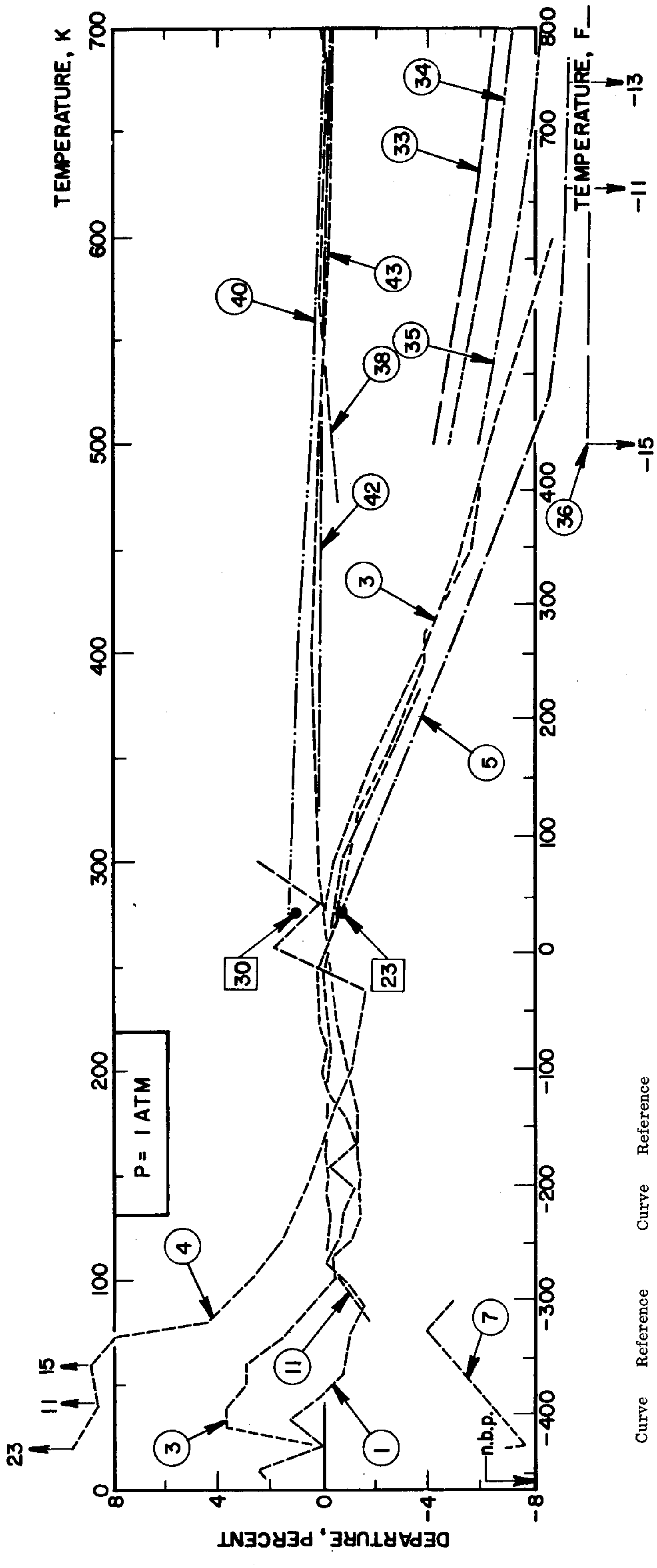
Curve	Reference
1	187
2	418
3	535, 536, 537
4	728

FIGURE 75. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM



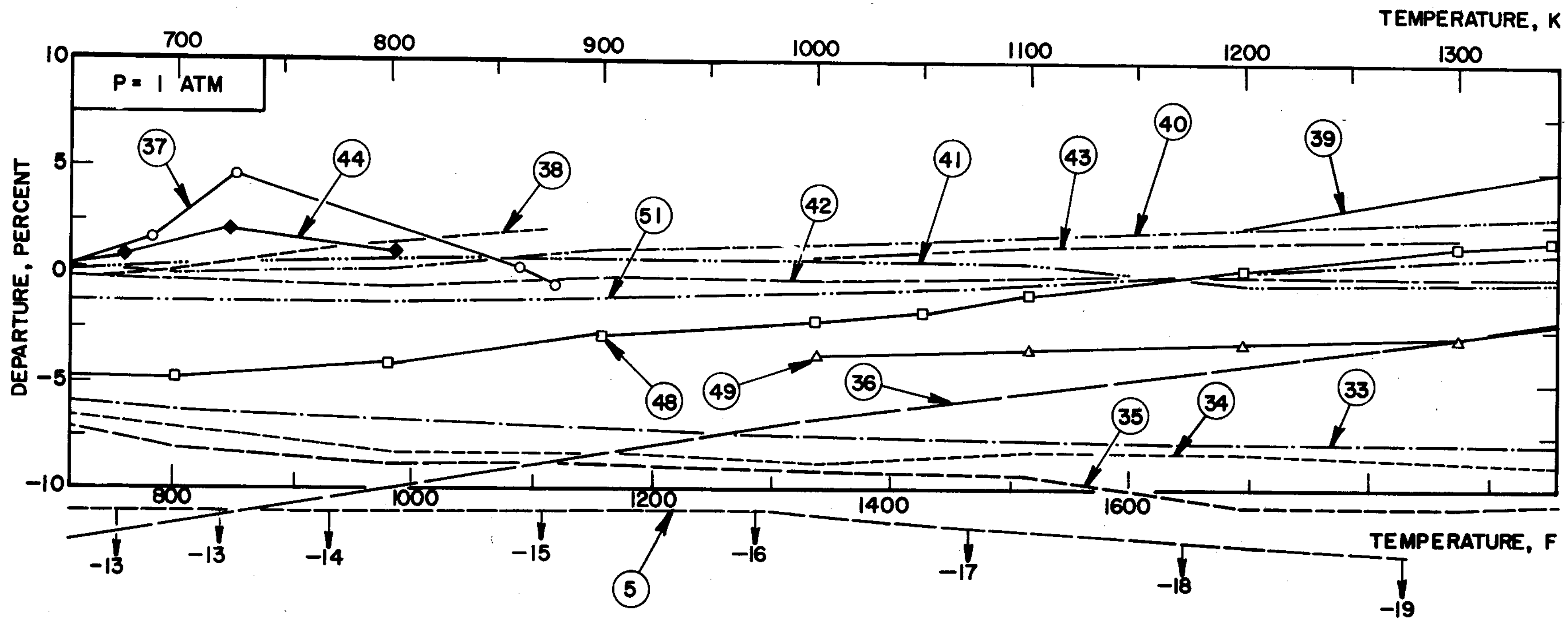
Curve	Reference	Curve	Reference
2	1446	27	401
6	746	28	710
8	689	29	1517
9	402	31	360
10	284	32	276
12	401	37	1084
13	1405	44	1597
15	1249, 1250	45	301a
18	455	46	107a
21	401, 676	47	472
22	305, 306	48	1417
25	72	53	838
26	403		

FIGURE 75. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



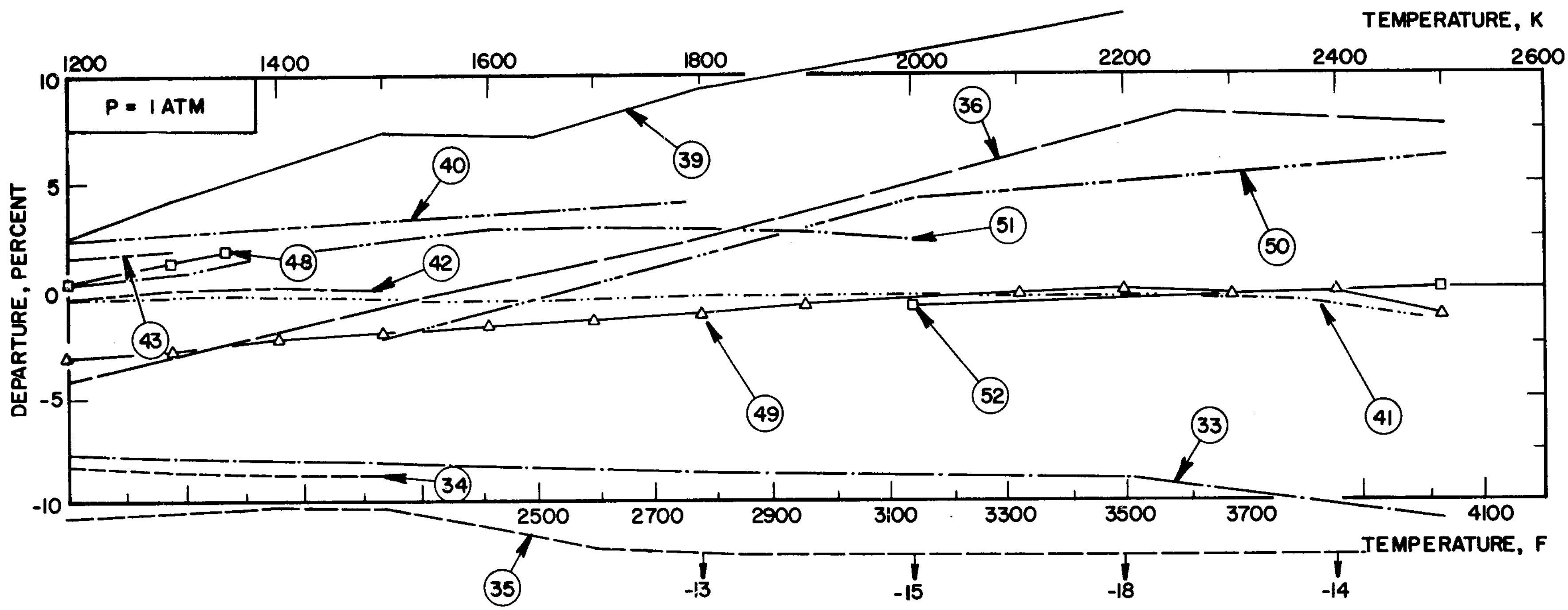
Curve	Reference	Curve	Reference
1	839	35	652
3	605	36	1303
4	264	38	273
7	53	40	1083
11	689	42	743
33	1381	43	371
34	387		

FIGURE 75. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



Curve	Reference	Curve	Reference
5	746	40	1083
33	1381	41	1430
34	387	42	743
35	652	43	371
36	1303	44	1597
37	1084	48	1417
38	273	49	1448
39	167	51	1474

FIGURE 75. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



Curve	Reference	Curve	Reference
33	1381	42	743
34	387	43	371
35	652	48	1417
36	1303	49	1448
39	167	50	55
40	1083	51	1474
41	1430	52	286

Holmium

The situation of the experimental information on the thermal conductivity of holmium has been much improved since the completion of the preliminary report [608]. There were only two sets of data available in 1967: those of Aliev and Volkenshtein [45] (curve 1) for the range 2.0 to 100 K and of Jolliffe, Tye, and Powell [1127] (curve 2) at 291 K, and both are for polycrystalline samples. Ten sets of data are now available, six of which are for single crystals and four for polycrystalline samples. The polycrystalline sample measured by Ratnalingam and Sousa [1183] (curve 8) was apparently the same as that measured by Rao [1171] (curve 9), but their results are very different.

At present, the provisional curves for $k_{\parallel}$ and $k_{\perp}$ of holmium single crystal have been drawn through the data of Nellis and Legvold [1021] (curves 5 and 6) for the two principal directions over the temperature range from 5 to 300 K. These two samples were the purest in the group and were prepared from the same batch. The samples for $k_{\parallel}$ and $k_{\perp}$ have their respective electrical resistivity ratios, $\rho_{300\ K}/\rho_{4.2\ K}$, of 18.9 and 37.8, while the respective electrical resistivities at 4.2 K were 3.21 and 2.67 $\mu\Omega$ cm. It is noted that, while their $k_{\parallel}$ is always greater than $k_{\perp}$ in the full range of their measurement temperatures from 5 to 300 K, their electrical resistivity data for $\rho_{\parallel}$ and $\rho_{\perp}$ cross at about 85 K such that $\rho_{\parallel} < \rho_{\perp}$ above about 85 K and $\rho_{\parallel} > \rho_{\perp}$ below.

The provisional values for polycrystalline holmium from 5 to 300 K were derived from $k_{\parallel}$ and $k_{\perp}$ as the average of those calculated from equations (11) and (12). This curve has been extrapolated from 5 K to 1 K following the slope of the two curves of Ratnalingam and Sousa.

In order to extrapolate the provisional curve for polycrystalline holmium from 300 K to 500 K, the thermal conductivity was regarded as the sum of an electronic component given by $2.443 \times 10^{-8}\ T\ \rho^{-1}$ and a lattice component of 12.45 T^{-1}. The electrical resistivity values given by Meaden [912] were extrapolated from 295 K to 500 K and the resistivity curve was adjusted to pass through the value of 60.7 $\mu\Omega$ cm at 300 K so that the calculated thermal conductivity value at 300 K matched the value derived from $k_{\parallel}$ and $k_{\perp}$. The thermal conductivity values from 300 K to 500 K have thus been obtained.

The provisional values are for well-annealed high-purity holmium and those below 150 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 3.21, 2.82, and 2.67 $\mu\Omega$ cm, respectively. The values are thought to be accurate to within ± 20 percent at temperatures above 150 K. Those below 150 K are very uncertain.

TABLE 68. Provisional thermal conductivity of holmium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid							
	‖ to c-axis	⊥ to c-axis	Poly-crystalline		‖ to c-axis	⊥ to c-axis	Poly-crystalline
T	k	k	k	T	k	k	k
0			0	60	0.182	0.149	0.160
1			0.0140	70	0.176	0.144	0.156
2			0.0282	80	0.170	0.139	0.149
3			0.0428	90	0.163	0.133	0.142
4			0.0580	100	0.158	0.127	0.136
5	0.0803	0.0701	0.0733	123.2	0.159	0.116	0.129
6	0.0962	0.0846	0.0883	132	0.166	0.113	0.128
7	0.109	0.0967	0.101	132	0.169	0.115	0.131
8	0.118	0.105	0.109	150	0.179	0.116	0.135
9	0.124	0.112	0.116	173.2	0.190	0.120	0.140
10	0.130	0.117	0.121	200	0.200	0.126	0.147
11	0.135	0.121	0.125	223.2	0.207	0.130	0.152
12	0.139	0.125	0.129	250	0.212	0.134	0.156
13	0.142	0.128	0.132	273.2	0.215	0.136	0.159
14	0.146	0.131	0.136	298.2	0.222	0.138	0.162
15	0.149	0.134	0.138	300	0.222	0.138	0.162
16	0.152	0.136	0.141	323.2			0.165*
18	0.157	0.140	0.146	350			0.167*
20	0.160	0.140	0.144	373.2			0.170*
25	0.161	0.139	0.146	400			0.173*
30	0.168	0.142	0.150	473.2			0.180*
35	0.173	0.146	0.154	500			0.183*
40	0.177	0.149	0.158				
45	0.180	0.150	0.160				
50	0.182	0.152	0.161				

†The provisional values are for well-annealed high-purity holimum, and those below 150 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_o = 3.21$, 2.82, and 2.67$\mu\Omega$ cm, respectively.

*Extrapolated or esttmated.

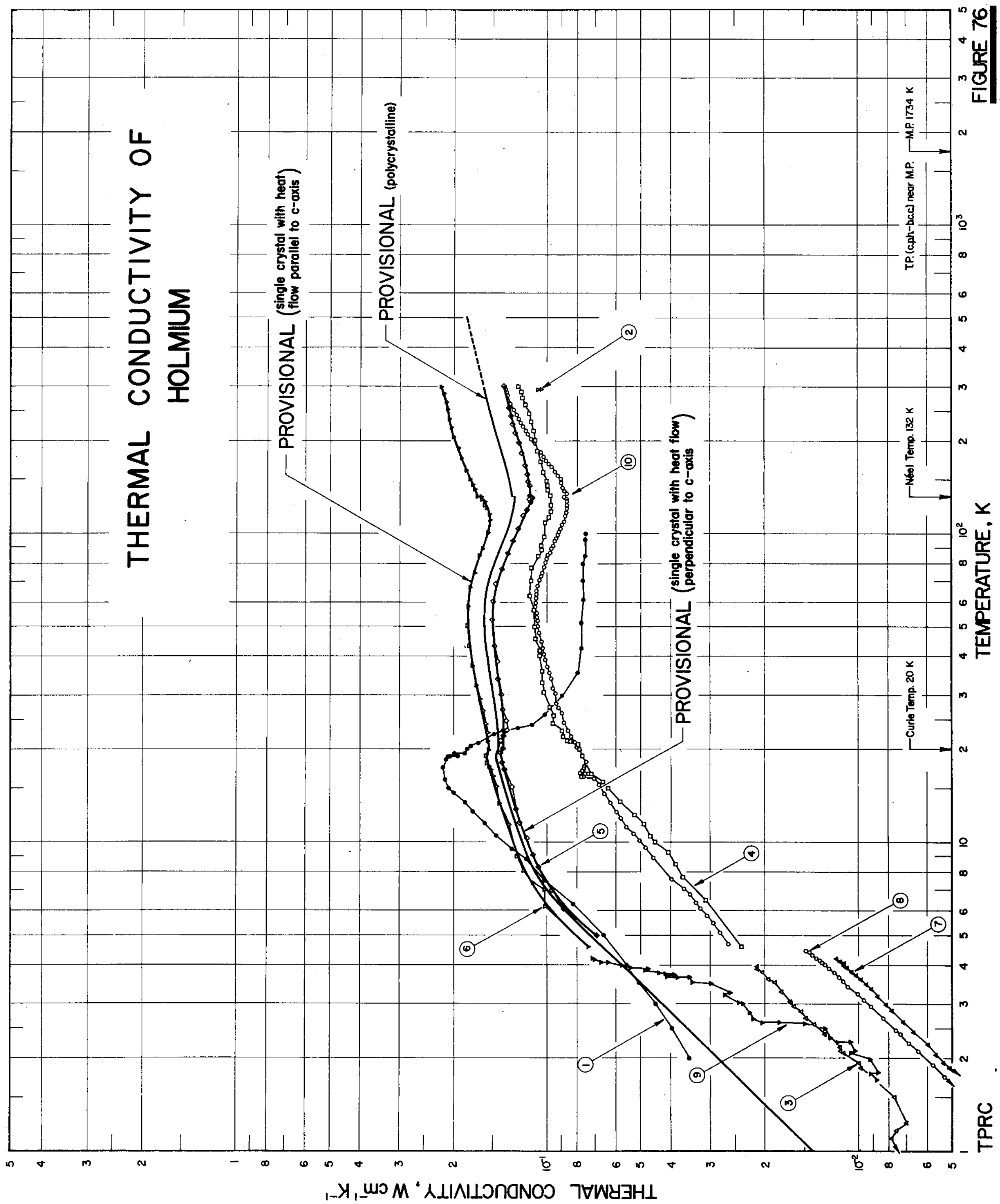

THERMAL CONDUCTIVITY OF
HOLMIUM
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
Curie Temp. 20 K
Néel Temp. 132 K
T.P. (c.p.h.-b.c.c.) near M.P.
M.P. 1734 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 76

TABLE 69. THERMAL CONDUCTIVITY OF HOLMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	45	Aliev, N.G. and Volkenstein, N.V.	1965	L	2.0-100		99.9 pure; polycrystalline; dimensions 3 x 0.2 x 0.025 cm; annealed at 700 C for 3 hrs in vacuum of 10^{-3} mm Hg; electrical resistivity 7.32 μohm cm at 4.2 K; electrical resistivity ratio $\rho(298K)/\rho(4.2K)$ = 10.9; ferromagnetic below 20 K, antiferromagnetic between 20 and 133 K.
2	1127	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1965	C	291		High purity; polycrystalline; 0.25 in. dia, 0.25 in. long; supplied by Johnson, Matthey and Co. Ltd.; electrical resistivity 108 μohm cm at 18 C; thermal conductivity data obtained from two measurements using different thermal comparators; Monel metal used as comparative material.
3	1172	Rao, K.V.	1969	L	0.88-4.0		Single crystal; specimen 4.66 mm in dia and 4.6 cm long; obtained from Metals Research Limited, Cambridge; grown by zone-passing technique in argon atm; residual electrical resistivity ρ_0 = 5.2 μohm cm; electrical resistivity ratio $\rho(298K)/\rho_0$ = 16.6; Lorenz function 2.9 x 10^{-8} V^2 K^{-2} at 4.2 K; heat flow almost along the c-axis.
4	1021	Nellis, W.J. and Legvold, S.	1969	L	4.6-299	Specimen a-axis I	Production batch analysis: <0.0200 Dy, <0.0060 Ni, 0.0048 O_2, and <0.0040 Fe; single crystal; specimen 2 x 2 x 6-20 mm; grown by the strain-anneal technique, mechanically polished, etched, and electropolished; residual electrical resistivity 15.24 μohm cm at 4.2 K; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 7.1; heat flow along the <11$\bar{2}$0> direction (a-axis) of the hexagonal close-packed crystal structure.
5	1021	Nellis, W.J. and Legvold, S.	1969	L	5.0-299	Specimen a-axis II	Similar specimen to above but purer; prepared from another ingot of same production batch; residual electrical resistivity 2.67 μohm cm at 4.2 K; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 37.8; electrical resistivity reported as 2.4, 2.9, 3.7, 5.0, 6.7, 9.0, 12.1, 18.4, 27.2, 36.6, 50.0, 60.0, 64.2, 67.3, 68.9, 70.0, 72.1, 77.5, 83.4, 90.0, 97.8, and 101.5 μohm cm at 6.0, 9.9, 13.7, 18.3, 21.6, 27.4, 34.5, 47.9, 64.2, 80.0, 100.0, 113.6, 121.3, 127.5, 133.9, 140.0, 149.5, 175.0, 204.9, 240.0, 280.0, and 300.0 K, respectively; Lorenz function reported as 4.05, 3.87, 3.70, 3.68, 3.77, 4.09, 4.45, 4.35, 5.10, 5.62, 6.05, 6.33, 6.46, 6.36, 6.12, 5.72, 5.48, 5.33, 5.00, and 4.70 x 10^{-8} V^2 K^{-2} at 5.0, 8.0, 11.8, 13.8, 15.8, 18.4, 20.0, 22.8, 33.0, 42.5, 53.6, 65.6, 81.9, 100.0, 120.0, 140.0, 156.0, 173.4, 227.5, and 300.0 K, respectively.
6	1021	Nellis, W.J. and Legvold, S.	1969	L	4.6-279	Specimen c-axis II	c-axial specimen prepared from another ingot of same production batch; residual electrical resistivity 3.21 μohm cm at 4.2 K; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 18.9; electrical resistivity reported as 3.6, 4.1, 4.7, 6.7, 8.1, 10.6, 13.7, 20.0, 28.3, 35.4, 45.9, 51.8, 52.2, 51.0, 46.5, 45.6, 45.1, 45.5, 46.8, 50.0, 53.7, 58.2, and 60.5 μohm cm at 5.7, 9.7, 13.4, 17.3, 21.8, 27.1, 34.5, 47.9, 64.0, 77.3, 94.9, 108.5, 119.1, 124.2, 129.7, 132.6, 140.0, 149.3, 174.2, 204.0, 240.0, 279.4, and 297.9 K, respectively; Lorenz function reported as 5.28, 4.89, 4.89, 5.00, 5.43, 5.71, 5.93, 5.88, 6.78, 7.32, 7.77, 7.89, 7.70, 7.20, 6.67, 5.80, 5.38, 5.10, 4.79, and 4.48 x 10^{-8} V^2 K^{-2} at 4.5, 9.6, 12.2, 14.4, 16.3, 16.9, 19.5, 22.7, 33.5, 44.1, 58.5, 72.6, 91.8, 109.2, 122.1, 131.9, 154.0, 179.6, 224.6, and 300.0 K, respectively; heat flow along the c-axis.

TABLE 69. THERMAL CONDUCTIVITY OF HOLMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
7	1182	Ratnalingam, R. and Sousa, J. B.	1968	L	0.80–4.5	I	Single crystal; residual electrical resistivity $\rho(4.2K)$ = 9.73 μohm cm; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 7.23.
8	1182	Ratnalingam, R. and Sousa, J. B.	1968	L	0.84–4.2	II	Polycrystalline; residual electrical resistivity $\rho(4.2K)$ = 9.33 μohm cm; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 9.95.
9	1171	Rao, K. V.	1967	L	1.7–4.2		Polycrystalline; 0.08 Dy, 0.02 Tm, 0.0005 Si, 0.0003 Fe, and < 0.0001 Mg; 1.372 mm dia x 5 cm long; residual electrical resistivity 9.33 μohm cm; electrical resistivity ratio $\rho(r.t.)/\rho(4.2\ K)$ = 9.95; Lorenz function 12.0 x 10^{-8} $V^2 K^{-2}$ at 4.2 K.
10	1173	Rao, K. V., Loo, H. Y., and Meaden, G. T.	1969	L	4.7-300		Single crystal; specimen axis at an angle of about 30° to c-axis.

Hydrogen

The thermal conductivity of normal and para-hydrogen in various physical states are discussed separately below. Information on solid para-hydrogen is included in the subsection on solid normal hydrogen. The thermal conductivities of deuterium and tritium are discussed in the sections that follow.

Solid (Normal Hydrogen)

Available data for the thermal conductivity of solid hydrogen appears to be confined to two sources [603, 385]. The first reports data for 0.5, 1, and 5 percent ortho-hydrogen in para-hydrogen for temperatures below 11 K while the latter contains experimental data for a one per-cent ortho-hydrogen, ninety-nine per cent para-hydrogen mixture for temperatures between 15 and 17 K and pressures from 88 to 201 atmospheres.

The recommended values were obtained by smoothing of values read from a large scale reproduction of the [385] curve. For the lowest temperature datum, 4 K, the value cited was obtained by extrapolation of the various ortho-hydrogen content data to a zero percent ortho-hydrogen content. Values for temperatures below 4 K appear to be even more sensitive to the ortho-hydrogen content. While possibly the thermal conductivity of pure para-hydrogen reaches a maximum at about 3 K, the available information was not sufficiently detailed to enable this to be determined accurately. The tables extend to 17 K, a temperature higher than the triple (14 K) or melting (15 K) points. Some uncertainty is introduced into the values due to the pressures of 88 to 201 atmospheres used by [385] but this is considered much less than the uncertainty in the data themselves, which is assessed at eleven percent by [385] and which could be even larger than their estimates.

Based upon the smoothness of the data reported by the two workers, the values from 5 to 10 K should be consistent to about five percent, from 10 to 17 K to about fifteen percent, and at 4 K by about twenty percent. The word "consistent" is used here to emphasize the fact that no overlap between the different measurements exists and that confirmatory measurements are very desirable. As only a graphical reproduction of the [603] values was available at the time of this correlation, no departure plot is given.

Saturated Liquid (Normal Hydrogen)

Only one set of experimental data is available on the thermal conductivity of liquid hydrogen. The measurement was made in a parallel-plate apparatus for normal and para-hydrogen covering the temperature range between 16 and 25 K by Powers, et al. [1151]. The thermal conductivity of liquid hydrogen was found to have a positive temperature coefficient. No significant difference was observed between normal and para-hydrogen within the experimental error of 3.5 percent. The authors fitted their data by a linear equation which was used by Friedman and Hilsenrath [462] to tabulate the thermal conductivity between 16 and 30 K. These values have been cited in a number of compendia on cryogenics [263, 684, 264, 851].

Since the appearance of the above works a number of other studies have been made [1256, 691, 298, 742, 385]. These consist of generalized analyses, based either upon critical properties alone and the principle of corresponding states [1256] or upon a more extended analysis which involves the quantum parameter which becomes significant for hydrogen [691, 298, 742, 385]. However, no new measurements of the thermal conductivity of the saturated or compressed liquid have been located. The entire body of material in the literature would seem to rest upon the experimental measurements of Powers, Mattox, et al. [1151].

In several works [691, 298, 742, 385], the temperature dependence of the thermal conductivity is shown to change from positive to negative at about 25 K whereas in the Schaefer and Thodos correlation [1256] no such effect is exhibited. The latter must therefore be regarded as inaccurate below this temperature. The remaining works [691, 298, 742, 385] were found to agree in trend, but not in magnitude, as to the variation of thermal conductivity with temperature. The differences between the various estimates increases markedly as the critical point is approached. Somewhat arbitrarily, it was decided to base the recommended values upon the tables of Jones [691] as the latter appear to be the most recent and also the most detailed available.

The recommended values, derived from the tables of Jones [691], should be accurate to about three percent for temperatures below 25 K. Due to the lack of precise knowledge of the critical point parameters, the uncertainty increases rapidly for higher temperatures and can be assessed as about thirty percent at 30 K and as high as a hundred percent for the critical temperature.

Saturated Vapor (Normal Hydrogen)

No experimental data have been located for the thermal conductivity of saturated hydrogen vapor. The correlations of Schaefer and Thodos [1256] and of Jones [691] have been examined. The former was found to yield values for the gas at atmospheric pressures which were somewhat lower than those considered most probable. The shape of the envelope enclosing the two-phase mixture of liquid and vapor was found to disagree at the saturated liquid boundary. The correlations of Jones proved much more satisfactory for both cases.

The proposed values were therefore obtained from a large-scale graph of the Jones values. They should be accurate to within three percent below 25 K. As the critical point is approached the uncertainty increases due to the errors possible in the correlated values and due to the difficulty of interpolating these values. Possibly, uncertainties of twenty percent at 30 K and as high as a hundred percent at the critical point may prove to be reliable error estimates. As noted by Jones, experimentation to confirm the accuracy of these estimates is urgently required. The values must therefore be regarded as provisional pending this work.

Gas (Normal Hydrogen)

Experimental data for the thermal conductivity of gaseous hydrogen extend from 15 to 2000 K. Calculated values have appeared for the range 10 to 10^{12} K. In this analysis, recommended values were generated to 1000 K only.

In preparing the recommended values, initially little difficulty was found for temperatures from 100 to 250 K, the earlier NBS correlation [604, 605] being perfectly adequate. Some other correlations [263, 905a, 1577] were found to exhibit rather large errors in certain temperature intervals. At temperatures above 250 K, all these correlations yield values which are progressively larger than the recommended values with increasing temperature. In this range, the previous correlations by Keyes [746] and Svehla [1381] appear most accurate. The recommended values above about 450 K were based on the experimental measurements of Geier and Schäfer [481] which extend to 1473 K and which are in reasonable accord with theoretical estimates even at 2000 K. The data of Blais and Mann [569] were found to be considerably higher than all other measured or estimated values and were not used in preparing the recommended values. However, a later NBS correlation [587] very exhaustively calculated the thermal conductivity and compared this with the newer measurements of Diller [363]. As can be seen from the departure plots, the Diller data closely parallel the Eucken measurements (curve 15) which disagree with other results (curves 4, 16, 18, 20). The ascribed tolerance of 0.5 percent in the Diller measurements is difficult to reconcile with the other results. Likewise, a four percent uncertainty is ascribed to the calculations. While the values presented here may be in error in this extent below 65 K, the values from 120 to 240 K appear reasonable. Difficulty again arises above 400 K. Here the present values may be somewhat low. The opinion expressed by NBS [587] that the situation is not satisfactory is very appropriate. Further experimental measurements are most desirable below 100 K and above 500 K to reconcile the discord noted above.

The accuracy of the recommended values can be estimated as two percent or better from 100 to 400 K, within five percent below 100 K and above 400 K.

Saturated Liquid (Para-Hydrogen)

Only two studies of the thermal conductivity of liquid para-hydrogen were noted: the measurements of Diller and Roder reported in [363] and then in [1207] and also summarized in [362], and of Powers, et al. [1151]. The two different data sets show considerable disagreement, the Powers, et al. values being some 20 percent larger. Furthermore, the Powers, et al. data showed no trend toward a decrease in conductivity with increasing temperature. The Powers, et al. data were therefore not considered further.

The recommended values were obtained from the various graphs in Diller, et al. publications which agree well with four of the five values tabulated in [1207] for the saturated liquid, but a value lower than the 30 K table value was obtained.

The Diller, et al. values were considered by these authors to be accurate to within 2 percent. In view of the disagreement with Powers, et al. for the liquid and with some other works for the gas, possibly the uncertainty could be closer to five percent, especially near the critical point.

Saturated Vapor (Para-Hydrogen)

Only Roder, et al. [363, 1207] have published estimates of the thermal conductivity of the saturated vapor, based on measurements at near-saturation conditions which are claimed accurate to about two percent. In view of the fact that some of their dilute gas measurements appear to be high by more likely four percent, their saturated vapor values are thus considered to have a probable uncertainty of five percent. A summary of their values appear in [362].

The proposed values presented here were based on a smooth curve drawn through values extracted from their various published graphs. Due to the absence of direct experimental values no departure plot is given. As stated above, the uncertainty may be five percent.

Gas (Para-Hydrogen)

Available values for the thermal conductivity of gaseous para-hydrogen appear to be confined to the measurements of Diller, et al. [587, 362] below 125 K and to the calculations of Hanley, et al. [587]. In this work, the tabulated experimental low pressure values cited in [363] were used rather than attempting to read the graphical values in [587, 362]. The analysis of the calculated values is more difficult than usual since the difference in thermal conductivity between the normal and para forms depends on the base values for one of these forms. Here, the normal form was used.

As indicated in the discussion for the normal form, the recent NBS tables [363] appear to be possibly high in the range of 120–240 K and hence the normal tables were not adjusted to take account of the NBS work. The procedure used to generate the para-hydrogen tables was to form these by adding the difference between the NBS para and normal values to our present normal values. The result is that lower values than the NBS values result. The departure plot shows that this results in a better concordance with the NBS experimental data [587, 362]. A detailed examination of all the NBS calculations has not yet been made, but it is felt that perhaps both the present and the NBS tables fall on either side of the more probably correct values. The tables presented here are felt to be accurate to 3 percent between 100 and 400 K and 5 percent for all other temperatures tabulated.

TABLE 70. Recommended thermal conductivity of hydrogen

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid (normal hydrogen)		Saturated liquid (normal hydrogen)		Saturated vapor (normal hydrogen)	
T	k	T	$k \times 10^3$	T	$k \times 10^3$
4	2.30				
5	0.550	15	1.022	15	0.117*
6	0.190	16	1.055	16	0.126*
7	0.083	17	1.088	17	0.134*
8	0.043	18	1.121	18	0.142*
9	0.023	19	1.153	19	0.150*
10	0.0158	20	1.184	20	0.159*
11	0.0125	21	1.213	21	0.169*
12	0.0100	22	1.238	22	0.180*
13	0.0095	23	1.258	23	0.192*
14	0.0090	24	1.272	24	0.205*
15	0.0090	25	1.269	25	0.22*
16	0.0089	26	1.251*	26	0.23*
17	0.0089	27	1.217*	27	0.25*
		28	1.168*	28	0.27*
		29	1.117*	29	0.29*
		30	1.06*	30	0.31*
		31	1.00*	31	0.35*
		32	0.91*	32	0.40*
		33	0.60*‡	33	0.60*‡

*Extrapolated or estimated, hence provisional.
‡Pseudo-critical value.

TABLE 70. Recommended thermal conductivity of hydrogen—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (Normal hydrogen, at 1 atm)					
T	$k \times 10^3$	T	$k \times 10^3$	T	$k \times 10^3$
20	0.159				
25	0.193	350	2.033	700	3.25
30	0.227	360	2.069	710	3.29
35	0.261	370	2.106	720	3.32
40	0.294	380	2.142	730	3.36
45	0.328	390	2.177	740	3.39
50	0.361	400	2.212	750	3.43
60	0.426	410	2.248	760	3.46
70	0.489	420	2.283	770	3.50
80	0.552	430	2.318	780	3.53
90	0.614	440	2.354	790	3.56
100	0.676	450	2.389	800	3.60
110	0.738	460	2.424	810	3.63
120	0.801	470	2.459	820	3.67
130	0.864	480	2.494	830	3.70
140	0.926	490	2.529	840	3.74
150	0.986	500	2.564	850	3.77
160	1.046	510	2.60	860	3.80
170	1.105	520	2.64	870	3.84
180	1.164	530	2.67	880	3.87
190	1.222	540	2.70	890	3.91
200	1.280	550	2.74	900	3.94
210	1.338	560	2.77	910	3.97
220	1.395	570	2.80	920	4.01
230	1.451	580	2.84	930	4.04
240	1.506	590	2.88	940	4.08
250	1.560	600	2.91	950	4.11
260	1.613	610	2.95	960	4.14
270	1.665	620	2.98	970	4.18
280	1.717	630	3.01	980	4.21
290	1.767	640	3.05	990	4.25
300	1.815	650	3.08	1000	4.28
310	1.863	660	3.12		
320	1.910	670	3.15		
330	1.954	680	3.19		
340	1.994	690	3.22		

TABLE 70. Recommended thermal conductivity of hydrogen—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid (para-hydrogen)		Saturated vapor (para-hydrogen)	
T	$k\times10^3$	T	$k\times10^3$
14	0.824		
15	0.855	10	0.081*
16	0.885	11	0.089*
17	0.910	12	0.096*
18	0.933	13	0.103*
19	0.954	14	0.111*
20	0.972	15	0.118*
21	0.988	16	0.128*
22	0.999	17	0.137*
23	1.007	18	0.147*
24	1.006	19	0.157*
25	0.998	20	0.168*
26	0.975	21	0.181*
27	0.947	22	0.194*
28	0.910	23	0.209*
29	0.870	24	0.224*
30	0.826	25	0.242*
31	0.74*	26	0.260*
32	0.58*‡	27	0.280*
		28	0.304*
		29	0.332*
		30	0.363*
		31	0.45*
		32	0.58*‡

*Extrapolated or estimated, hence provisional.
‡Pseudo-critical value.

TABLE 70. Recommended thermal conductivity of hydrogen—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (para-hydrogen, at 1 atm)					
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
20	0.168				
25	0.198	300	1.880*	650	3.08*
30	0.229	310	1.920*	660	3.12*
35	0.261	320	1.958*	670	3.15*
40	0.294	330	1.994*	680	3.19*
45	0.328	340	2.028*	690	3.22*
50	0.363	350	2.061*	700	3.25*
60	0.434	360	2.093*	710	3.29*
70	0.513	370	2.126*	720	3.32*
80	0.601	380	2.159*	730	3.36*
90	0.696	390	2.191*	740	3.39*
100	0.797	400	2.223*	750	3.43*
110	0.899	410	2.258*	760	3.46*
120	1.000	420	2.292*	770	3.50*
130	1.093*	430	2.326*	780	3.53*
140	1.177*	440	2.361*	790	3.56*
150	1.251*	450	2.395*	800	3.60*
160	1.316*	460	2.429*	810	3.63*
170	1.372*	470	2.463*	820	3.67*
180	1.426*	480	2.497*	830	3.70*
190	1.470*	490	2.532*	840	3.74*
200	1.512*	500	2.565*	850	3.77*
210	1.551*	510	2.60*	860	3.80*
220	1.588*	520	2.64*	870	3.84*
230	1.624*	530	2.67*	880	3.87*
240	1.660*	540	2.70*	890	3.91*
250	1.696*	550	2.74*	900	3.94*
260	1.732*	560	2.77*	910	3.97*
270	1.768*	570	2.80*	920	4.01*
280	1.806*	580	2.84*	930	4.04*
290	1.843*	590	2.88*	940	4.08*
		600	2.91*	950	4.11*
		610	2.95*	960	4.14*
		620	2.98*	970	4.18*
		630	3.01*	980	4.21*
		640	3.05*	990	4.25*
				1000	4.28*

*Extrapolated or estimated, hence provisional.

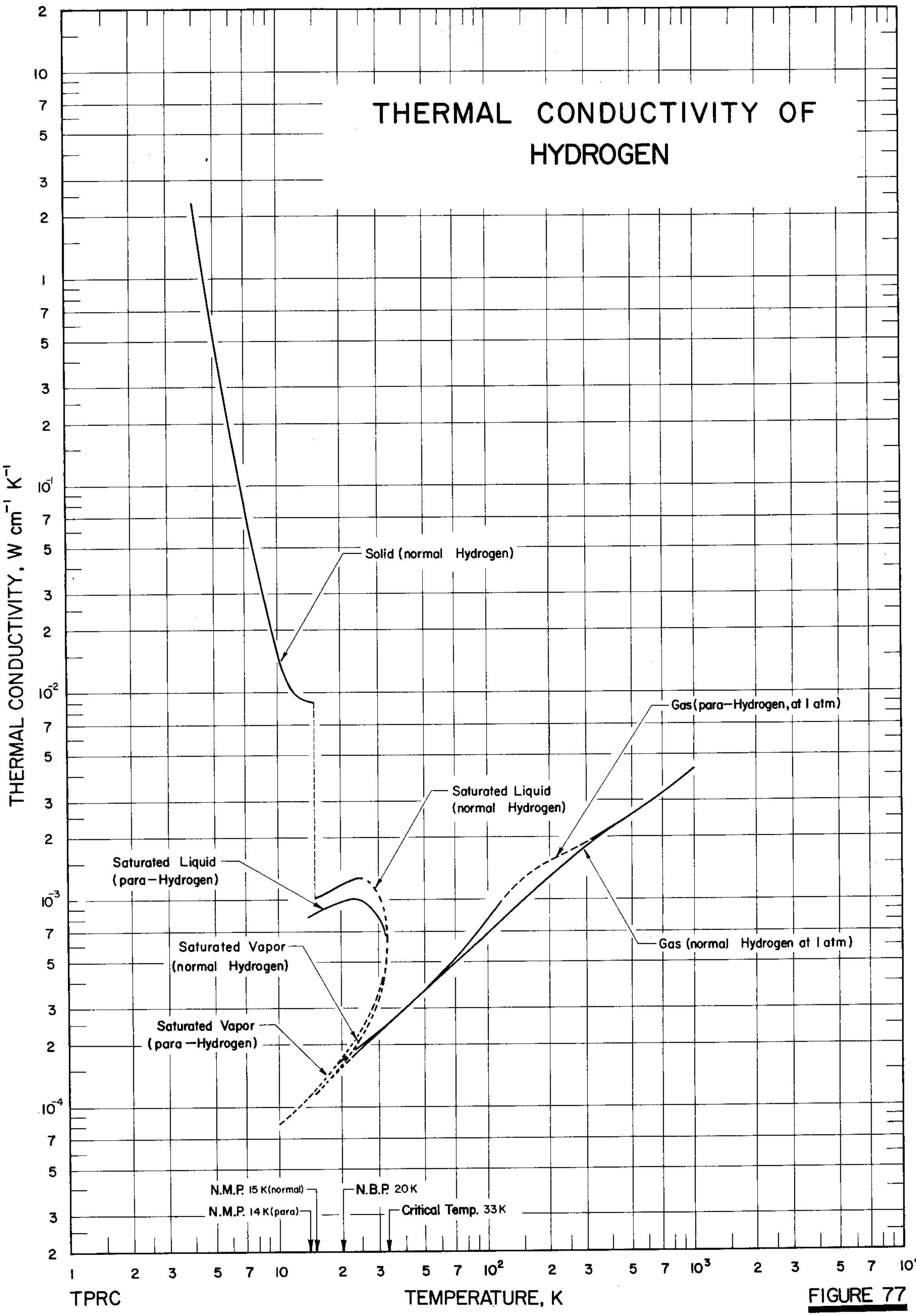
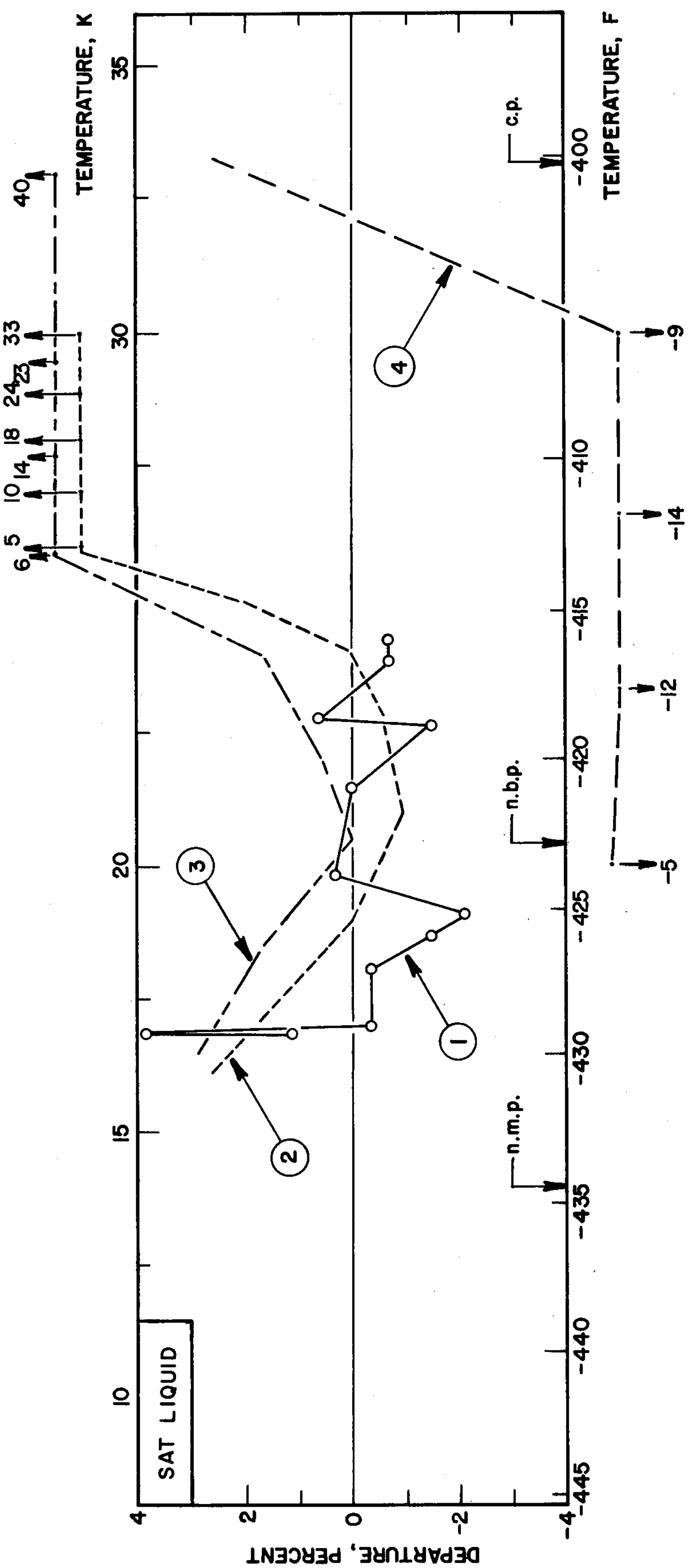

THERMAL CONDUCTIVITY OF HYDROGEN
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Solid (normal Hydrogen)
Saturated Liquid (normal Hydrogen)
Saturated Liquid (para–Hydrogen)
Saturated Vapor (normal Hydrogen)
Saturated Vapor (para–Hydrogen)
Gas (para–Hydrogen, at 1 atm)
Gas (normal Hydrogen at 1 atm)
N.M.P. 15 K (normal)
N.M.P. 14 K (para)
N.B.P. 20 K
Critical Temp. 33 K
TPRC

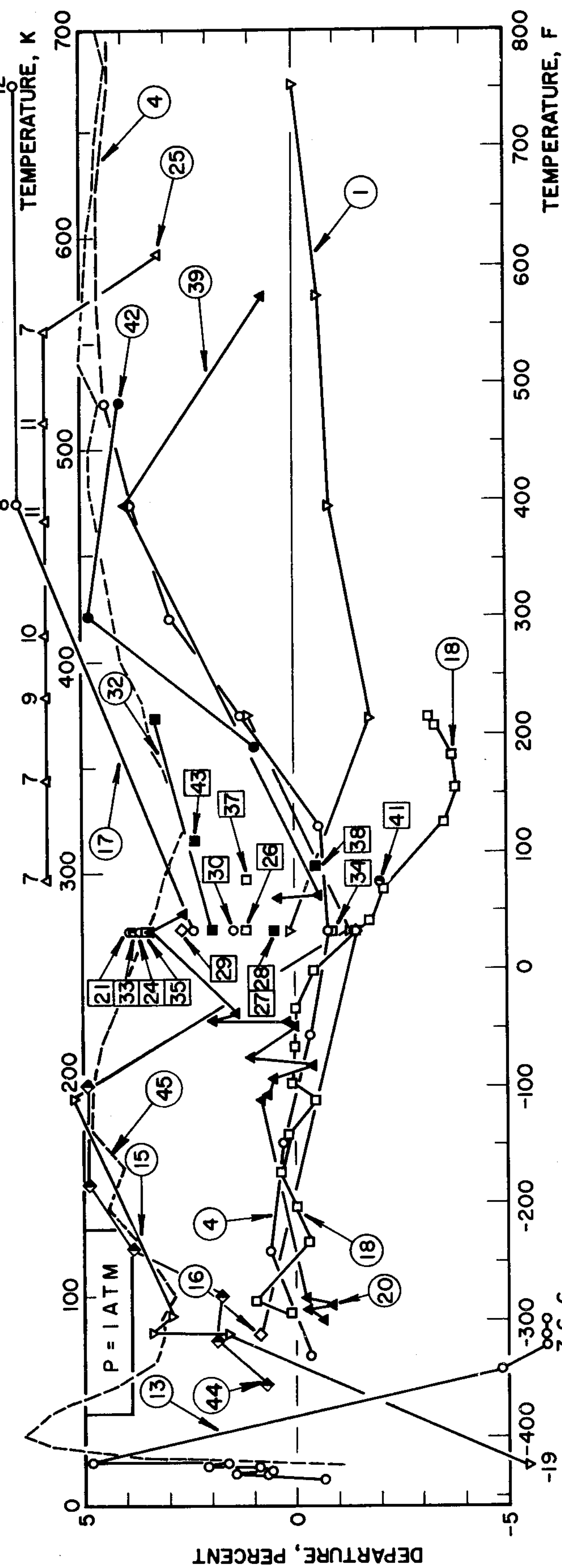
FIGURE 77

FIGURE 78. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID normal HYDROGEN



Curve	Reference
1	1151
2	462
3	742
4	1256

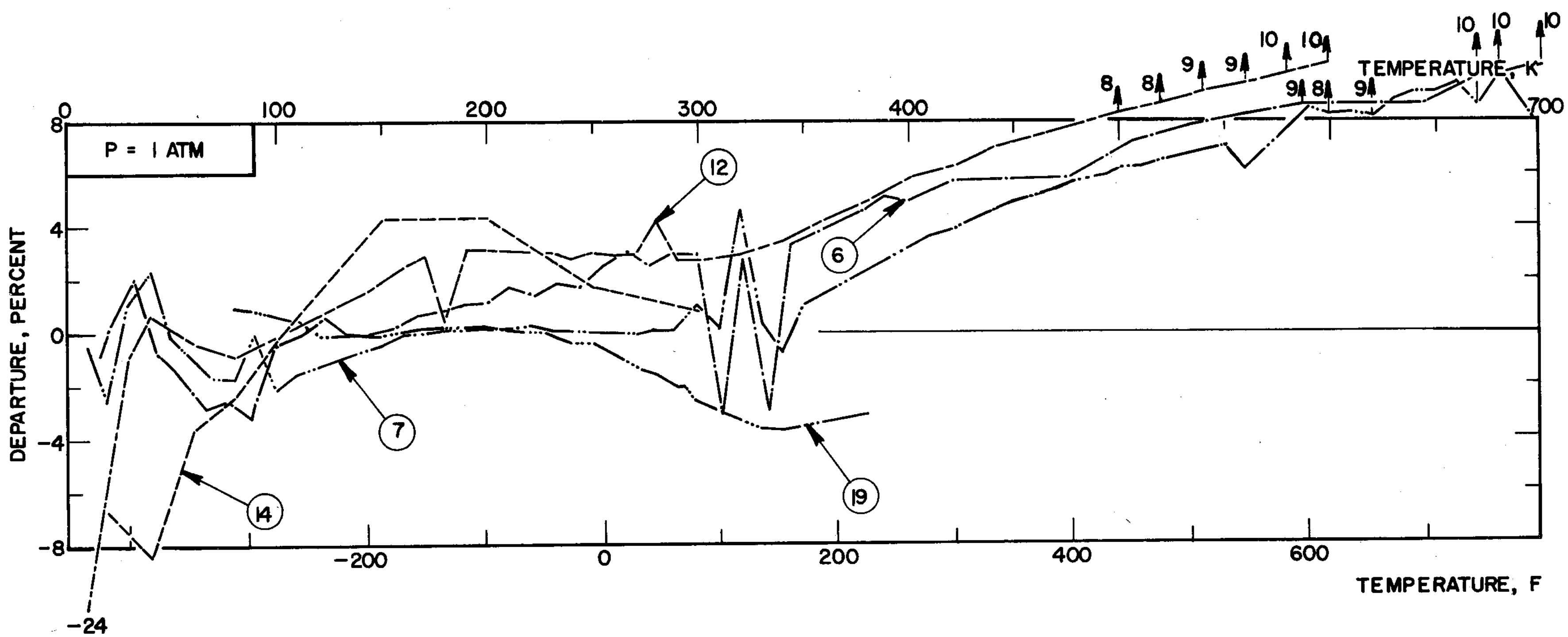
FIGURE 79. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS normal and para-HYDROGEN



Curve	Reference
1	484
4	746
13	1445
15	401
16	402
18	689
20	530
21	72
24	360
25	527
26	528
27	529
28	651
29	710

Curve	Reference
30	833
32	1263
33	1266
34	1372
35	1515,1517
38	1235
39	1366
41	1502
42	747
44	363,587
45	587

FIGURE 79. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS normal- and para-HYDROGEN (continued)



Curve	Reference
6	839
7	604, 605
12	1577
14	263
19	689

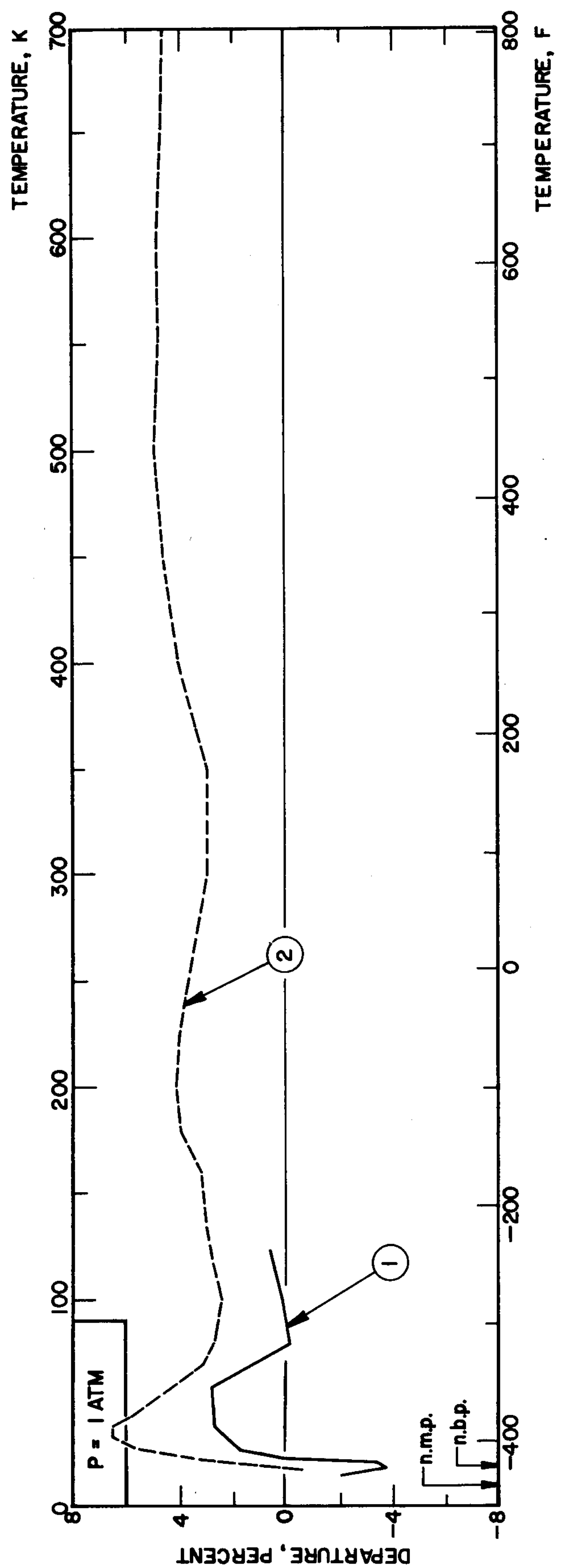
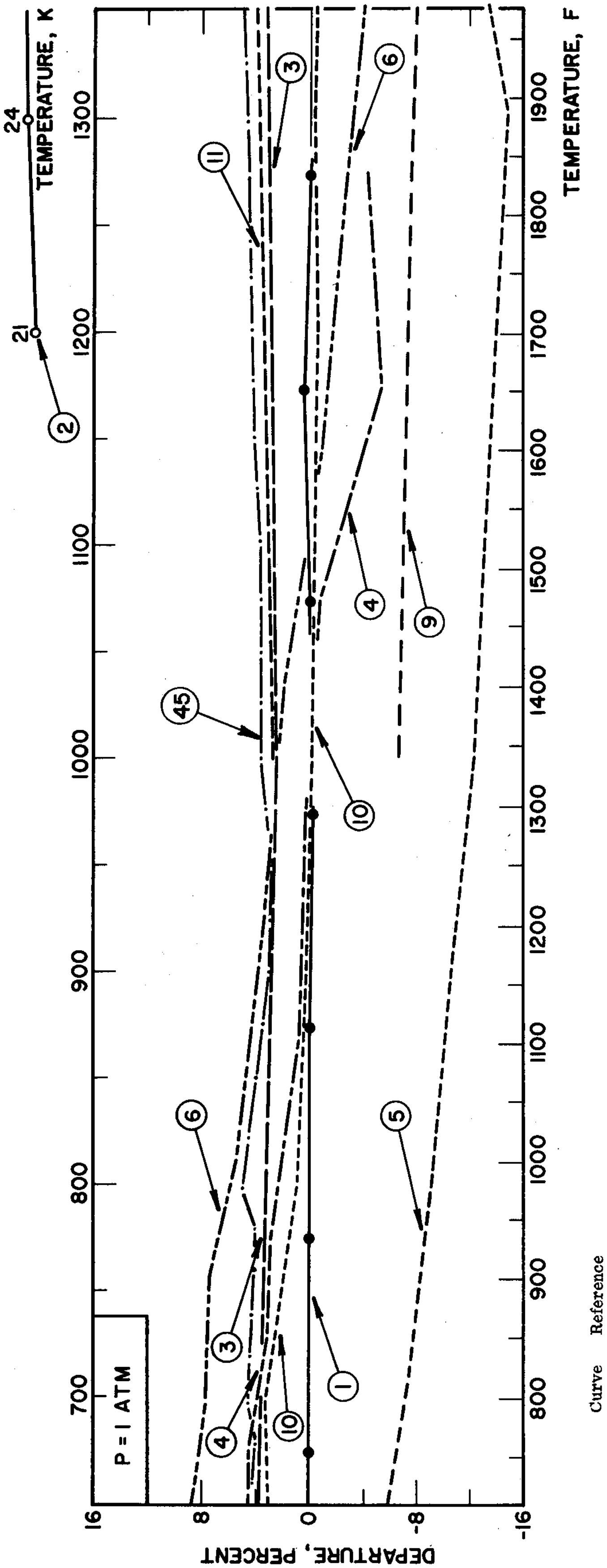


FIGURE 79. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS normal and para-HYDROGEN (continued)

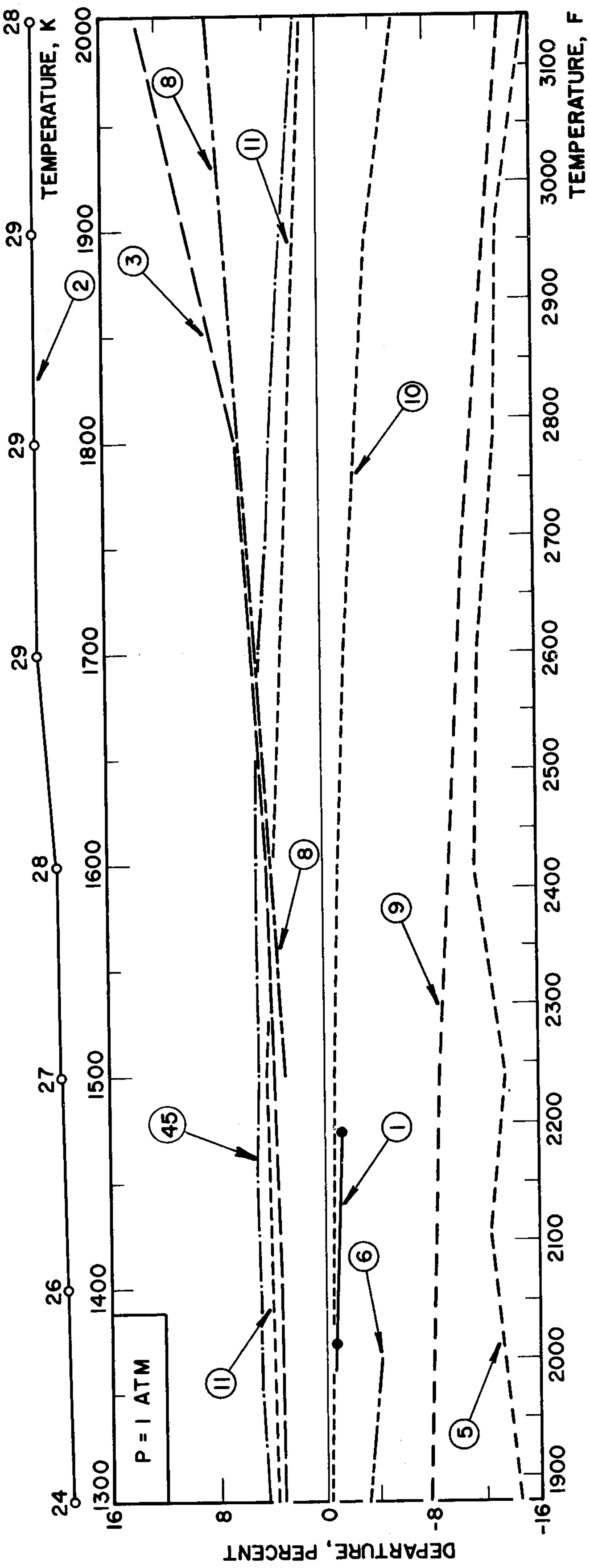
Curve	Reference
1	362, 363, 587
2	363

FIGURE 79. DEPARTURE PLOT FOR THE THERMAL CONDUCTIVITY OF GASEOUS normal- and para-HYDROGEN (continued)



Curve	Reference
1	484
2	167
3	540
4	746
5	759
6	839
9	1224
10	1381
11	1457
45	587

FIGURE 79. DEPARTURE PLOT FOR THE THERMAL CONDUCTIVITY OF GASEOUS normal and para-HYDROGEN (continued)



Curve	Reference
1	484
2	167
3	540
5	759
6	839
8	1213
9	1224
10	1381
11	1457
45	587

Deuterium (Hydrogen Isotope)

No information is available for the thermal conductivity of solid deuterium. The thermal conductivity of deuterium in each of the other physical states is discussed separately below.

Saturated Liquid

Only one set of experimental data was located for the thermal conductivity of liquid deuterium. Powers, et al. [1152] made measurements in a parallel-plate apparatus for normal and ortho deuterium for temperatures between 20 and 24 K. To within a two percent uncertainty they considered the thermal conductivity to be independent of the ortho-para composition. The values so obtained were fitted to a linear equation in temperature by Friedman and Hilsenrath [462] who then used the equation to generate values from 20 to 30 K.

In this work the correlation of Kerrisk, et al. [742] was also compared with the above measurements. As read from the source graph, values some six percent lower than the data [1152] were obtained. These were adjusted to coincide with the data values and a curve drawn through the latter to exhibit the same trend as the Kerrisk curve in that the thermal conductivity reaches a maximum just below 28 K and then decreases rapidly to the critical point value of [742]. The recommended values were read from this smooth curve.

The accuracy of the recommended values depends on the accuracy of the only set of experimental data [1152] and on the [742] estimate for the critical point. It is considered that five percent is a reasonable estimate below 30 K, ten percent from 30 to 35 K and steadily increasing uncertainty to the critical point of about 38 K.

Saturated Vapor

No experimental measurements or estimates were found for the thermal conductivity of saturated deuterium vapor apart from a critical point estimate of Kerrisk, et al. [742]. An attempt was made in this work to provide a set of estimated values using the above-mentioned critical point value, the value obtained from the atmospheric pressure tables for the normal boiling point (23 K) and the fact that the Kerrisk correlation indicated a maximum in the saturated liquid conductivity just below 28 K.

The thermal conductivity-temperature values for the saturated liquid were plotted on a graph together with the atmospheric pressure value at 23 K. Assuming the rectilinear diameter relation to apply for thermal conductivity above about 36 K, values for the saturated liquid were used to obtain values for the saturated vapor. The rectilinear diameter line so obtained clearly did not pass through the point obtained at 23 K so a curve of minimum curvature was drawn which passed through this point and the critical point. Values for a few other temperatures for the saturated vapor were thus obtained and a smooth curve drawn to pass through these and the values at 23 K and the critical point.

The proposed values, obtained in this manner, are of uncertain accuracy. In addition to possible quantum effects and phenomena near the critical point they depend upon the rectilinear diameter and visual smoothing for their accuracy. They must be regarded as extremely provisional. Due to the lack of experimental data, no departure plot is given.

Gas

Available data for the thermal conductivity of deuterium gas are confined to a set of experimental measurements from 15 to 20 K and from 65 to 89 K [1445] and single measurements at the ice point [71, 90, 91, 1455, 703, 1041, 1381]. A correlation by Lenoir [839] extends from 16 to 366 K and fits the data very well. After analysis of the data it was decided to base the recommended values on a smooth curve which is almost identical to that through the Lenoir correlation.

Some evidence exists from the data of [1445] that a quantum effect may occur between 50 and 70 K but no confirmation from independent measurements is available. In the preparation of the recommended values the deviation from the smooth curve was regarded as being due to experimental error and therefore neglected. Should new measurements show that the deviation is real then the recommended values in this range will need revision.

Between 20 and 280 K the recommended values may be accurate to within five percent. Values above 280 K may be in error by as much as ten percent. Further experimental data are to be desired, especially above 30 K.

TABLE 71. Recommended thermal conductivity of deuterium

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor	
T	$k \times 10^3$	T	$k \times 10^3$
19	1.24*		
20	1.26	20	0.084*
21	1.28	21	0.096*
22	1.30	22	0.109*
23	1.33	23	0.123*
24	1.34	24	0.138*
25	1.36*	25	0.155*
26	1.37*	26	0.174*
27	1.38*	27	0.193*
28	1.38*	28	0.215*
29	1.38*	29	0.238*
30	1.37*	30	0.26*
31	1.35*	31	0.29*
32	1.32*	32	0.32*
33	1.29*	33	0.36*
34	1.25*	34	0.40*
35	1.21*	35	0.45*
36	1.15*	36	0.51*
37	1.07*	37	0.58*
38	0.83*‡	38	0.83*‡

*Extrapolated or estimated, hence provisional.
‡Pseudo-critical value.

TABLE 71. Recommended thermal conductivity of deuterium—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (At 1 atm)			
T	$k \times 10^3$	T	$k \times 10^3$
24	0.135		
25	0.139	200	1.014*
30	0.175	210	1.056*
35	0.206	220	1.097*
40	0.236	230	1.138*
45	0.268	240	1.178*
50	0.299	250	1.217*
60	0.360	260	1.256*
70	0.421	270	1.294*
80	0.475	280	1.331*
90	0.527	290	1.369*
100	0.577*	300	1.406*
110	0.625*	310	1.44*
120	0.672*	320	1.48*
130	0.718*	330	1.51*
140	0.762*	340	1.55*
150	0.806*	350	1.59*
160	0.848*	360	1.62*
170	0.890*	370	1.66*
180	0.931*	380	1.69*
190	0.973*	390	1.73*
		400	1.76*

*Extrapolated or estimated, hence provisional.

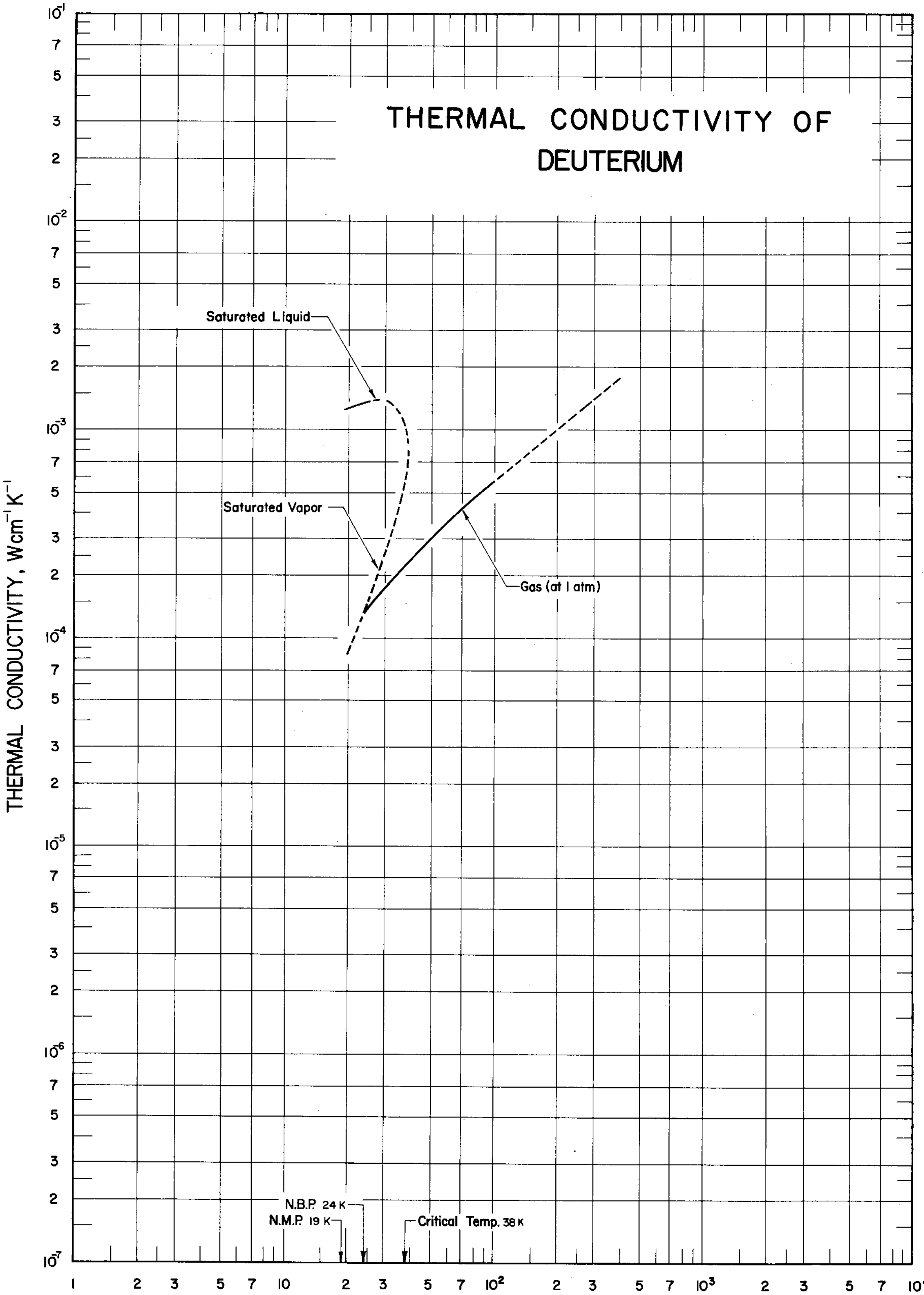
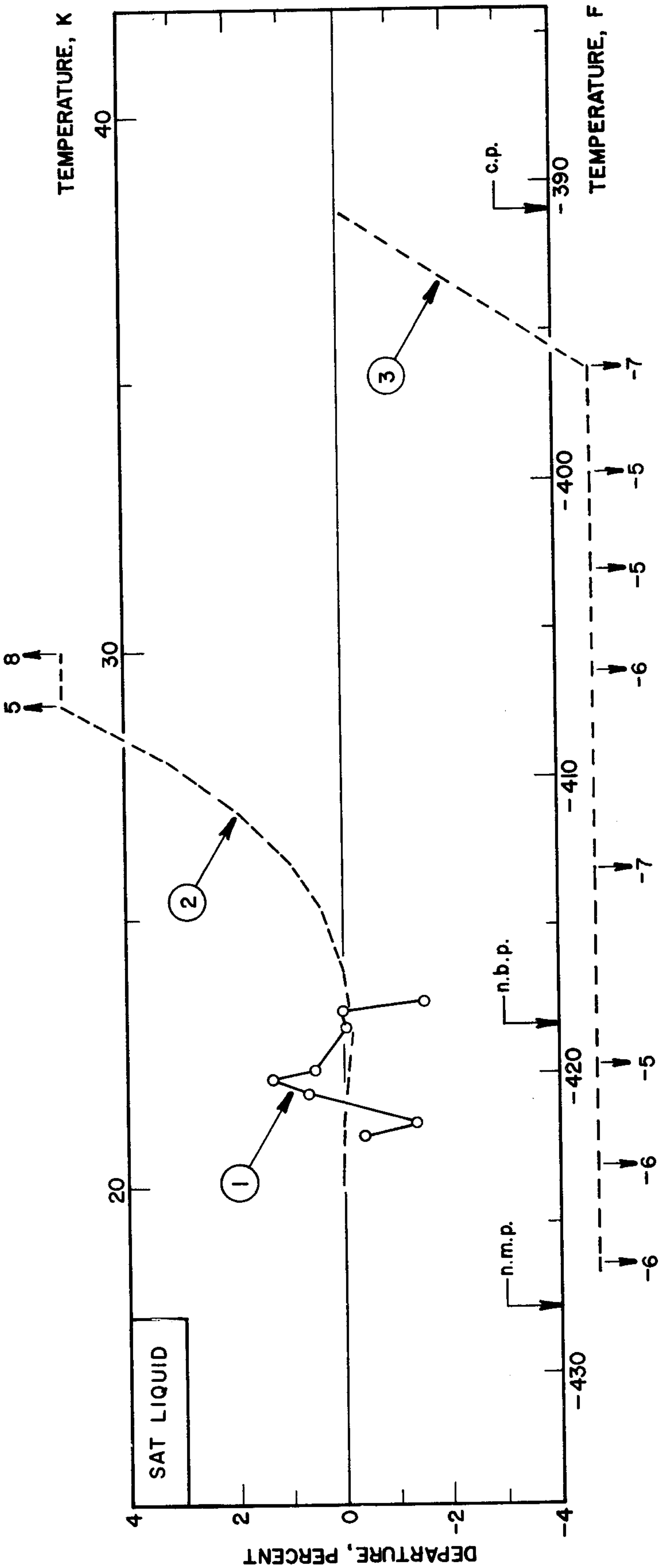

THERMAL CONDUCTIVITY OF
DEUTERIUM
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.B.P. 24 K
N.M.P. 19 K
Critical Temp. 38 K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TEMPERATURE, K
TPRC

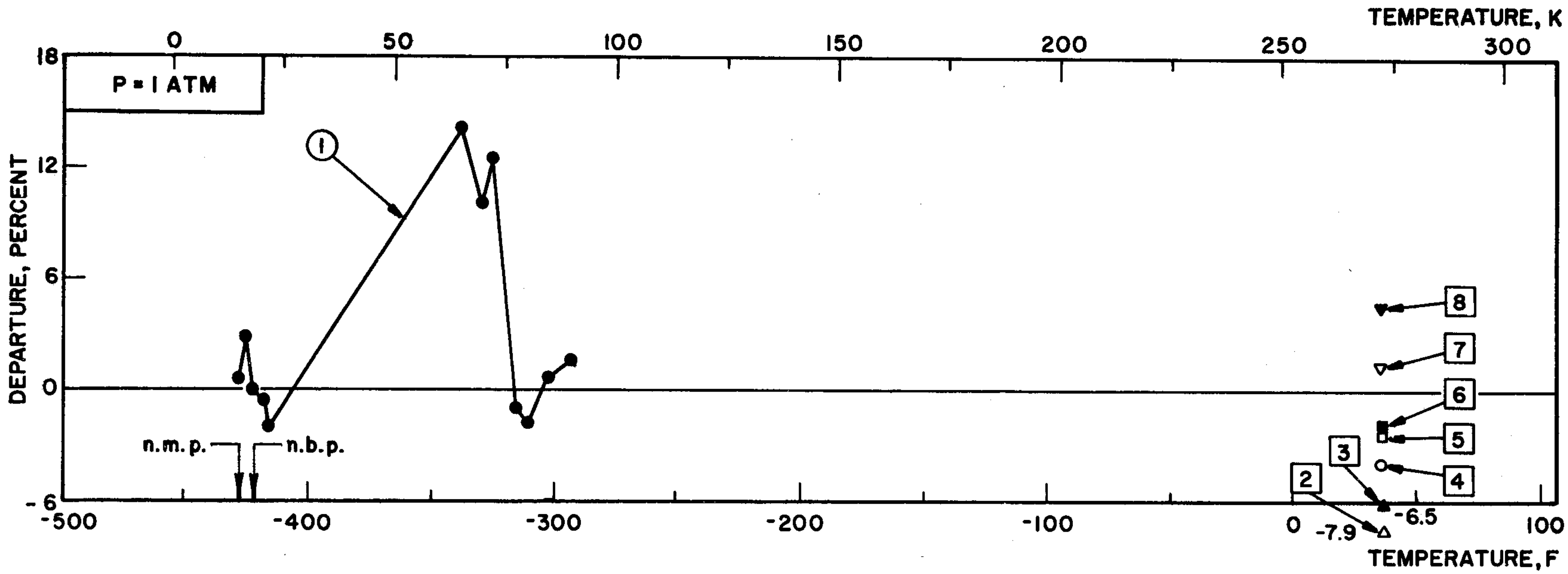
FIGURE 80

FIGURE 81. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID DEUTERIUM



Curve	Reference
1	1152
2	462
3	742

FIGURE 82. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS DEUTERIUM



Curve	Reference
1	1445
2	71
3	1455
4	1041
5	90
6	91
7	1381
8	703

Tritium (Hydrogen Isotope)

No information is available for the thermal conductivity of tritium in the solid, saturated vapor, or gaseous states. The thermal conductivity of saturated liquid is discussed below.

Saturated Liquid

No experimental values of the thermal conductivity of saturated liquid tritium have been located. The values presented here were obtained from a large-scale plot of the correlated values of Kerrisk, et al. [742] and must thus be regarded as provisional pending experimental verification. Due to the complete absence of experimental data no departure plot or error estimate can be given.

TABLE 72. Provisional thermal conductivity of tritium

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid	
T	$k \times 10^3$
21	1.25*
22	1.28*
24	1.32*
26	1.36*
28	1.37*
30	1.34*
32	1.30*
34	1.25*
36	1.18*
38	1.10*
40	1.00*
42	0.89*
44	0.68*‡

*Estimated or extrapolated.
‡Pseudo-critical value.

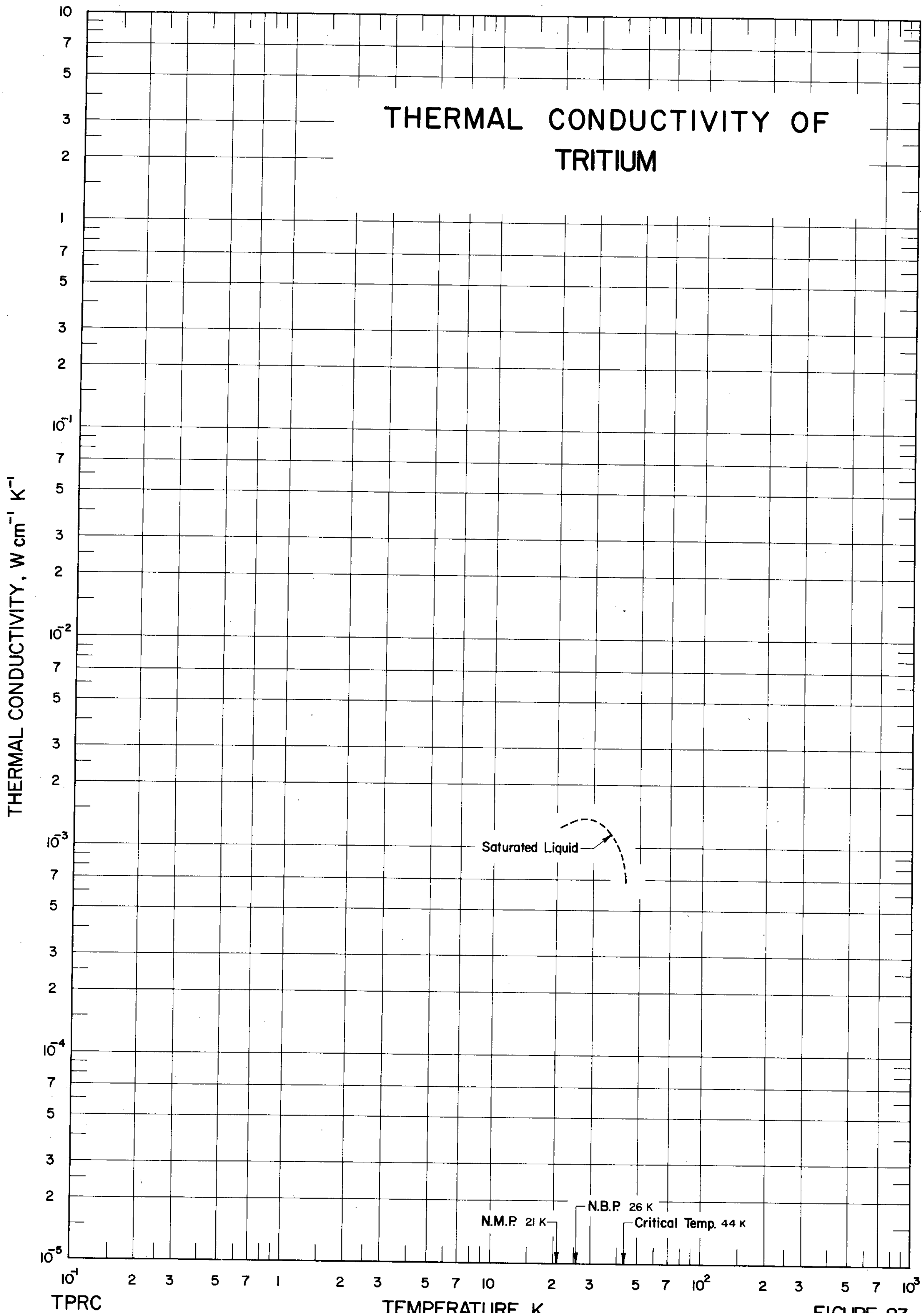

THERMAL CONDUCTIVITY OF
TRITIUM
Saturated Liquid
N.M.P. 21 K
N.B.P. 26 K
Critical Temp. 44 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 83

Indium

Indium becomes superconducting at about 3.4 K, and the majority of the thermal conductivity determinations made on this metal have been in the low-temperature region for which the study could include both normal and superconducting states. In the superconducting state the thermal conductivity decreases with decrease in temperature at a rate which is so much greater than that of the normal state that by 0.3 K the ratio of the values for the two states is of the order of 1000.

At low temperatures the recommended values for a polycrystalline sample in the normal state having residual electrical resistivity $\rho_0 = 0.000587\ \mu\Omega$ cm are based on the measurements of Wyder [1582] (curve 34). The values at temperatures below about 1.5 T_m are calculated to fit the experimental data by using equation (7) and using the constants m, n, and α'' as listed in table 1 and the parameter $\beta = 0.0240$. This curve has been extended smoothly to higher temperatures following the trend of the curve of Mendelssohn and Rosenberg [937] (curve 5) for a sample of lower purity to about 30 K.

Two groups of workers have made determinations in the approximate range 80 to 380 K: Barisoni, Williams, and McElroy [115] (curves 30–32) for a polycrystalline sample and two single crystal samples yielding $k_{\parallel}$ and $k_{\perp}$, and Powell, Woodman, and Tye [1146] (curves 13 and 14) for a polycrystalline sample. The curves for $k_{\parallel}$ and $k_{\perp}$ differ by about 2.5 percent over the range 200 K to the upper temperature limit of these experiments and coverage at their lower limit. The upper curve is that for $k_{\parallel}$, but, whereas the polycrystalline curve of Barisoni, et al. agrees closely with $k_{\perp}$ at higher temperatures, it is higher by about 1.3 percent at about 86 K where $k_{\parallel}$ and $k_{\perp}$ converge. Although the corresponding electrical resistivity measurements on the single crystal samples showed a similar trend, the small differences that have been observed are considered comparable with other experimental uncertainties and no distinction is made for the single crystals. All samples are treated as providing data for polycrystalline indium. Since the curve due to Powell, et al. is some 10 percent higher at about 90 K and some 4 percent higher at room temperature, the recommended curve has been drawn in an intermediate position with about twice the weighting to the lower set of data. It will be noticed that neither set of measurements had exended down to the temperature at which a marked increase in thermal conductivity occurs, and, when the recommended curve is drawn from 33 K to link with this intermediate curve at about 80 K, the steep decrease is assumed to phase off and the curve to flatten out at about 50 K. This is very tentative and there is a strong possibility that indium might have a thermal conductivity minimum between 30 and 80 K which calls for measurements in this region, particularly as aluminum has a minimum in the corresponding temperature region and belongs to the same group of the periodic table.

The recent measurements of Yuchak and Smirnov [1595] (curve 55) at room temperature and above agree well with the recommended curve derived as above [608]. They have also reported data for the thermal conductivity of indium in the liquid state (curve 56). The recommended curve for liquid indium has been drawn through their data. Further measurements on liquid indium are needed for confirmation, since their reported Lorenz function decreases rapidly from $3.00 \times 10^{-8}\ V^2\ K^{-2}$ at 435 K, to $2.55 \times 10^{-8}\ V^2\ K^{-2}$ at 632 K, and to $2.39 \times 10^{-8}\ V^2\ K^{-2}$ at 894 K.

The recommended values are thought to be accurate to within ±15 percent at temperatures below 100 K and ±5 percent above. The values below 60 K are, of course, applicable only to a sample having $\rho_0 = 0.000587\ \mu\Omega$ cm. For liquid indium the values are provisional and are probably good to ±15 to ±20 percent.

TABLE 73. Recommended thermal conductivity of indium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid
Polycrystalline

T	k	T	k
0	0	60	1.02*
1	40.2*	70	1.00*
2	64.9	80	0.992*
3	64.0	90	0.983
4	49.6	100	0.976
5	32.4	123.2	0.958
6	20.7	150	0.939
7	14.1	173.2	0.920
8	10.1	200	0.897
9	7.47	223.2	0.878
10	5.88	250	0.856
11	4.86	273.2	0.837
12	4.12	298.2	0.818
13	3.59	300	0.816
14	3.18	323.2	0.798
15	2.86	350	0.778
16	2.61	373.2	0.762
18	2.22	400	0.745
20	1.94	429.784	0.729*
25	1.51		
30	1.28		
35	1.15*		
40	1.09*		
45	1.06*		
50	1.04*		

Liquid

T	k
429.784	0.382
473.2	0.387
500	0.394
573.2	0.417
600	0.425
673.2	0.446
700	0.458
773.2	0.472
800	0.479
873.2	0.492
900	0.494

†The values are for well-annealed high-purity indium, and those below 60 K are applicable only to a specimen having $\rho_0 = 0.000587$ $\mu\Omega$ cm. The values for the liquid state are provisional.

*Extrapolated or interpolated.

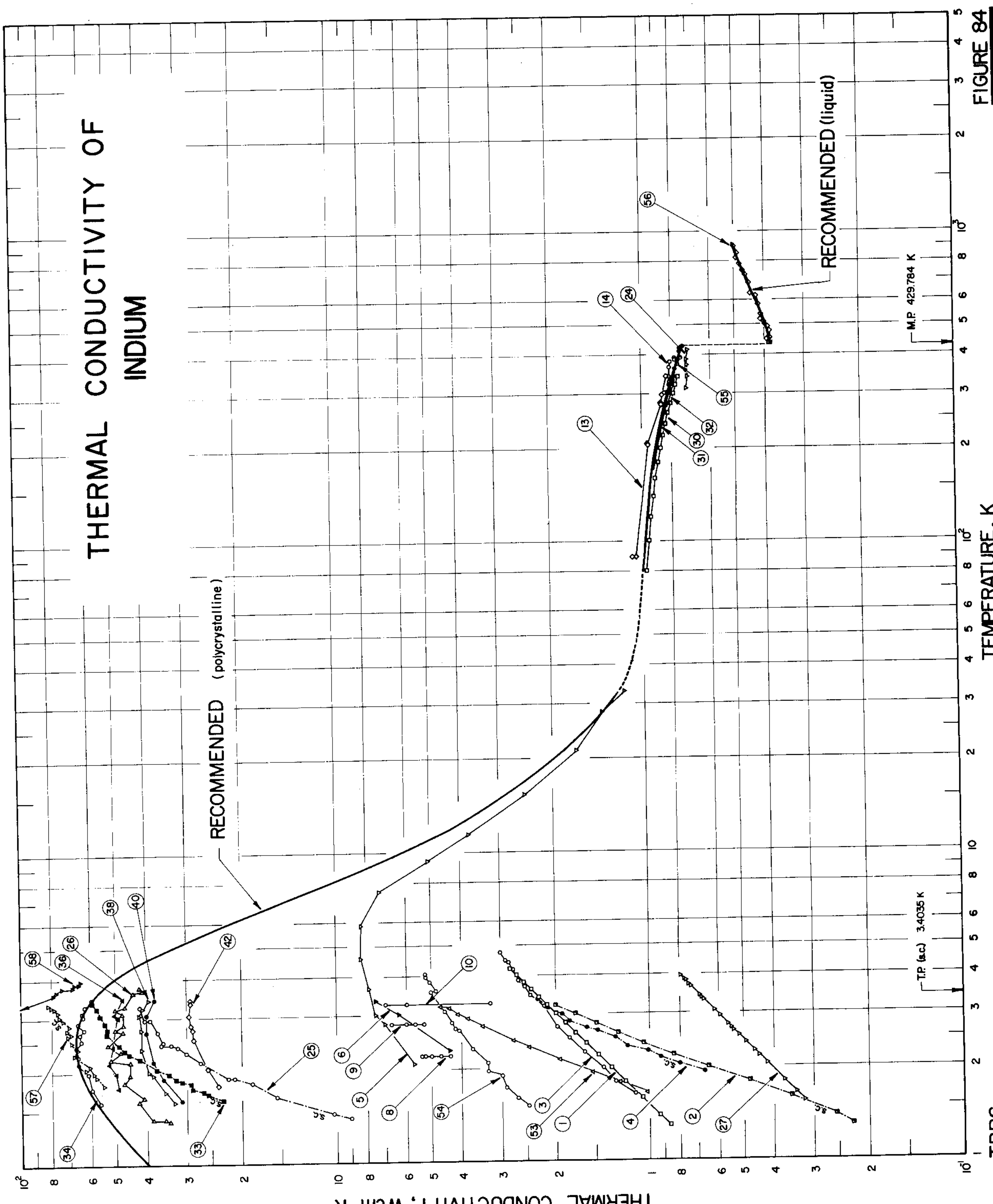

THERMAL CONDUCTIVITY OF
INDIUM
RECOMMENDED (polycrystalline)
RECOMMENDED (liquid)
M.P. 429.784 K
T.P. (s.c.) 3.4035 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 84

TABLE 74. THERMAL CONDUCTIVITY OF INDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	1323	Sladek, R.J.	1955	L	1.3-4.2		99.95 pure; single crystal; cylindrical specimen; obtained from Stout, J.W. and Guttman, L.; residual electrical resistivity 0.0371 μohm cm; measured in a vacuum of $< 5 \times 10^{-7}$ mm Hg and in a longitudinal magnetic field at approx 1000 oersteds; in normal state; data from smoothed curve.
2	1323	Sladek, R.J.	1955	L	1.3-3.2		The above specimen measured in superconducting state; data from smoothed curve.
3	643	Hulm, J.K.	1952	L	1.7-5		99.9^+ pure; single crystal; supplied by Stout, J.W. and Guttman, L.; transition temp 3.40 K; measured in a magnetic field of ~100 gauss; in normal state.
4	643	Hulm, J.K.	1952	L	1.9-3.4		The above specimem measured in superconducting state.
5	937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.1-33	JM 4398; In 1	99.993 pure; polycrystalline; 1-2 mm dia x 5 cm long; supplied by Johnson Matthey; in normal state.
6	937	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-3.3	JM 4398; In 1	The above specimen measured in superconducting state.
7*	929, 935	Mendelssohn, K. and Renton, C.A.	1953	L	0.46-0.87	In 2	99.993 pure; single crystal; in superconducting state; preliminary result.
8	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.2	JM 4398; In 1	99.993 pure; polycrystalline; 1-2 mm dia x 5 cm long; supplied by Johnson Matthey; annealed in vacuo; measured in transverse magnetic fields of strength ranging from 0.34 to 2.87 kilooersteds kOe.
9	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8	JM 4398; In 1	The above specimen measured in magnetic fields of strength ranging from 0.34 to 2.87 kOe.
10	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.25	JM 4398; In 1	The above specimen measured in H ranging 1.10 to 3.94 kOe.
11*	352, 351	Detwiler, D.P. and Fairbank, H.A.	1952	L	2.13	JM 3249; In	Pure; single crystal; 2.79 mm dia x 8 cm long; spectroscopically standardized indium supplied by Johnson Matthey; cast; somewhat strained in mounting; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 5500$; measured in transverse magnetic fields of strength ranging from 0 to 190 gauss.
12*	352, 351	Detwiler, D.P. and Fairbank, H.A.	1952	L	2.13	JM 3249; In	The above specimen measured in transverse fields of decreasing strength ranging from 184 to 0 gauss.
13	1146	Powell, R.W., Woodman, M.J., and Tye, R.P.	1962	L	89-342		Total impurity < 0.03 (probably Sn and Pb); ~0.85 cm dia x 6.5 cm long; supplied by Johnson Matthey; electrical resistivity reported as 1.65, 3.08, 4.60, 6.22, 8.0, 10.0, 12.15, and 13.0 μohm cm at 73, 123, 173, 223, 273, 323, 373, and 393 K, respectively; Lorenz function reported as 2.46, 2.60, 2.62, 2.60, 2.57, 2.59, 2.61, and 2.61×10^{-8} Wohm K^{-2} at the above temps, respectively; density 7.334 g cm^{-3}.
14	1146	Powell, R.W., Woodman, M.J., and Tye, R.P.	1962	C	303-390		The above specimen measured in another apparatus; Armco iron used as comparative material.

*Not shown in figure.

TABLE 74. THERMAL CONDUCTIVITY OF INDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
15*	523	Graham, G.M.	1958	L	0.26-0.56	JM 10281; A0	Spectroscopically pure; single crystal; 4.79 mm dia; indium supplied by Johnson Matthey; cast, crystallized; annealed in air at 120 C and electropolished; residual electrical resistivity 0.00125 μohm cm; in superconducting state.
16*	523	Graham, G.M.	1958	L	0.27-0.58	JM 10281; A1	The above specimen etched with 25% H_2SO_4 solution; in superconducting state.
17*	523	Graham, G.M.	1958	L	0.36-0.59	JM 10281; A2	The above specimen etched with 25% H_2SO_4 solution and annealed at 120 C for 9 days; in superconducting state.
18*	523	Graham, G.M.	1958	L	0.32-0.65	JM 10281; A3	The above specimen electropolished (dia reduced to 1.86 mm); damaged by bending during reduction; in superconducting state.
19*	523	Graham, G.M.	1958	L	0.34-0.65	JM 10281; A4	The above specimen etched with 25% H_2SO_4 solution; in superconducting state.
20*	523	Graham, G.M.	1958	L	0.30-0.74	JM "chem pure"; B0	99.9 pure (by difference); single crystal; 3.13 mm dia; supplied by Johnson Matthey; cast, crystallized, electropolished, and annealed in air at 120 C; in superconducting state.
21*	523	Graham, G.M.	1958	L	0.30-0.76	JM "chem pure"; B1	The above specimen etched with 25% H_2SO_4 solution; in superconducting state.
22*	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.25-0.93	JM 4938	99.993 pure; single crystal; ~1 mm dia x 4 cm long; made from Johnson Matthey metal; in superconducting state.
23*	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.29-0.79	JM 4938	99.993 pure; polycrystal; 1.6 mm dia x 4 cm long; made from Johnson Matthey metal; in superconducting state.
24	1215	Roizin, N.M., Mostovlyanskii, N.S., and Strod, R.K.	1964	L	313-417		99.997 pure.
25	693, 694	Jones, R.E. and Toxen, A.M.	1960	L	1.4-3.3		Spectroscopically pure; polycrystalline; ~0.5 mm in dia; extruded; annealed at room temp for several months; electrical resistivity ratio ρ(room temp)/ρ(0 K) estimated to be 11000; in superconducting state.
26	693, 694	Jones, R.E. and Toxen, A.M.	1960	L	1.4-4.0		The above specimen measured in a longitudinal magnetic field; in normal state (data corrected to zero field).
27	849	Lindenfeld, P. and Rohrer, H.	1965	L	1.6-4.0	In 1	Bi as major impurity; specimen ~3 mm dia; In supplied by American Smelting and Refining Co.; cast in vacuum; annealed near melting point for at least 2 weeks; residual electrical resistivity 0.122 μohm cm; transition temp 3.39 K; measured in a magnetic field; in normal state.
28*	882	March, R.H. and Symko, O.G.	1965	L	0.023-0.70		99.999 pure (nominal); 0.5 mm dia x 5 cm long; supplied by Koch-Light Laboratories Ltd. (Colnbrook, England); measured in a longitudinal magnetic field of 350 gauss; in normal state.
29*	1216	Roizin, N.M., Mostovlyanskii, N.S., and Strod, R.K.	1963	L	312-415		99.997 pure.

* Not shown in figure.

TABLE 74. THERMAL CONDUCTIVITY OF INDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
30	115	Barisoni, M., Williams, R.K., and McElroy, D. L.	1968	L	80-340		0.002 Ag, 0.0015 Si, 0.0004 each of Ca, Cd, and K, 0.0002 each of Bi, Cu, Ti, Tl, and S, 0.00015 Fe, 0.0001 Pb, 0.0001 Zn, 0.00008 Ni, 0.00007 Al, 0.00006 Na, 0.00006 Th, 0.00005 each of Cr, Mn, and Sc, 0.00002 Mg, 0.00001 B, and 0.000005 Co; single crystal; specimen 0.79 cm in dia and 7.6 cm long; supplied by Semi Elements, Inc., Saxonburg, Penn.; density 7.285 g cm^{-3}; electrical resistivity reported as 1.7731, 2.3429, 2.9301, 3.5359, 4.1616, 4.8082, 5.4770, 6.1692, 6.8860, 7.6285, 8.3980, 9.1957, 10.0227, and 10.8802 μohm cm at 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, and 340 K, respectively; heat flow perpendicular to c-axis; thermal conductivity values obtained from smooth data corrected for thermal expansion.
31	115	Barisoni, M., et al.	1968	L	80-340		Specimen from the same lot as the above specimen; 0.79 cm in dia and 7.6 cm long; electrical resistivity reported as 1.7734, 2.3087, 2.8661, 3.4456, 4.0470, 4.6699, 5.3143, 5.9799, 6.6666, 7.3742, 8.1025, 8.8512, 9.6202, and 10.4094 at 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, and 340 K, respectively; heat flow parallel to c-axis; thermal conductivity values obtained from smooth data corrected for thermal expansion.
32	115	Barisoni, M., et al.	1968	L	80-320	Specimen PC	0.003 Ag, 0.003 Zn, 0.001 Cd, 0.0007 Tl, 0.0007 S, 0.0005 Fe, 0.0004 Pb, 0.0002 each of Cu, Na, and Th, 0.00015 each of Cr, and Si, 0.0001 each of Ca, K, and Sc, 0.00005 Bi, 0.00004 Ti, 0.00003 B, 0.00002 each of Al and Mg, 0.000008 Ni, and 0.000005 Co; polycrystalline; specimen 0.79 cm in dia and 7.6 cm long; supplied by Semi Elements Inc., Saxonburg, Penn.; density 7.281 g cm^{-3}; electrical resistivity reported as 1.7584, 2.3186, 2.8930, 3.4838, 4.0929, 4.7225, 5.3744, 6.0508, 6.7536, 7.4849, 8.2466, and 9.0408 at 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, and 300 K, respectively; electrical resistivity ratio $\rho_{273K}/\rho_{4.2K}$ = 10.7 x 10^3; thermal conductivity values obtained from smooth data corrected for thermal expansion.
33	1582	Wyder, P.	1964	L	1.6-3.3		High purity; wire specimen 1.43 mm in dia; extruded; annealed at room temp for several wks; in superconducting state.
34	1582	Wyder, P.	1964	L	1.6-3.4		The above specimen measured in a longitudinal magnetic field; in normal state.
35*	1582	Wyder, P.	1964	L	2.0-3.2		Similar to the above specimen but 0.485 mm in dia; in superconducting state.
36	1582	Wyder, P.	1964	L	1.8-3.4		The above specimen measured in a longitudinal magnetic field; in normal state.
37*	1582	Wyder, P.	1964	L	1.6-3.3		Similar to the above specimen but 0.282 mm in dia; in superconducting state.
38	1582	Wyder, P.	1964	L	1.6-3.4		The above specimen measured in a longitudinal magnetic field; in normal state.
39*	1582	Wyder, P.	1964	L	1.7-3.2		Similar to the above specimen but 0.186 mm in dia; in superconducting state.
40	1582	Wyder, P.	1964	L	1.6-3.4		The above specimen measured in a longitudinal magnetic field; in normal state.
41*	1582	Wyder, P.	1964		1.9-3.2		Similar to the above specimen but 0.094 mm in dia; in superconducting state.
42	1582	Wyder, P.	1964		1.8-3.4		The above specimen measured in a longitudinal magnetic field; in normal state.

* Not shown in figure.

TABLE 74. THERMAL CONDUCTIVITY OF INDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
43*	1582	Wyder, P.	1963	L	2.8		High purity; disk specimen 1.3 mm thick; in superconducting state.
44*	1582	Wyder, P.	1963	L	2.8		The above specimen measured in normal state.
45*	1582	Wyder, P.	1963	L	2.8		High purity; disk specimen 0.5 mm thick; in superconducting state.
46*	1582	Wyder, P.	1963	L	2.8		The above specimen measured in normal state.
47*	1582	Wyder, P.	1963	L	2.8		High purity; disk specimen 0.3 mm thick; in superconducting state.
48*	1582	Wyder, P.	1963	L	2.8		The above specimen measured in normal state.
49*	1582	Wyder, P.	1963	L	2.8		High purity; disk specimen 0.2 mm thick; in superconducting state.
50*	1582	Wyder, P.	1963	L	2.8		The above specimen measured in normal state.
51*	1582	Wyder, P.	1963	L	2.8		High purity; disk specimen 0.1 mm thick; in superconducting state.
52*	1582	Wyder, P.	1963	L	2.8		The above specimen measured in normal state.
53	1424	Toxen, A. M., Chang, G. K., and Jones, R. E.	1962	L	1.7-3.3	A	0.17 Hg; polycrystalline; wire specimen; extruded; in superconducting state.
54	1424	Toxen, A. M., et al.	1962	L	1.5-4.0	A	The above specimen measured in normal state.
55	1595	Yurchak, R. P. and Smirnov, B. P.	1969	E	295-419		In solid state; Lorenz function 2.51, 2.50, 2.50, and 2.47 x 10^{-8} V^2 K^{-2} at 250, 300, 350, and 424 K, respectively; melting point 429 K.
56	1595	Yurchak, R. P. and Smirnov, B. P.	1969	E	432-891		In liquid state; Lorenz function 3.00, 2.88, 2.81, 2.75, 2.69, 2.64, 2.59, 2.55, and 2.39 x 10^{-8} V^2 K^{-2} at 435, 451, 466, 483, 507, 530, 582, 632, and 894 K, respectively.
57	340	de la Cruz, M. E., de la Cruz, F., Cotignola, J. M., Bressan, O. J., and Luengo, C. A.	1968	L	1.8-3.3		99.9999 pure; polycrystalline; supplied by Consolidated Mining and Smelting Co., Canada, Ltd; rectangular specimen with the ratio of cross sectional area to length A/L = 3.96 x 10^{-3} cm; rolled between Teflon plates to 1.5 mm thick; electrical resistivity 9.1 μohm cm at 293 K; in superconducting state.
58	340	de la Cruz, M. E., et al.	1968	L	1.5-3.9		The above specimen measured in normal state.
59*	340	de la Cruz, M. E., et al.	1968	L	2.22		The above specimen measured in longitudinal magnetic fields ranging from 310 to 11 030 oersted.
60*	340	de la Cruz, M. E., et al.	1968	L	3.60		The above specimen measured in longitudinal magnetic fields ranging from 90 to 11 040 oersted.

* Not shown in figure.

Iodine

The thermal conductivity of iodine in each of the physical states is discussed separately below.

Solid

Only one experimental determination of the thermal conductivity of solid iodine has been located, four data points of Pochettino and Fulcheris [1095] from 298 to 316 K.

The provisional values here presented were read from a smooth curve drawn through the [1095] data in such a manner as to parallel the general trend of curves for other nonmetallic solids. They can thus be said to rely upon a corresponding-state principle, the validity of which, in this case, is not presently established. Therefore, no estimate of the accuracy of the values is possible except within the range of 300 to 330 K where an uncertainty of ten percent is likely.

Saturated Liquid

No experimental values were located for the thermal conductivity of saturated liquid iodine. The proposed values presented here are based on the correlation of Schaefer and Thodos [1257]. In the complete absence of any thermal conductivity values for the saturated liquid, saturated vapor, or vapor at atmospheric pressure, the values must be regarded as provisional and of uncertain accuracy.

Saturated Vapor

No experimental values were located for the thermal conductivity of saturated iodine vapor. The proposed values presented here are based on the correlation of Schaefer and Thodos [1257]. In the complete absence of any thermal conductivity values for the saturated liquid, saturated vapor, or vapor at atmospheric pressure, the values must be regarded as provisional and of uncertain accuracy.

Gas

No experimental values were located for the thermal conductivity of iodine at atmospheric pressure. The experimental data of Franck [454] were obtained for temperatures of 447, 579, and 693 K at pressures of 0.072, 0.158, and 0.230 atmospheres. A considerable variation in the thermal conductivity occurred with pressure at these temperatures. The Franck data were employed in the construction of a correlation for the thermal conductivity of diatomic substances by Schaefer and Thodos [1257]. It would appear that that correlation considered the highest pressure data cited by Franck only, i.e., that for 0.072 atm at 447 K and 0.230 atm at 579 and 693 K.

The proposed values were obtained from the correlation and must be regarded as provisional. A more detailed analysis which considers dimerization, dissociation, etc., is highly desirable. However, the present state of the art in calculating the thermal conductivity of such a system is by no means developed to a satisfactory stage. Possibly a twenty-five percent error estimate is reasonable for the values presented here.

TABLE 75. Provisional thermal conductivity of iodine

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid (Polycrystalline)		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
250	5.12*	386.8	1.16*	350	0.038*
273.2	4.81*	400	1.14*	375	0.041*
275	4.79*	425	1.11*	400	0.044*
300	4.49	450	1.07*	425	0.047*
325	4.24	475	1.03*	450	0.050*
350	4.01*	500	0.99*	475	0.053*
375	3.83*	525	0.95*	500	0.056*
386.8	3.75*	550	0.90*	525	0.060*
		575	0.86*	550	0.064*
		600	0.82*	575	0.069*
		625	0.77*	600	0.074*
		650	0.71*	625	0.079*
		675	0.65*	650	0.085*
		700	0.58*	675	0.093*
		725	0.51*	700	0.104*
		750	0.43*	725	0.119*
		775	0.32*	750	0.143*
		785	0.26*‡	775	0.186*
				785	0.26*‡

Gas (At 1 atm)

T	$k\times10^3$	T	$k\times10^3$
457.5	0.051		
475	0.052	600	0.065
500	0.055	625	0.068
525	0.058	650	0.071
550	0.060	675	0.073
575	0.063	700	0.076
		725	0.079*
		750	0.082*
		775	0.084*
		800	0.087*

*Estimated or extrapolated.
‡Pseudo-critical value.

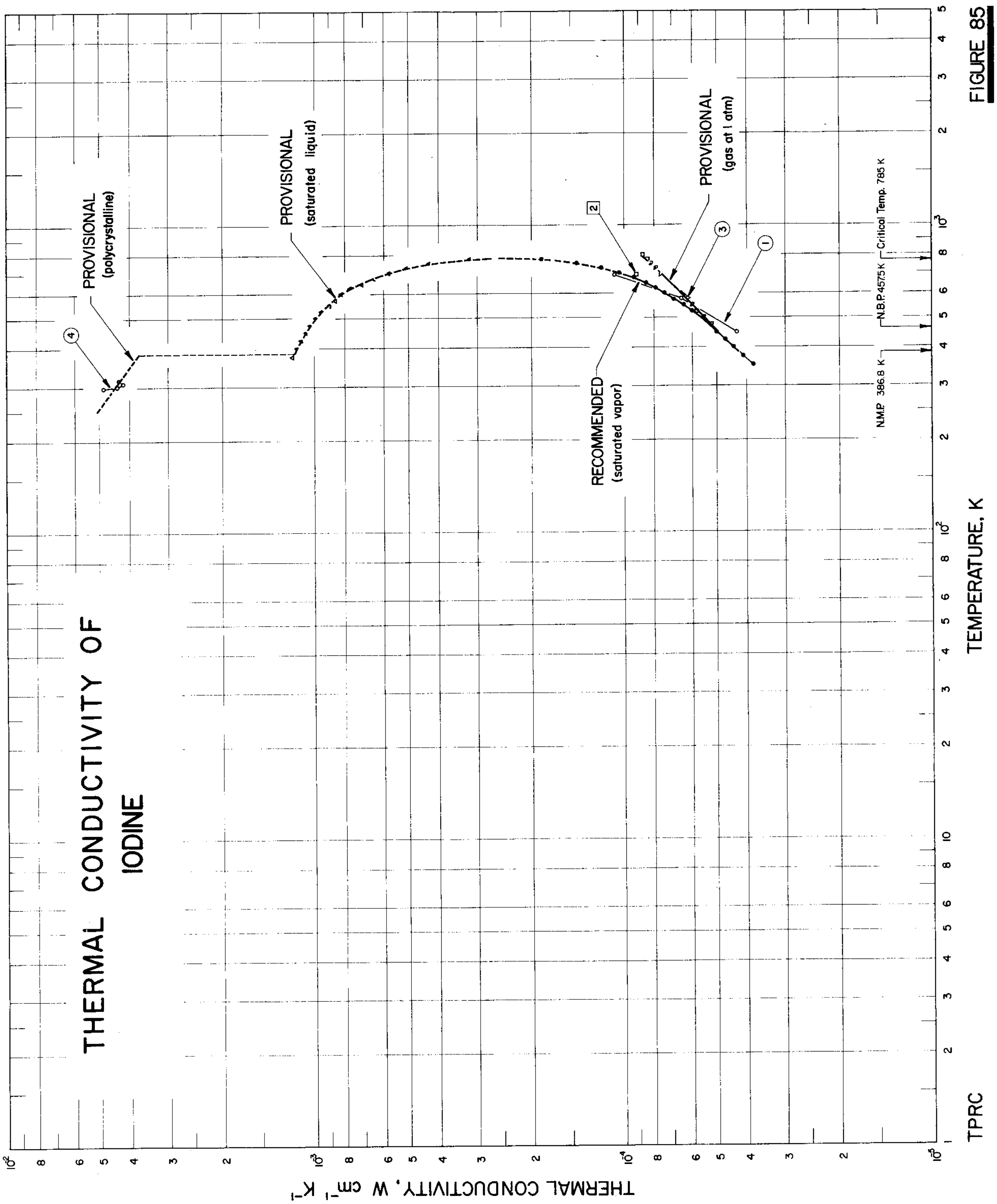


FIGURE 85
THERMAL CONDUCTIVITY OF
IODINE
PROVISIONAL
(polycrystalline)
PROVISIONAL
(saturated liquid)
PROVISIONAL
(gas at 1 atm)
RECOMMENDED
(saturated vapor)
N.M.P. 386.8 K
N.B.P. 457.5 K
Critical Temp. 785 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

Iridium

Two sets of measurements are available for the thermal conductivity of iridium at low temperature. The sample (curve 1) tested by Mendelssohn and Rosenberg [937] and Rosenberg [1220] had an electrical resistivity ratio ρ_{273}/ρ_{20} of 225 so was considerably purer than the sample studied by White and Woods [1545] (curve 2) for which the corresponding ratio was about 47. The recommended curve, which is for a sample having $\rho_0 = 0.0191\ \mu\Omega$ cm, has been mathematically fitted to the data of Rosenberg using $m = 4.40$, $n = 3.00$, $\alpha'' = 2.72 \times 10^{-4}$, and $\beta = 0.781$ and extrapolated beyond his upper limit to the liquid nitrogen temperature region. Here it still lies about 2 percent above the upper limit of the measurements of White and Woods but agrees more closely with the data of Powell, Tye, and Woodman [1141] (curves 6 and 7). It follows closer to the higher of the two sets of results of these workers to about 500 K and has a gradually decreasing slope over the range 100 to 350 K and a linear decrease to 500 K.

The present upper limit of the thermal conductivity determinations on iridium is 493 K, but from 300 to 500 K the curve now recommended yields a Lorenz function that increases from about 2.62×10^{-8} to $2.66 \times 10^{-8}\ V^2\ K^{-2}$. The linear extrapolation of the recommended curve to 1500 K together with the electrical resistivity values of Powell, Tye, and Woodman [1141] gives Lorenz functions of $(2.65 \pm 0.10) \times 10^{-8}\ V^2\ K^{-2}$ and it is suggested that this extrapolation could be used to give provisional values for the thermal conductivity of iridium at high temperatures.

No information is available for the thermal conductivity of molten iridium.

The recommended values are thought to be accurate to within ±5 percent of the true values below 500 K and ±10 percent above 500 K. The values at temperatures below 150 K are, of course, applicable only to a sample having $\rho_0 = 0.0191\ \mu\Omega$ cm.

TABLE 76. Recommended thermal conductivity of iridium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	1.50
1	1.30*	273.2	1.48
2	2.60	298.2	1.47
3	3.90	300	1.47
4	5.19	323.2	1.47
5	6.48	350	1.45
6	7.77	373.2	1.45
7	9.04	400	1.44
8	10.3	473.2	1.42
9	11.5	500	1.41*
10	12.7	573.2	1.39*
11	13.8	600	1.38*
12	14.9	673.2	1.36*
13	15.9	700	1.35*
14	16.7	773.2	1.33*
15	17.5	800	1.32*
16	18.1	873.2	1.30*
18	18.9	900	1.29*
20	19.0	973.2	1.27*
25	17.2	1000	1.26*
30	13.7	1073.2	1.24*
35	10.1	1100	1.23*
40	7.50	1173.2	1.21*
45	5.89	1200	1.20*
50	4.72	1273.2	1.18*
60	3.31	1300	1.17*
70	2.54	1373.2	1.15*
80	2.09	1400	1.14*
90	1.84	1473.2	1.12*
100	1.72	1500	1.11*
123.2	1.65		
150	1.59		
173.2	1.56		
200	1.53		
223.2	1.51		

†The recommended values are for well-annealed high-purity iridium, and those below 150 K are applicable only to a specimen having $\rho_0 = 0.0191\ \mu\Omega$ cm.

*Extrapolated.

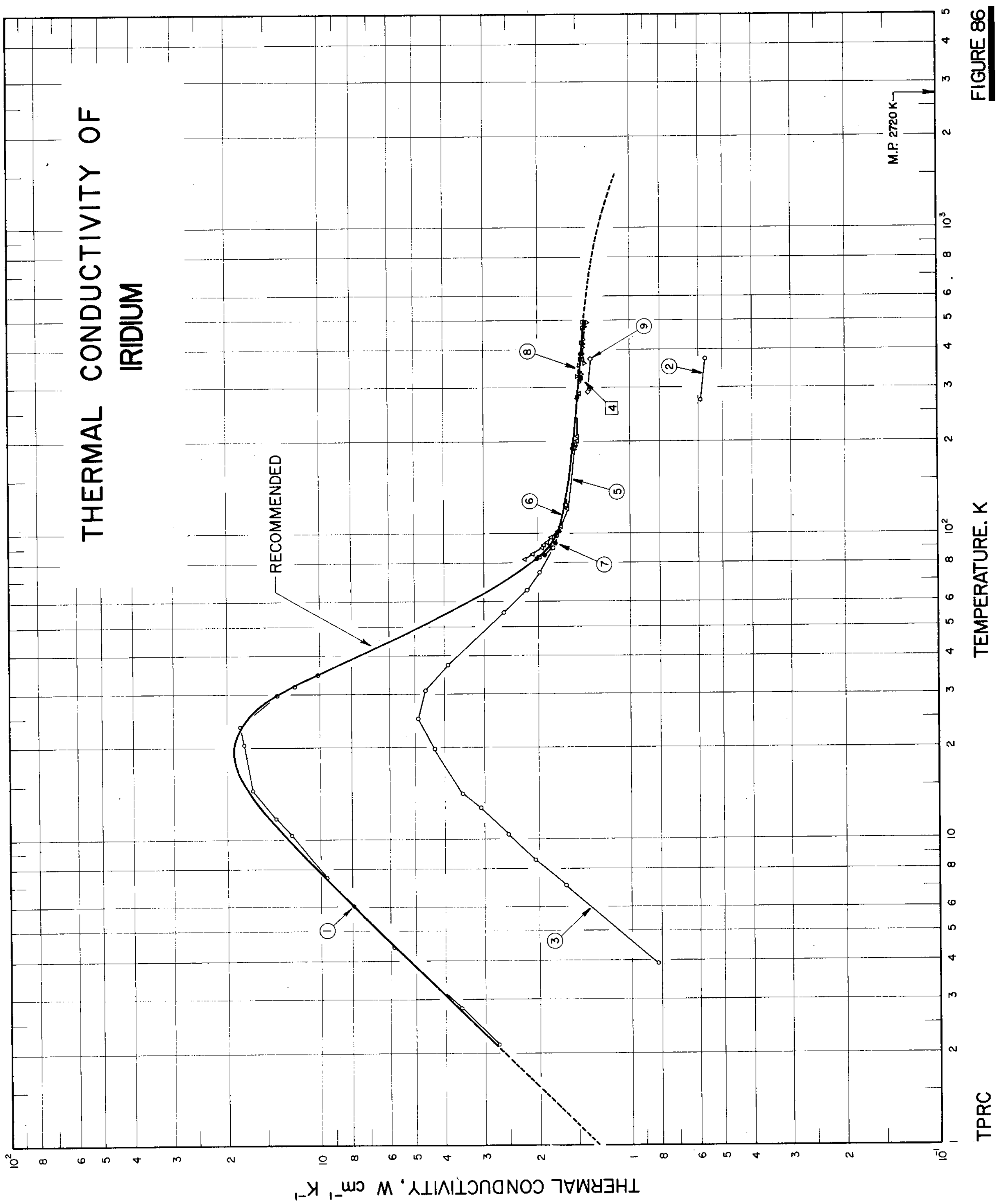

THERMAL CONDUCTIVITY OF
IRIDIUM
RECOMMENDED
M.P. 2720 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 86

TABLE 77. THERMAL CONDUCTIVITY OF IRIDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.2-35	JM 3441; Ir 1	99.995 pure; 1-2 mm dia x 5 cm long; supplied by Johnson Matthey; annealed; electrical resistivity ratio $\rho(293\ K)/\rho(20\ K) = 225$.
2	116	Barratt, T.	1914	F	290,373		Pure; square cross section 0.103 x 0.103 cm, 10.0 cm long; specific gravity 22.33; electrical resistivity reported as 8.190, 8.480, 10.521, and 10.59 μohm cm at 0, 12.11, 97.20, and 100 C, respectively.
3	1545	White, G.K. and Woods, S.B.	1957	L	3.9-90	JM 10371; Ir 2	99.98^+ pure; approx impurities: 0.01 Rh, 0.002 Pt, and 0.001 Cu; 2 mm dia x 5-7 cm long; supplied by Johnson Matthey; annealed at 1300 C; residual electrical resistivity $(\rho_0) = 0.1034\ \mu$ohm cm; electrical resistivity ratio $\rho(295\ K)/\rho(0\ K) = 49.5$; Lorenz function $2.50 \times 10^{-8} V^2 K^{-2}$ at 0 K.
4	1129	Powell, R.W. and Tye, R.P.	1955	C	323.2		Impurities estimated: 0.02-0.05 Rh, 0.002-0.005 Ru, and 0.001 Pd; 5 cm long, 0.3182 cm in dia; supplied by Johnson Matthey; annealed at 1313 C; density 22.49 g cm^{-3}.
5	1129	Powell, R.W. and Tye, R.P.	1955	L	83-289		The above specimen; electrical resistivity reported as 0.79, 0.85, 0.95, 1.00, 1.02, 1.10, 1.20, 1.29, 1.59, 3.05, 3.17, 3.31, 3.43, 4.83, 4.92, and 5.07 μohm cm at -190.5, -187.5, -183.2, -180.8, -179.6, -175.8, -171.2, -166.9, -152.7, -82.2, -77.0, -70.0, -64.1, 4.3, 8.8, and 16.1 C, respectively.
6	1141	Powell, R.W., Tye, R.P., and Woodman, M. J.	1962	L, C	83-493		0.02-0.05 Rh, 0.002-0.005 Ru, and 0.001 Pd; 5.0 cm long, 0.318 cm in dia; supplied by Johnson Matthey; heated to 1310 C; density 22.43 g cm^{-3}; electrical resistivity 4.71 μohm cm at 273 K; residual electrical resistivity 0.055 μohm cm; data obtained by using two methods of measurement for low and moderate temp ranges; Armco iron used as comparative material for the moderate temp measurement.
7	1145	Powell, R.W., Tye, R.P., and Woodman, M.J.	1967	L	83-386		0.02-0.05 Rh, 0.002-0.005 Ru, and 0.001 Pd; specimen 0.318 cm in dia and 5 cm long; supplied by Johnson Matthey; annealed at 1590 K; density 22.43 g cm^{-3}; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 85.7$; electrical resistivity reported as 1.16, 3.25, 5.33, 7.39, and 9.42 μohm cm at 100, 200, 300, 400, and 500 K, respectively.
8	1145	Powell, R.W., Tye, R.P., and Woodman, M.J.	1967	C	315-492		The above specimen measured in a comparative apparatus using Armco iron as reference material.
9	617	Holborn, L., Scheel, K., and Henning, F. (editors)	1919	E	291,373		Cast rod; electrical conductivity 18.9 and 14.4 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively; thermal conductivity data measured by Jaeger, W. and Diesselhorst, H.

Iron

It is interesting to note that iron was included as a specimen in nearly all the experiments in the early historical developments of the thermal conductivity measurements. The first known experiments on the thermal conductivity of solids were those of Fordyce [451e], who pioneered in 1787 with experiments on the "conducting powers" of iron and pasteboard. Iron was one of the specimens in the earliest steady-state comparative measurements of Ingen-Hausz [655a] in 1789, and in the subsequent well-known comparative measurements of Despretz [349a, 349b] in 1822 and 1827 and of Wiedemann and Franz [1556a] in 1853. It was iron that Forbes [451a–451d] measured in his development in 1851–52 of the first absolute method for measuring the thermal conductivity of solids. Iron was also measured by Angström [75, 75a] in his development of the first nonsteady-state periodic heat flow method in 1861–63 and by Neumann [1025a] in his development of the first nonsteady-state transient heat flow method in 1862.

At low temperatures Arajs, et al. [86] appear to have worked with the purest iron so far studied, but the values of T_m of their thermal conductivity curves (curves 34 and 35) appear to be displaced on the high side by several degrees, and the β-value of 0.585 derived from the thermal conductivity data is much smaller than that of 1.34 derived from the residual electrical resistivity, which is estimated to be 0.0327 $\mu\Omega$ cm. At the present, his residual electrical resistivity value is ignored, and the recommended thermal conductivity values below 1.5 T_m are calculated to fit the first several points of curve 34 by using equation (7) and $m = 2.20$, $n = 2.00$, $\alpha'' = 0.517 \times 10^{-4}$, and $\beta = 0.585$. Above 1.5 T_m, the recommended curve continues smoothly, following the general trend, to join the moderate and high temperature curve discussed below.

Above room temperature, the Oak Ridge National Laboratory workers, Fulkerson, Moore, and McElroy [467] (curve 32) have used the same radial heat flow method for measurements on both Armco iron and iron of high purity over the range 323 to 1273 K. From a linear plot of the thermal conductivity at 373 K against the equivalent carbon content of the two irons they obtained a value for the thermal conductivity of an iron with no impurities. This seems a reasonable procedure, and the values thought to be most probable for pure iron above 323 K have been obtained by applying the same increase to the recommended values for Armco iron as the ORNL workers found when comparison was made with their own Armco iron results.

Partial independent confirmation for these ORNL values is furnished by some results obtained at the National Physical Laboratory [1015] (curve 98) for another sample of high purity iron. The two sets of values are known to be in close agreement particularly in the 900 to 1200 K region. The ORNL data suggest a higher temperature coefficient for gamma iron of high purity, but this requires confirmation over a wider range of temperatures and has been largely ignored in making the present recommendations. Further support in the 1173–1273 K region has come from the Lorenz function values obtained by Hopkins and Jones [633] with the necked-down-sample method. At temperatures of 1223 and 1273 K their Lorenz functions are respectively only 1.5 percent above and 0.4 percent below the ORNL pure iron values.

From 1273 to 1673 K, the values were extrapolated [1126] using a lower temperature coefficient than that indicated by the ORNL data which cover up to 1273 K only. These extrapolated values [1126] were supported by the subsequent measurements of Zinov'ev, et al. [1615] (curve 87) whose data are well within 2 percent of the proposed values.

No information is available for the thermal conductivity of δ-iron. The recommended values for γ-iron have been linearly extrapolated to the melting point without a discontinuity at the γ-δ phase transformation at 1673 K, since the available electrical resistivity data [1419] show no discontinuity at this phase transformation.

No experimental thermal conductivity data are available for molten iron. The limited information available for the electrical resistivity of iron in the vicinity of the melting point indicates iron to be unusual in having relatively little change on passing from the solid to the liquid state. Powell [1115] reported an increase in the electrical resistivity of about 9 percent for the liquid state, and Mokrovskii and Regel [980] reported a slightly larger decrease. In view of the close correspondence found for other metals between the two conduction processes, it seems that only a small change is to be expected in the thermal conductivity of iron at the melting point. Near the melting point the thermal conductivity of liquid iron is probably 0.35 $\pm$0.08 W cm^{-1} K^{-1}. Grosse [546] (curve 97), by using only the electrical resistivity data of Mokrovskii and Regel, predicted a value of 0.403 W cm^{-1} K^{-1} at the melting point followed by a smooth curve rising to a maximum value of 0.458 W cm^{-1} K^{-1} at 2796 K and falling to near zero at 6750 K, the critical point. Iron is clearly another metal for which further electrical conductivity measurements are required, particularly for the molten phase. The unusually small change on melting should be an incentive, but, in addition, there is a difference of some 20 percent between the electrical resistivity data now available which serves to limit the reliability of any derived thermal conductivity data for molten iron. At present, the predicted values of Grosse have been adopted as the provisional values for molten iron from its melting point to the critical point.

The recommended values are for well-annealed high-purity iron, and those below 200 K are applicable only to a specimen having a residual electrical resistivity of 0.0143 $\mu\Omega$ cm. The values are thought to be accurate to within $\pm$5 percent below 100 K, $\pm$3 percent from 100 K to room temperature, $\pm$2 percent from room temperature to about 1000 K, the uncertainty probably increasing to about $\pm$8 percent at 1600 K and ±15 percent at the melting point. The provisional values for molten iron are very uncertain.

It seems amazing that the first several absolute thermal conductivity values that Forbes obtained 120 years ago [451a–451d] (curve 90) for iron in the temperature range from 298 to 398 K are within 1 percent to 2.7 percent of the recommended values. Angström's value obtained in 1863 [75a] (curve 89) for iron at 273 K is within 0.3 percent of the recommended value, though his value at 343 K is 9 percent too high.

In the following subsection, the thermal conductivity of a commercial grade of iron known as Armco iron is discussed. The recommended values for Armco iron are also given in addition to those for high-purity iron, because Armco iron has been extensively used as a reference standard of thermal conductivity.

TABLE 78. Recommended thermal conductivity of iron†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid	
T	k	T	k	T	k
0	0	250	0.865	1810	0.403*
1	1.71*	273.2	0.835	1873.2	0.413*
2	3.42	298.2	0.804	1900	0.415*
3	5.11	300	0.802	1973.2	0.423*
4	6.77	323.2	0.774	2000	0.426*
5	8.39	350	0.744	2073.2	0.432*
6	9.93	373.2	0.720	2173.2	0.439*
7	11.4	400	0.695	2200	0.441*
8	12.7	473.2	0.634	2273.2	0.446*
9	13.9	500	0.613	2400	0.450
10	14.8	573.2	0.564	2473.2	0.452*
11	15.6	600	0.547	2600	0.455*
12	16.3	673.2	0.504	2673.2	0.456*
13	16.7	700	0.488	2800	0.458*
14	16.9	773.2	0.448	2873.2	0.459*
15	17.0	800	0.433	3000	0.458*
16	16.9	873.2	0.394	3073	0.458*
18	16.3	900	0.380	3200	0.456*
20	15.4	973.2	0.342	3273	0.454*
25	12.7	1000	0.328	3400	0.451*
30	10.0	1059	0.297	3600	0.442*
35	7.88	1073.2	0.298	3800	0.430*
40	6.23	1100	0.298	4000	0.415*
45	4.99	1173.2	0.300	4500	0.368*
50	4.05	1183	0.300	5000	0.308*
60	2.85	1183	0.280	5500	0.233*
70	2.16	1200	0.283	6000	0.147*
80	1.75	1273.2	0.296	6500	0.051*
90	1.50	1300	0.300		
100	1.34	1373.2	0.309		
123.2	1.15	1400	0.312		
150	1.04	1473.2	0.319		
173.2	0.991	1500	0.321		
200	0.940	1573.2	0.327		
223.2	0.904	1600	0.330		
		1673.2	0.335*		
		1700	0.338*		
		1773.2	0.343*		
		1800	0.345*		
		1810	0.346*		

†The values are for well-annealed high-purity iron, and those below 200 K are applicable only to a specimen having $\rho_o = 0.0143$ $\mu\Omega$ cm. The values for molten iron are provisional.

*Extrapolated or estimated.

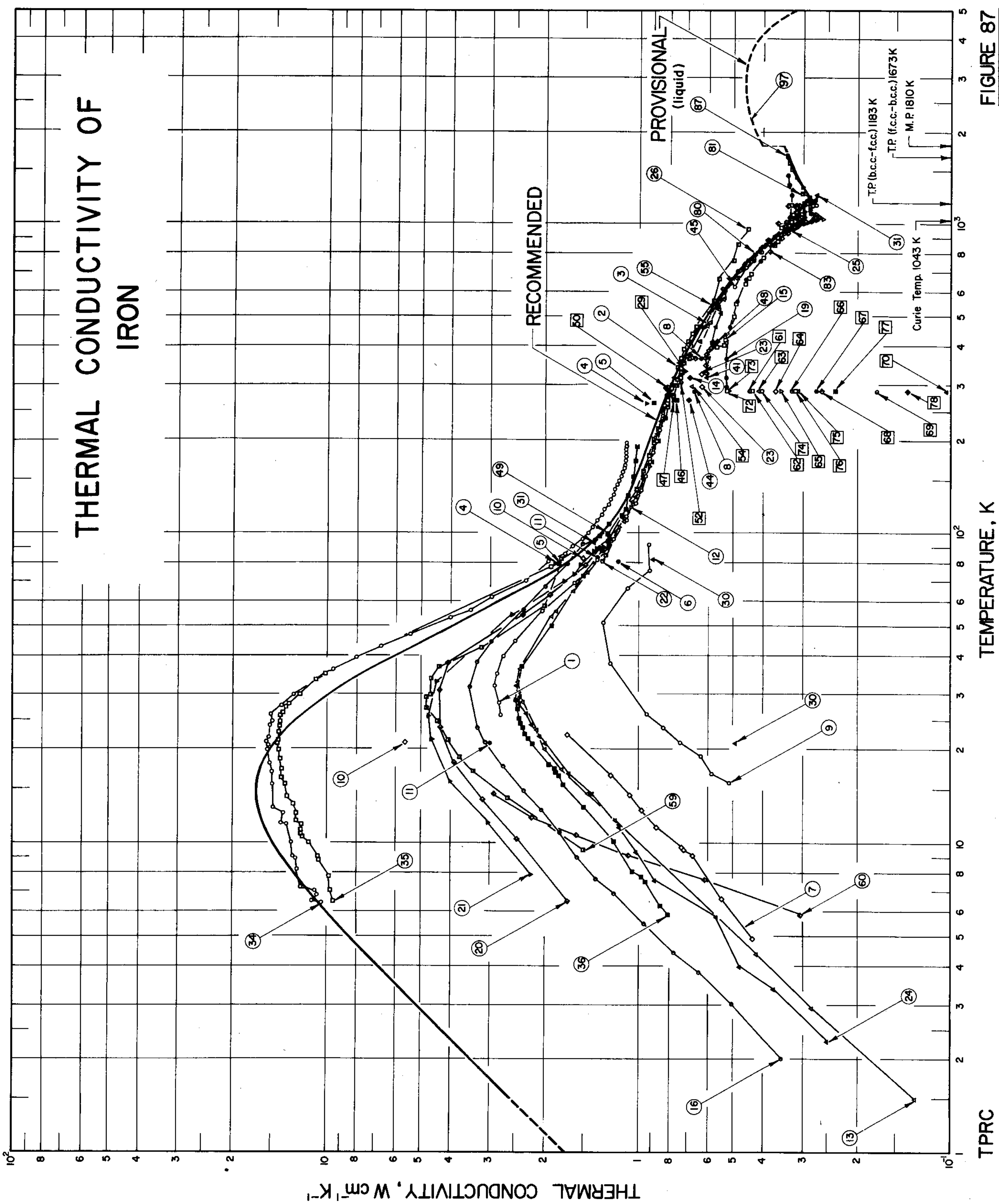
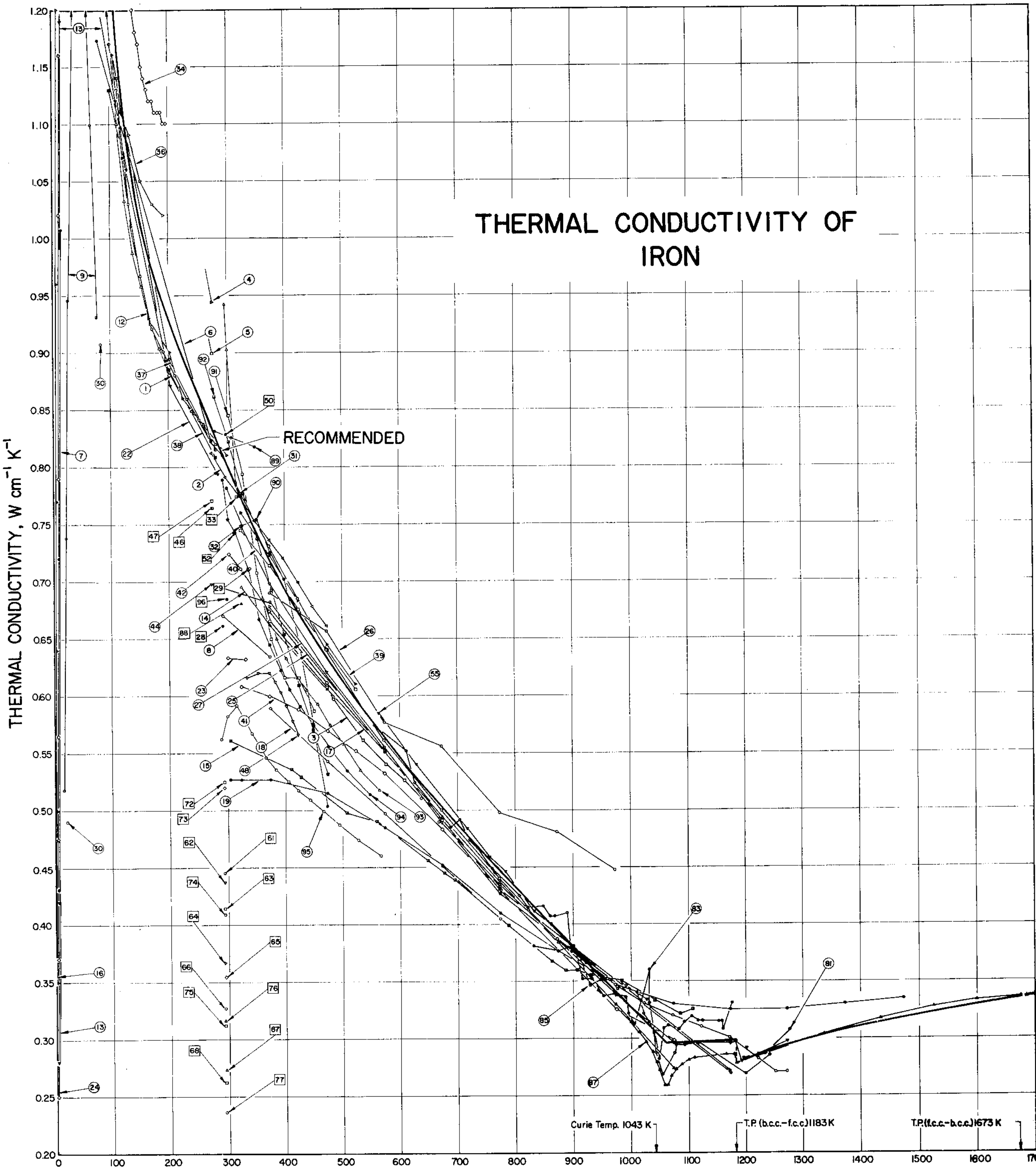

THERMAL CONDUCTIVITY OF IRON
RECOMMENDED
PROVISIONAL (liquid)
T.P. (b.c.c.-f.c.c.) 1183 K
T.P. (f.c.c.-b.c.c.) 1673 K
M.P. 1810 K
Curie Temp. 1043 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 87



TPRC

FIGURE 88

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1155	Powers, R.W., Ziegler, J.B., and Johnston, H.L.	1951	L	26-292		99.99 pure; supplied by Johnston Mackay Ltd.
2	23	Adcock, F. and Bristow, C.A.	1935	L	273-473		0.0045 C, 0.002 Mn, 0.0015 S, 0.001 P, 0.0006 Ni, 0.0002 Si, traces of Al and Mg; 1 cm dia x 15 cm long; density 7.871±0.002 g cm^{-3}; electrical resistivity reported as 11.5, 14.5, and 17.8 μohm cm at 50, 100, and 150 C, respectively; data taken from smoothed curve.
3	1302, 1301	Shelton, S.M. and Swanger, W.H.	1933	C	373-772	Basic open hearth iron	0.042 P, 0.03 Mn, 0.02 C, and 0.005 S; hot-rolled to 1 in. bar; high-purity lead used as comparative material; data taken from smoothed curve.
4	404	Eucken, A. and Dittrich, K.	1927	L	80,273	Electrolytic iron; 1	Coarse-grained; electrical conductivity reported as 121 and 10.4 x 10^4 ohm^{-1} cm^{-1} at 80 and 273 C, respectively.
5	404	Eucken, A. and Dittrich, K.	1927	L	80,273	Electrolytic iron; 2	Fine-grained; electrical conductivity reported as 121 and 9.7 x 10^4 ohm^{-1} cm^{-1} at 80 and 273 C, respectively.
6	404	Eucken, A. and Dittrich, K.	1927	L	80,273	Electrolytic iron; 3	Obtained from Firma Heraeus; electrical conductivity reported as 61.2 and 9.4 x 10^4 ohm^{-1} cm^{-1} at 80 and 273 C, respectively.
7	717	Karweil, J. and Schaefer, K.	1939	L	4.9-23	Electrolytic iron	Extremely pure; 2.545 mm dia x 12.32 cm long; electrical resistivity ratio $\rho(273K)/\rho_0$ = 29.4.
8	664	Jaeger, W. and Diesselhorst, H.	1900	E	291,373	Fe 1	0.1 C; 1.3007 cm dia x 27.0 cm long; density 7.84 g cm^{-3} at 18 C; electrical conductivity reported as 8.357 and 5.950 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
9	345	de Nobel, J.	1951	E	16-93	6936	99.93 pure; forged; measured in a vacuum of 5 x 10^{-6} mm Hg.
10	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Fe 1	Electrolytically refined; cold-worked and annealed; electrical resistivity reported as 0.0681, 0.778, and 8.71 μohm cm at -252, -190, and 0 C, respectively.
11	559	Grüneisen, E. and Goens, E.	1927	L	21,83	Fe 2	Technically pure; polycrystalline; electrolytically precipitated; electrical resistivity reported as 0.1437, 0.929, and 9.11 μohm cm at -252, -190, and 0 C, respectively.
12	774, 775	Kohlhaas, R. and Kierspe, W.	1964	L	88-300		0.0640, 0.0027 C, 0.002 S, 0.001 Mn, 0.001 N, 0.001 Si, and trace Cr; electrical resistivity reported as 1.22, 5.60, 6.50, 7.65, 8.96, 10.0, 11.3, 12.5, and 13.6 μohm cm at 83, 203, 223, 248, 273, 293, 313, 333, and 353 K, respectively.
13	738	Kemp, W.R.G., Klemens, P.G., and White, G.K.	1956	L	1.5-128	JM 5092	99.99 Fe, 0.005 Ni, 0.0002 Cu, 0.0001 Ag, traces of Mn and Mg; 2 mm dia rod supplied by Johnson, Matthey and Co.; annealed at 750 C for 4 hrs in vacuo; electrical resistivity reported as 0.248 and 10.0 μohm cm at 4.2 and 293 K, respectively.
14	1315	Silverman, L.	1953	C	323-1073	Swedish iron	0.028 Si, 0.026 C, 0.021 P, 0.02 Mn, and 0.011 S; annealed in vacuum at 900 C; Advance (55 Cu-45 Ni) used as comparative material.
15	628	Honda, K. and Simidu, T.	1917	L	303-1107	Swedish iron	Pure; cylindrical specimen of 1 cm dia x 8 cm long with a cavity of 6 mm dia x 16 mm long in its middle portion; electrical resistivity reported as 15.3, 20.0, 23.1, 26.3, 32.0, 36.4, 43.6, 45.3, 53.1, 61.6, 76.4, 80.7, 90.2, 92.1, 98.7, 100.0, 100.7, 102.2, 105.8, 108.6, 110.3, 111.3, 112.9, 113.8, 114.5, 115.1, 115.8, and 117.0 μohm cm at 30, 94, 140, 183, 254, 302, 375, 390, 462, 527, 627, 660, 700, 709, 742, 746, 751, 760, 772, 789, 810, 817, 851, 851, 862, 888, 890, and 901 C, respectively.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	1220	Rosenberg, H. M.	1955	L	2.0-93	JM 4975; Fe 1	99.99 pure; polycrystal; 0.020 cm diameter x 2.89 cm long; supplied by Johnson, Matthey and Co.; annealed in vacuo for several hrs at two thirds the melting temperature; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 67.8.
17	1301	Shelton, S. M.	1934	C	373-773		0.042 P, 0.03 Mn, 0.02 C, and 0.005 S; hot-rolled; lead used as comparative material; smoothed values reported.
18	1301	Shelton, S. M.	1934	C	373-773	Grade A wrought iron	0.265 Si, 0.136 P, 0.046 Mn, 0.04 C, and 0.025 S; lead used as comparative material; smoothed values reported.
19	904	Maurer, E.	1936	L	303-1473	PD 00	0.08 Mn, 0.022 S, 0.02 C, 0.016 P, and 0.01 Si.
20	737	Kemp, W. R. G., Klemens, P. G., and Tainsh, R. J.	1959	L	6.5-90	Electrolytic iron; 1	28 x 2.5 x 2.5 mm; doubly refined; cut out of a precipitated plate, annealed at 950 C, compressed, and reannealed in vacuo at 950 C; electrical resistivity ratio $\rho(273K)/\rho_0$ = 84.7 to 104.2; residual electrical resistivity 0.09 to 0.10 $\mu\Omega$ cm; specimen believed to be from the same material as that of Grüneisen, E. and Goens, E. (see curve No. 10).
21	737	Kemp, W. R. G., et al.	1959	L	7.9-90	2	Similar to the above specimen except dimensions 30 x 2.4 x 1.7 mm, and electrical resistivity reported as 0.092, 0.097, 0.100, 0.106, 0.120, 0.269, 0.368, 0.631, 0.744, 1.06, and 10.3 $\mu\Omega$ cm at 4.2, 15.2, 20.8, 26.1, 32.5, 54.4, 61.2, 74.2, 79.1, 90.2, and 293.0 K, respectively.
22	1557	Wilkes, K. E.	1968	L	82-373	18 AF 3	99.96 Fe, 0.007 Cu, 0.007 Ni, 0.0058 C, 0.004 Mn, 0.004 Si, 0.003 Si, 0.0023 N, 0.002 Cr, 0.001 Al, 0.001 P, and 0.0008 O; 1.247 cm dia. x 10.44 cm long; prepared by National Physical Laboratory, England; as received; density 7.872 g cm^{-3} at 24 C; electrical resistivity reported as 0.925, 5.26, 8.97, and 10.33 $\mu\Omega$ cm at 77.78, 194.8, 273.3, and 298.8 K, respectively; Lorenz function reported as 1.625, 1.885, 2.420, 2.704, and 2.884 x 10^{-8} V^2 K^{-2} at 70.2, 100, 200, 300, and 389.8 K, respectively; measured in a vacuum of 5 x 10^{-5} torr.
23	576	Hall, E. H.	1900	L	301, 331		99.93 Fe and 0.059 C; density 7.785 g cm^{-3}.
24	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-32	JM 4975; Fe 1	99.99 pure; 1-2 mm dia. x ~5 cm long; supplied by Johnson, Matthey and Co., Ltd.; annealed.
25	801	Kuprovskii, B. B. and Gel'd, P. V.	1956	R	372-1172		Pure.
26	1169	Ranque, G., Henry, P., and Chaussain, M.	1935	L	373-973		0.034 Mn, 0.03 C, 0.012 S, 0.005 P, and 0.003 Si.
27	485	Gel'd, P. V.	1957	R	373-1173		Pure.
28	758	Kikuchi, R.	1932	E	289.6	Electrolytic iron	Wire specimen of 200 mm long.
29	695	Jones, T. I., Street, K. N., Scoberg, J. A., and Baird, J.	1963	C	338.2		99.82 pure; 0.500 in. dia. x 3 in. long; hot-rolled; measured in a vacuum of < 5 x 10^{-4} mm Hg; nickel-plated copper used as comparative material.
30	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Fe 3	Polycrystalline; made by electrolytic method; hammered; tempered for 1 hr at 500 C; electrical resistivity reported as 1.060, 1.917, and 9.95 $\mu\Omega$ cm at -252, -100, and 0 C, respectively.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
31	1194, 1195, 1196	Richter, F. and Kohlhaas, R.	1964	R	93-1273		0.012 O, 0.008 P, 0.007 C, 0.007 Al, 0.004 S, and 0.002 N; test disks annealed for several hrs at 900 C; electrical resistivity reported as 1.1, 1.7, 2.4, 3.1, 4.0, 5.0, 5.9, 6.9, 7.9, 8.8, 9.87, 11.6, 14.7, 18.1, 21.4, 26.0, 30.1, 35.0, 40.3, 46.8, 53.3, 60.1, 68.0, 76.0, 84.6, 94.2, 102.1, 106.3, 109.0, 111.1, and 113.1 μohm cm at -180, -160, -140, -120, -100, -80, -60, -40, -20, 0, 20, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500; 550, 600, 650, 700, 750, 800, 850, 900, 950, and 1000 C, respectively.
32	467	Fulkerson, W., Moore, J.P., and McElroy, D.L.	1966	R	323-1273	High purity iron	99.95 Fe (approx.); 0.002-0.02 Si, 0.014 C, 0.00095-0.0095 Ni, 0.0088 O, <0.0056 H, 0.0052 S, 0.00021-0.0021 Al, 0.002 P, 0.002 N, 0.00014-0.0014 Ca, and 0.00009-0.0009 Cu; obtained by electron beam melting Armco iron; electrical resistivity reported as 0.40, 1.01, 5.31, 9.04, 11.72, 14.70, 18.06, 21.84, 26.10, 30.72, 35.90, 41.51, 47.53, 54.12, 61.22, 68.89, 77.10, 86.22, 96.46, 105.53, 109.58, 112.56, 113.09, 112.54, 113.66, and 115.49 μohm cm at -269, -195.7, -79.1, 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 910, 920, 950, and 1000 C, respectively.
33	124	Bednar, J., Broz, J., Smirous, K., and Trousil, Z.	1954	L	316.2		0.01 Si, traces of Ni, Cu, Al, Mn, Mo, and Ti (in order of decreasing amounts); 0.4 cm dia x 3.5 cm long; prepared by repeated electrolyses, machined; density 7.874 g cm^{-3}.
34	86	Arajs, S., Oliver, B.F., and Dunmyre, G.R.	1965	L	6.5-198	A-I	99.998$^+$ Fe; <0.0020 O, <0.0006 N, 0.0004 C, 0.0015 Co, 0.00011 Cu, 0.000065 Cr, 0.00002 Ti, 0.000019 Ge, and 0.000018 V; polycrystalline; specimen 0.305 cm in dia made from commercial electrolytic iron; fabricated by swaging to 0.483 cm dia with intermediate annealing treatments in Pd-purified hydrogen, and after the final annealing at 650 C for 0.5 hr, a 0.305 cm dia gauge section chemically polished into the specimen; final equiaxed grain size about 0.1 mm; electrical resistivity ratio $\rho(297K)/\rho(4.2K)$ = 302.
35	86	Arajs, S., et al.	1965	L	6.5-78	A-II	The second run of the above specimen.
36	86	Arajs, S., et al.	1965	L	6.0-193	B	99.925 Fe, 0.0230 C, 0.0140 O, 0.0116 S, 0.0100 Si, 0.0040 P, 0.0023 Cu, 0.0017 Ti, 0.0016 Zr, 0.0013 Ge, 0.0010 Ni, 0.0009 Cr, 0.0009 Mg, 0.0007 Mn, 0.0005 As, 0.0004 Co, and 0.0003 Ca; polycrystalline; specimen made by vacuum melting commercial electrolytic iron in the conventional fashion; annealed; electrical resistivity ratio $\rho(297K)/\rho(4.2K)$ = 27.1
37	100	Bäcklund, N.G.	1961	L	100-280		"Very pure"; manufactured by Philips Research Labs, Eindhoven, Holland; wire 2.5 mm in dia; annealed at about 500 C for 10 hrs; electrical resistivity 9.8 μohm cm at 20 C.
38	100	Bäcklund, N.G.	1961	L	100-280		Spectroscopically standardized iron from Johnson, Matthey and Co.; rod 5.0 mm in dia; annealed at about 500 C for 10 hrs; electrical resistivity 9.9 μohm cm at 20 C.
39	1137	Powell, R.W. and Tye, R.P.	1967	L	316-483	Pure iron No. 1	0.0250 Ni, 0.0100 Cu, 0.0100 Mo, 0.0070 Cr, 0.0050 C, 0.0040 O, 0.0040 S, 0.0040 V, 0.0030 P, 0.0010 Mn, <0.0010 Si, 0.0006 N, and 0.000048 H; 1.27 cm dia x 15 cm long; supplied by Metals Research; electrical resistivity reported as 11.7, 14.7, 17.9, 21.6, and 25.6 μohm cm at 50, 100, 150, 200, and 250 C, respectively.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
40	1137	Powell, R.W. and Tye, R.P.	1967	L	307-499	Pure iron No. 2	0.0055 Ni, 0.0053 Si, 0.0038 Al, 0.0035 S, 0.0020 Co, 0.0017 P, 0.0014 C, 0.0010 Cr, <0.0010 Mn, 0.0008 O, 0.0007 N, and 0.000016 H; short rod of 1.27 cm dia; prepared by Metallurgy Division of National Physical Lab; machined from a disk; electrical resistivity reported as 11.9, 14.9, 18.2, 21.8, 25.8, 30.3, 41.0, 53.3, 67.9, 85.2, and 104.2 μohm cm at 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, and 800 C, respectively.
41	1137	Powell, R.W. and Tye, R.P.	1967	L	323-573	Purefree iron	0.0800 Si, 0.0300 C, 0.0150 P, 0.0100 Mn, and 0.0100 S; 2.54 cm dia x 20 cm long; supplied by Low Moor Best Yorkshire Iron Limited; electrical resistivity reported as 15.8, 18.7, 22.0, 25.9, 30.0, 34.6, 45.0, 57.1, 71.0, 87.5, and 107.2 μohm cm at 50, 100, 150, 200, 250, 300, 400, 500, 600, 700, and 800 C, respectively.
42	904	Maurer, E.	1936	L	303-1473	II	0.05 Cu, 0.040 S, 0.02 Mn, 0.0011 P, 0.01 C, and trace of Si.
43*	318	Davey, G. and Mendelssohn, K.	1963		0.42-0.95		99.97 pure; polycrystalline wire; electrical resistivity measured by Mendelssohn, K., et al. (Bull. Inst. Intern. Froid. Annexe, (2), 49-56, 1965) reported as 0.341 μohm cm in the range 0.45 to 1.10 K.
44	859	Lorenz, L.	1881	L	273,373		Electrical conductivity 10.37 and 6.628 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C (author reported 10.37 and 6.628 x 10^5, probably a typographical error).
45	194	Braun, H.G.	1966	L	636-1102		Pure.
46	216	Brown, H.M.	1927	E	273.2		0.125 in. dia x 10 cm long; cut from a supply of commercial mild steel; electrical resistivity 15.8 μohm cm at 0 C; measured in a longitudinal magnetic field of 10,000 gauss.
47	216	Brown, H.M.	1927	E	273.2		The above specimen measured in a transverse magnetic field of 4000 gauss.
48	1364	Stewart, R.W.	1893	F	333-423		0.75 in. dia x 4.5 ft long; density 7.556 g cm^{-3} at 0 C.
49	987	Moore, J.P., McElroy, D.L., and Barisoni, M.	1966	L	100-380	Grade 1	Cylindrical specimen machined from electron-beam zone-refined iron (three pass) produced by Materials Research Corp; density 7.824 g cm^{-3}; electrical resistivity 0.97, 1.27, 1.95, 2.67, 3.47, 4.31, 5.20, 6.11, 7.04, 8.00, 8.99, 10.01, 11.09, 12.25, 13.48, 14.77, and 16.09 μohm cm at 90, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, 360, 380, and 400 K, respectively; $\rho(273K)/\rho(4.2K) = 201$. (Revised thermal conductivity data obtained from the authors in a private communication.)
50	1416	Todd, G.W.	1927	C	298.2		7.96 mm dia rod; copper used as comparative material; thermal conductivity obtained by comparing thermal expansion of the materials. (Measuring temp assumed 25 C.)
51*	217	Brown, H.M.	1928	E	312.1		10 cm x 0.0794 cm^2; electrical resistivity 11.99 μohm cm at 38.92 C.
52	217	Brown, H.M.	1928	E	312.1		The above specimen measured in a longitudinal magnetic field of 1000 gauss; electrical resistivity 12.01 μohm cm at 38.92 C.
53*	217	Brown, H.M.	1928	E	312.1		The above specimen measured in transverse magnetic fields of 4000 and 8000 gauss; electrical resistivity 11.99 μohm cm.

* Not shown in figure.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54	1489	Von Rudiger, O. and Dietze, H. D.	1955	E	302.3	Soft iron	0.3 cm dia x 6 cm long; electrical conductivity 7.36 x 10^4 ohm^{-1} cm^{-1} at the measuring temp.
55	1196	Richter, F. and Kohlhaas, R.	1965	R	562-1201		0.012 O, <0.01 Mn, <0.01 Si, 0.008 P, 0.007 Al, 0.007 C, 0.004 S, and 0.002 N; specimen stacked of disks 10 mm I. D., 63 mm O. D., and 10-30 mm thick; electrical resistivity 1.1, 1.7, 2.4, 3.1, 4.0, 5.0, 5.9, 6.9, 7.9, 8.8, 9.87, 11.6, 14.7, 18.1, 21.4, 26.0, 30.1, 35.0, 40.3, 46.8, 53.3, 60.1, 68.0, 76.0, 84.8, 94.2, 102.1, 106.3, 109.0, 111.1, and 113.1 μohm cm at -180, -160, -140, -120, -100, -80, -60, -40, -20, 0, 20, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, and 1000 C, respectively; Lorenz function 1.65, 2.13, 2.64, 2.88, 2.90, 2.94, 3.00, 3.06, 3.02, 3.03, 3.05, 2.93, 2.79, 2.49, and 2.41 x 10^{-8} V^2 K^{-2} at -180, -100, 0, 100, 200, 300, 400, 500, 600, 700, 800, 850, 900, 950, and 1000 C, respectively; Curie point 767 ± 2 C; T. P. (α-γ) 915-918 C; T.P. (γ-α) 909-913 C.
56*	1196	Richter, F. and Kohlhaas, R.	1965	R	1014-1072		Similar to the above specimen; measured in the neighborhood of the Curie point.
57*	1196	Richter, F. and Kohlhaas, R.	1965	R	1186-1197		Similar to the above specimen; measured in the neighborhood of the α-γ transition point with a rate of temp increase 0.07 C min^{-1}.
58*	1196	Richter, F. and Kohlhaas, R.	1965	R	1186-1197		Similar to above but rate of temp increase 0.06 C min^{-1}.
59	1196	McDonald, W. J., Jr.	1962	L	9.6-108		Cut from a zone-refined ingot prepared at BMI; machined into a rectangular parallelepiped 1.5 x 0.062 x 0.062 in.; electrical resistivity 0.0859, 0.0899, 0.0875, 0.0955, 0.0935, 0.101, and 0.659 μohm cm at 1.63, 3.14, 4.33, 6.3, 9.02, 20.8, and 80.7 K, respectively.
60	909	McDonald, W. J., Jr.	1962	L	5.9-14		The above specimen.
61	1011	Nakamura, T.	1965	L	293.2	F-I	1 cm dia x 1 cm thick; prepared from 99.5 pure commercial iron powder of grain size 53-105 μ by pressing under 1.5-15 ton cm^{-2}; reduced in a flowing hydrogen gas at a pressure of 1 atm at 600 C for 6 hrs; then sintered in a vacuum of 1 x 10^{-4} mm Hg at 800 C for 6 hrs, cooled; porosity 16.6%.
62	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 17.6%.
63	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 18.9%.
64	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 21.9%.
65	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 23.6%.
66	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 25.6%.
67	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 28.1%.
68	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 28.3%.
69	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 33.4%.
70	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 39.5%.
71*	1011	Nakamura, T.	1965	L	293.2	F-I	Similar to above but porosity 42.6%.

*Not shown in figure.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
72	1011	Nakamura, T.	1965	L	293.2	F-II	1 cm dia x 1 cm thick; prepared from 99.5 pure commercial iron powder of grain size 53-105 μ by pressing under 1.5-15 ton cm^{-2}; reduced in a hydrogen atm at 30 mm Hg at 605 C for 3 hrs, then sintered in a vacuum of 1 x 10^{-4} mm Hg at 900 C for 6 hrs, cooled; porosity 9.5%.
73	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 12.1%.
74	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 19.7%.
75	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 22.0%.
76	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 26.8%.
77	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 31.9%.
78	1011	Nakamura, T.	1965	L	293.2	F-II	Similar to above but porosity 38.0%.
79*	221	Bungardt, K. and Spyra, W.	1965	L	293-973		0.03 Ni, 0.015 C, 0.007 S, and traces Al, Mo, P, and Si; cylindrical specimen; electrical resistivity 10.4, 14.4, 22.0, 31.4, 42.2, 54.8, 69.4, 86.1, 106.0, 111.8, 115.0, and 118.0 μohm cm at 20, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 C, respectively; smoothed values reported.
80	983	Moore, J.P., Fulkerson, W., and McElroy, D.L.	1964	R	332-1173	High purity iron	0.001~0.01 Ni, 0.001~0.01 Si, 0.003 C, 0.003 S, 0.0025 O, 0.0011 P, 0.0001~0.001 Al, 0.0001~0.001 Ca, 0.0001~0.001 Cu, 0.0005 N, and 0.0001 H; prepared by arc-melting Armco iron stock in pure inert atmosphere to produce pancake shaped billets, rolled into sheets and cut to make feed stock for electron beam melting, then casted into 4 in. dia x 6 in. long billet, trimmed off outside edges and machined from center portion two disks of dimensions 3.25 in. dia x 1.130 in. thick and 3.25 in. dia x 1.450 in. thick, four Armco iron disks added as end backup disks to form specimen column of 9 in. high consisting of 6 disks in total; electrical resistivity reported as 1.037, 5.17, 9.04, 10.35, 11.06, 14.74, 21.92, 30.67, 41.07, 53.98, 68.33, 85.85, 105.48, 109.45, 112.35, 112.47, 113.92, and 115.30 μohm cm at -200, -84, 0, 24, 37, 100, 200, 300, 398, 501, 598, 700, 801, 850, 900, 925, 964, and 1000 C, respectively.
81	983	Moore, J.P., et al.	1964	R	1193-1273	High purity iron	2nd run of the above specimen.
82*	983	Moore, J.P., et al.	1964	R	1166-1272	High purity iron	3rd run of the above specimen; after 2nd run, temp raised to 1065 C and left overnight to stabilize thermocouples.
83	1534	Wheeler, M.J.	1969	P	829-1173		99.85 Fe, 0.03 N, 0.02 C, <0.015 each of Ca, Cd, and Tl, <0.007 each of Be, Ga, and Sn, 0.005 Si, 0.003 each of Al, O, and Pb, <0.003 Ba, Ge, Mg, and Ti, <0.0015 each of In, Mo, Pd, Sr, and V, 0.001 each of Cu and Ni, <0.001 each of P and S, <0.0007 each of Be and Cr, <0.0005 each of Co and Mn, and <0.0002 Zn; specimen 1 cm in dia and 0.128 cm thick; as-received (clean surfaces); density 7.886 g cm^{-3}; thermal conductivity values calculated from the measurement of thermal diffusivity, using the specific heat data of Kollie, T.G. (Rev. Sci. Instr., 38 (10), 1452-63, 1967).

* Not shown in figure.

TABLE 79. THERMAL CONDUCTIVITY OF IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
84*	1534	Wheeler, M.J.	1969	P	556-1115		The above specimen heated on each face over a Bunsen flame to ~600 C in air; surfaces oxidized.
85	1534	Wheeler, M.J.	1969	P	555-1238		Thermal conductivity values of the above oxide-surface specimen calculated from the measured data of thermal diffusivity, using the specific heat data of Braun, M. (Ph.D. Thesis, Univ. Köln, 1964).
86*	1534	Wheeler, M.J.	1969	P	831-1284		Thermal conductivity values of the clean-surface specimen reported in curve No. 84 calculated from the same method as the above.
87	1615	Zinovyer, V.E., Krentsis, R.P., and Gel'd, P.V.	1968	P	940-1671	1	Pure; specimen 6 x 10 mm^2 in size ground to a depth of 0.2-0.3 mm; supplied by Johnson, Matthey and Co.; mean grain size ~2 mm; annealed at 1300 K; electrical resistivity ratio $\rho(298K)/\rho(4.2K)$ = 114; Curie temp 1043 K; measured in a vacuum of ~10^{-6} mm Hg; thermal conductivity values calculated from the measured data of thermal diffusivity, using specific heat values of Kraftmakher, Ya. A. (Sb. Raboty po fiz-tverd. tel., Novosibirsk, OTD Izd. Nauke, 1, 37, 1967) and Anderson, P.O., et al. (Trans. Met. Soc. AIME, 224, 842, 1962), and density values of Bozorth, R. ("Ferromagnetism"); values taken from smoothed curve.
88	75	Angström, A.J.	1861	P	323.2		Thermal conductivity measured by the Angström method which was originated in this measurement; units not given and here assumed to be in cal cm^{-1} min^{-1} C^{-1}.
89	75a	Angström, A.J.	1863	P	273-343		35 mm diameter x 1178 mm long; thermal conductivity measured by the Angström method; data given in the form of the formula k = 11.927 (1 - 0.002874 t); units not given and here assumed to be in cal cm^{-1} min^{-1} C^{-1}.
90	451c	Forbes, J.D.	1864	F	298-473		In the "statical" experiment a square wrought iron bar of 1.25 in. side and 8 ft long with density 7.79 g cm^{-3} was heated at one end by molten lead or solder; in the "dynamical" experiment a similar bar but only about 20 in. long was cooled from a high uniform temperature.
91	451c	Forbes, J.D.	1864	F	298-448		The above specimen covered with "tea paper".
92	451c	Forbes, J.D.	1864	F	273-473		The above specimen.
93	451d	Forbes, J.D.	1865	F	290-561		1.25 in. square bar specimen.
94	451d	Forbes, J.D.	1865	F	290-546		The above specimen covered with paper.
95	451d	Forbes, J.D.	1865	F	289-566		1 in. square bar specimen.
96	1025a	Neumann, F.	1862	P	298.2		Density 7.74 g cm^{-3}; measuring temperature not given and here assumed to be 25 C.
97	546	Grosse, A.V.	1965	→	1808-6750		In liquid state; thermal conductivity values calculated from electrical conductivity data of Mokrovskii, H.P. and Regel, A.R. (Zh. Tekhn. Fiz., 23(12), 2121-5, 1953) and estimated electrical conductivity values over the whole liquid range derived from the hyperbola relationship.
98*	1015	National Physical Laboratory	1965	R	373-1273		99.97 pure; disk-shaped specimens 10.45 cm in diameter with an axial hole 1.27 cm in diameter; measured in a vacuum of 2 x 10^{-5} mm Hg.

* Not shown in figure.

Armco Iron

Armco Magnetic Ingot Iron is a registered trade name of a commercially pure iron produced by Armco Steel Corporation, Middletown, Ohio, which was originally called American Rolling Mill Company before 1948. This iron is generally known as Armco iron. The nominal composition of Armco iron given by the Corporation [93a] as ladle analysis in weight percent is: 0.01 percent (max.) P, 0.030 percent (max.) S, 0.10 percent (max.) total of C, Mn, P, S, and Si, and 0.15 percent (max.) Cu. It is stated that in analyzing Magnetic Ingot Iron, only the total of the five elements—carbon, manganese, phosphorus, sulfur, and silicon—is considered. The typical amount of these five elements given as typical analysis of the iron in sheet form [93a] is: 0.015 C, 0.028 Mn, 0.005 P, 0.025 S, and 0.003 Si.

Since the thermal conductivity of Armco iron was first measured at low temperatures by Kannuluik, et al. [707] (curve 8) and at high temperatures by Powell [1106] (curve 10), many subsequent measurements have been made. Ninety-eight sets of data are now available, and Armco iron has been used extensively as a reference standard of thermal conductivity.

In 1962, Powell [1118], on the basis of some 17 sets of available data for the thermal conductivity of Armco iron, produced a set of most probable values for the temperature range 273 to 1573 K. Since that time some round-robin measurements have been made on a sample of Armco iron supplied by the Battelle Memorial Institute. The values obtained by several laboratories for the thermal conductivity of this sample have been published [245, 765, 811, 815, 1125, 1296].

On comparing five sets of round-robin values as given at 100 C intervals, with the suggested 1962 most probable values, quite good agreement is obtained. No difference exceeds 4 percent, and 38 percent of the new determinations agree to within 1 percent with the 1962 proposed values. After taking the averages of the round-robin value at each temperature, differences from the earlier proposal [1126] were noted to be +1.7 percent at 1273 K, +1.1 percent at 1173 K, and —1.1 percent at 973 K whilst all the other values agreed to better than 1 percent.

The values now proposed for the thermal conductivity of Armco iron from 273 to 773 K are the averages of Powell's most probable values and the mean of the five round-robin values. In the Curie temperature region and the phase transformation region the curve has been lowered by up to 3 percent so as to conform with the data obtained by the Oak Ridge National Laboratory [984] (curve 41). These workers have used the radial heat flow method. This method, which uses smaller temperature differences, has allowed the fine structure of the curve to be derived in this interesting temperature region. Furthermore, their results are known to agree closely with measurements of the National Physical Laboratory [1125] (curve 35). At 1059 K, about 16 K above the Curie temperature, the thermal conductivity ceases to fall and remains almost constant up to the beta-to-gamma phase transformation where a drop of about 4 percent occurs. In the gamma phase, the thermal conductivity of iron has a small positive temperature coefficient. These changes would have led to rather too high thermal conductivities being obtained in the region of the Curie temperature by observers who based their results on a large temperature difference and this is thought to justify the treatment of the results that has been adopted. The recommended curve has been extrapolated to the melting point following and slightly below the recommended curve for high-purity iron.

Below room temperature the National Bureau of Standards [445] (curve 36) and the National Physical Laboratory [1125] (curve 35) have obtained values that agree closely for this round-robin sample. Also available are results from the National Bureau of Standards [446] (curve 42) and the Battelle Memorial Institute [866] (curve 5) for two different samples. Throughout the range 123 to 273 K these four sets of values agree to within about 3 percent. At 273 K their arithmetic mean value is the same as that derived above, so it has been decided to use the average value from these four curves as the most probable value for the thermal conductivity of Armco iron at subnormal temperatures. Recently two samples of Armco iron cut from a rod supplied also by Battelle Memorial Institute have been measured by Hust [646] (curves 51–53) of the National Bureau of Standards at Boulder over the temperature range from 6 K to 300 K. These are the only data available for Armco iron at low temperatures. At temperatures below 200 K his data are in good agreement with the subnormal-temperature values mentioned above, and his data have been adopted as the most probable values at low temperatures. His data on the Lorenz function of Armco iron have also been listed in the table as recommended values. For other specimens having different residual electrical resistivities, low-temperature thermal conductivity values may be derived from measured electrical resistivity data and values of the Lorenz function given in the table.

These recommended thermal conductivity values are thought to be accurate to within ±5 percent of the true values at temperatures below 100 K, ±3 percent from 100 K to room temperature, ±2 percent from room temperature to about 1000 K, the uncertainty probably increasing to about ±8 percent at 1600 K and ±15 percent near the melting point. The values below 200 K are applicable only to a sample having a residual electrical resistivity of 0.690 $\mu\Omega$ cm.

Electrical resistivity determinations made on Armco iron before and after heating to 1653 K have shown changes of as much as 3 percent at the ice point [445]. Similar changes may occur in the thermal conductivity and it is clear that check measurements should be made after an Armco iron thermal conductivity standard has been heated into the gamma-phase.

TABLE 80. Recommended thermal conductivity of Armco iron†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	0.765
1	0.0358*	273.2	0.747
2	0.0718*	298.2	0.728
3	0.108*	300	0.727
4	0.144*	323.2	0.710
5	0.180*	350	0.691
6	0.217	373.2	0.676
7	0.253	400	0.657
8	0.290	473.2	0.610
9	0.326	500	0.593
10	0.362	573.2	0.547
11	0.398	600	0.531
12	0.434	673.2	0.488
13	0.470	700	0.473
14	0.505	773.2	0.435
15	0.541	800	0.422
16	0.575	873.2	0.386
18	0.644	900	0.372
20	0.712	973.2	0.336
25	0.858	1000	0.323
30	0.982	1059	0.293
35	1.07	1073.2	0.293
40	1.13	1100	0.294
45	1.15	1173.2	0.296
50	1.15	1183	0.296
60	1.13	1183	0.285
70	1.09	1200	0.287
80	1.05	1273.2	0.294
90	1.00	1300	0.296
100	0.956	1373.2	0.303
123.2	0.896	1400	0.306
150	0.855	1473.2	0.312
173.2	0.831	1500	0.314
200	0.806	1573.2	0.320
223.2	0.786	1600	0.322*
		1673.2	0.328*
		1700	0.330*
		1773.2	0.336*
		1800	0.338*

†The recommended values are for well-annealed Armco iron, and those below 200 K are applicable only to a specimen having $\rho_0 = 0.690$ $\mu\Omega$ cm.

*Extrapolated.

TABLE 81. Recommended Lorenz function of Armco iron

(Temperature, T, K; Lorenz Function, L, $10^{-8}V^2$ K^{-2})

T	L	T	L
6	2.505	65	1.905
7	2.523	70	1.895
8	2.531	75	1.895
9	2.533	80	1.903
10	2.532	85	1.917
12	2.529	90	1.935
14	2.528	95	1.956
16	2.528	100	1.980
18	2.527	110	2.034
20	2.521	120	2.091
25	2.477	130	2.150
30	2.395	140	2.209
35	2.292	150	2.266
40	2.188	160	2.320
45	2.096	170	2.371
50	2.021	180	2.418
55	1.965	190	2.461
60	1.927	200	2.499

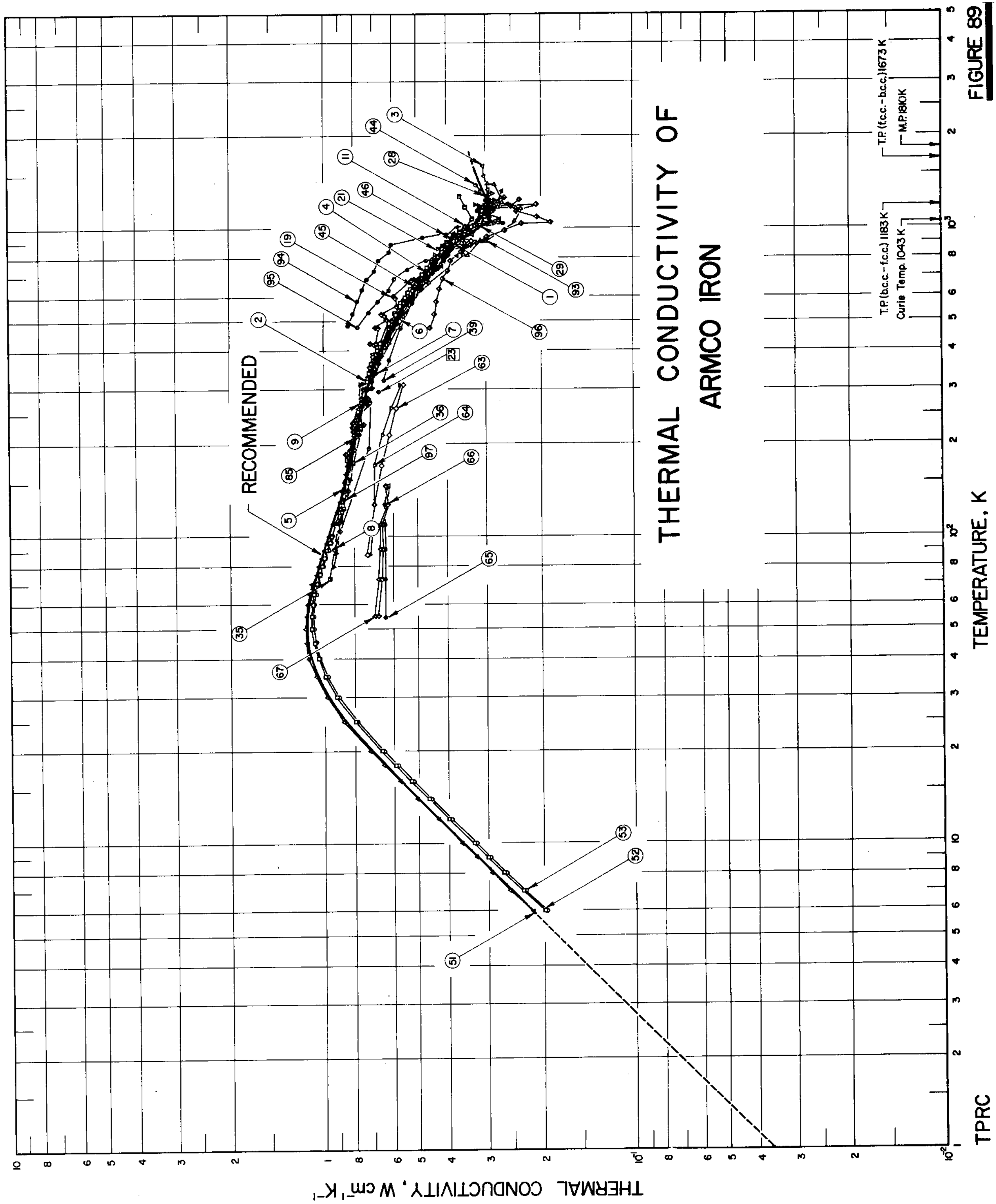

THERMAL CONDUCTIVITY OF
ARMCO IRON
RECOMMENDED
T.P. (f.c.c.-b.c.c.) 1673 K
M.P. 1810 K
T.P. (b.c.c.-f.c.c.) 1183 K
Curie Temp. 1043 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 89

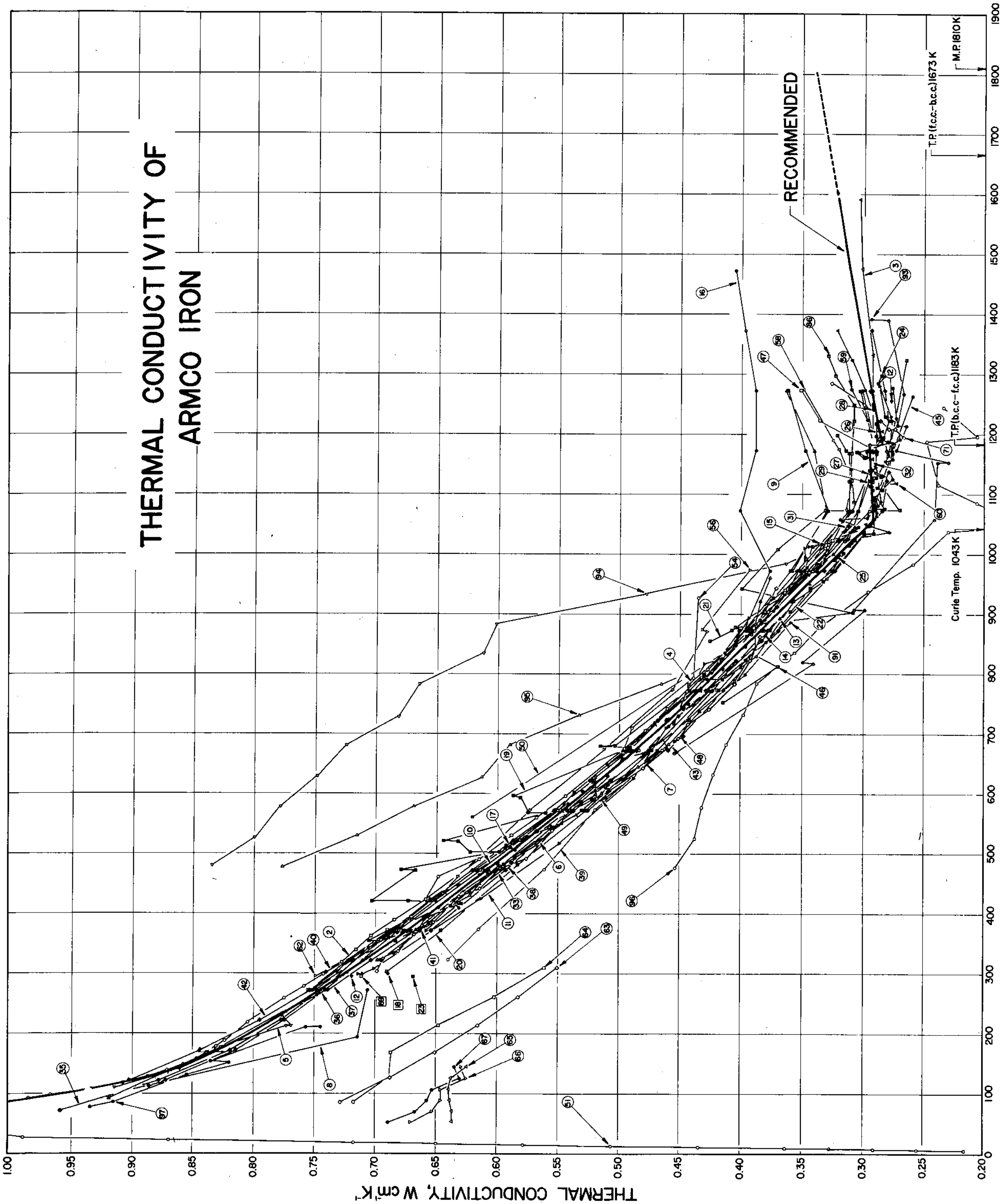

THERMAL CONDUCTIVITY OF ARMCO IRON
RECOMMENDED
T.P.(f.c.c.–b.c.c.)1673 K
M.P.1810 K
T.P.(b.c.c.–f.c.c.)1183 K
Curie Temp. 1043 K
TEMPERATURE , K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TPRC

FIGURE 90

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	194	Braun, H. G.	1966		629-973	Armco Iron	No details reported.
2	94	Armstrong, L. D. and Duaphinee, T. M.	1947	L	320-1016	Armco Iron	99.808 Fe (by difference), 0.067 Cu, 0.039 S, 0.035 Mn, 0.028 C, and 0.024 Ni; 2.50 cm dia x 8.00 cm long; machined from a hot-rolled 1.5 in. rod.
3	426	Fieldhouse, I. B., Hedge, J. C., and Lang, J. I.	1958	R	371-1594	Armco Iron	Specimen consisted of three annular rings each of 0.625 in. I. D., 3.0 in. O. D., and 1 in. thick.
4	224	Burr, A. C.	1951	R	718-1008	Armco Iron	Annular cylindrical specimen of 1.5 in. I. D., 6 in. O. D., and 2.25 in. thick.
5	866	Lucks, C. F., Thompson, H. B., Smith, A. R., Curry, F. P., Deem, H. W., and Bing, G. F.	1951	C	111-394	Armco Iron	0.035 Cu, 0.026 S, 0.015 Mn, 0.014 C, and 0.004 P; 2 cm dia x 15 cm long; Armco iron used as comparative material.
6	593	Hattori, D.	1937	L	323-961	Armco Iron; 1	0.032 Mn, 0.03 S, 0.015 C, 0.013 Cu, 0.01 Si, and 0.003 P; 1.4 cm dia x 10 cm long; annealed at 950 C.
7	593	Hattori, D.	1937	L	304-943	Armco Iron; 2	Similar to the above specimen.
8	707	Kannuluik, W. G., Eddy, C. E., and Oddie, T. H.	1933	E	90-273	Armco Iron	0.056 Cu, 0.026 S, 0.017 Mn, 0.011 C, 0.006 P, and 0.002 Si; 0.3924 cm dia x 14.53 cm long; electrical resistivity reported as 1.531, 5.74, 9.57, and 15.49 μohm cm at -183.00, -78.50, 0, and 100 C, respectively.
9	862	Lucks, C. F. and Deem, H. W.	1956	C	273-1273		99.906 Fe (by difference), 0.035 Cu, 0.026 S, 0.015 Mn, 0.014 C, and 0.004 P; measured in a vacuum of ~2 x 10^{-5} mm Hg; a section of the specimen used as comparative material.
10	1106, 1108	Powell, R. W.	1934	L	273-1073	Armco Iron	99.918 Fe, 0.025 Mn, 0.023 C, 0.020 S, 0.007 P, and 0.007 Si; 2.895 in. dia x 84 in. long; made from two similar rods of Armco ingot iron each 3 in. dia x 42 in. long; electrical resistivity reported as 9.6, 15.0, 22.6, 31.4, 43.1, 55.3, 69.8, 87.0, and 105.5 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, and 800 C, respectively.
11	16, 14	Abeles, B., Cody, G. D., and Novak, R.	1959	P	300-1298	Armco Iron; V	0.1875 in. dia x 2 in. long; machined from Armco stock supplied by Mapes and Sprowl Steel Co.; Curie point 770 C; transition point (α-γ) 910 C; measured in a vacuum of ~5 x 10^{-4} mm Hg; thermal conductivity values calculated from measured thermal diffusivity data and specific heat values taken from literature.
12	16	Abeles, B., et al.	1959	P	295, 1256	Armco Iron; IV	Similar to above.
13	1109	Powell, R. W.	1939	C	512-1046	Armco Iron	99.918 Fe, 0.025 Mn, 0.023 C, 0.020 S, 0.007 P, and 0.007 Si; 1.28 cm dia x 14 cm long; machined; lower section of the specimen used as comparative material.
14	1109	Powell, R. W.	1939	C	730-1138	Armco Iron	Similar to above except specimen of 1 in. dia.
15	1109	Powell, R. W.	1939	R	369-1278	Armco Iron	Specimen consisted of two superimposed disks of 1.1 cm I. D., 6.3 cm O. D., and 2.54 cm thick; machined from the similar original rods as for curve No. 10.
16	904	Maurer, E.	1936	L	303-1473	II	0.05 Cu, 0.040 S, 0.02 Mn, 0.0011 P, 0.01 C, and trace of Si.
17	1606	Zegler, S. T. and Nevitt, M. V.	1959	C	410-1057	Armco Iron	99.745 Fe, 0.16 Cu, 0.03 C, 0.03 S, 0.015 Si, 0.01 Mn, and 0.01 P; obtained from commercial source in wrought form; iron used as comparative material (data of H. W. Deem).

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	1488	Von Lohberg, K. and Motz, J.	1957	L	300	Armco Iron	Commercial Armco iron; electrical conductivity 9.09 x 10^4 ohm^{-1} cm^{-1} at 300 K.
19	855	Loewen, E. G.	1956	L	355-800	Armco Iron	0.75 in. dia rod.
20	814	Laubitz, M. J.	1960	L	303-1273	Armco Iron	0.083 Cu, 0.030 Mn, 0.023 S, 0.006 P, 0.004 Si, and 0.02 C; specimen in two halves each of length 7.156 cm and 2.324 cm dia; supplied by BMI; annealed for 0.5 hr at 850 C; electrical resistivity reported as 10.4, 15.6, 22.9, 32.0, 42.9, 55.7, 70.3, 87.9, 106.0, 112.0, and 115.3 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 C, respectively; measured in a vacuum of 0.2-3 x 10^{-5} mm Hg. (See curve No. 38 for corrected values.)
21	1059	Paine, R. M., Stonehouse, A. J., and Beaver, W. W.	1959	R	855-1198	Armco Iron	Specimen consisted of three stacked hollow cylinders each of 2.5 in. O. D. and 2.5 in. high.
22	1047	Oak Ridge Nat'l. Lab.	1960		904-1108	Armco Iron	No details reported.
23	1065	Parker, W. J. and Jenkins, R. J.	1961	P	295	Armco Iron	1.9 x 1.9 x 0.100 cm; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat, and density 7.87 g cm^{-3} taken from Smithsonian Physical Tables (9th ed., 1954).
24	13	Abeles, B., Beers, D. S., Cody, G. D., Novak, R., and Rosi, F.	1960	P	995-1298	Armco Iron	0.1875 in. dia x 2 in. long; machined from rod stock Armco iron obtained from Mapes and Sprowl; thermal conductivity values calculated from measured thermal diffusivity data and specific heat values of Darken, L. S. and Smith, R. P. (Ind. Eng. Chem., 43, 1815, 1951).
25	500	Godfrey, T. G., Fulkerson, W., Kollie, T. G., Moore, J. P., and McElroy, D. L.	1964	R	385-1092	Armco Iron	0.1 Cu, 0.1 Ni, 0.086 O, 0.05 Mn, <0.05 Al, <0.05 Cr, <0.05 Mo, 0.023 S, <0.02 Si, <0.02 V, 0.013 C, <0.01 Ti, 0.006 P, 0.0050 N, and 0.0001 H; grain size 20–40 μ; electrical resistivity reported as 3.2, 5.3, 7.6, 10.2, 12.6, 15.9, 19.4, 23.3, 27.8, 32.7, 38.2, 44.0, 50.3, 56.7, 64.1, 72.0, 80.7, 90.2, 101.2, 108.7, 112.4, 114.5, 116.2, and 117.7 μohm cm at -150, -100, -50, 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, and 1000 C, respectively; run No. 1.
26	500	Godfrey, T. G., et al.	1964	R	484-1198	Armco Iron	The above specimen; run No. 2A.
27	500	Godfrey, T. G., et al.	1964	R	973-1206	Armco Iron	The above specimen; run No. 2B.
28	500	Godfrey, T. G., et al.	1964	L	1206-1273	Armco Iron	The above specimen; run No. 2C.
29	500	Godfrey, T. G., et al.	1964	R	1025-1198	Armco Iron	The above specimen; run No. 2D.
30*	1524, 1525	Weeks, J. L. and Seifert, R. L.	1952	C	343	Armco Iron	Rod specimen 1.75 in. long; density (25 C) = 7.8 g cm^{-3}; Armco iron used as comparative material.
31	598	Hedge, J. C. and Fieldhouse, I. B.	1956	R	803-1048	Armco Iron	Disk specimen.
32	427, 429	Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E.	1956	L	808-1153	Armco Iron	6.75 in. dia x 1.5 in. thick.
33	1606	Robinson, H. E.	1959		373-773	Armco Iron	Measured by Robinson, H. E., NBS and reported as a private communication.
34*	1079	Perova, V. I. and Knoroz, L. I.	1957	E	385-870	Armco Iron	0.045 S, 0.04 C, and 0.005 P; electrical resistivity reported as 16.36, 22.87, 32.13, 41.00, 53.48, 54.10, and 67.15 μohm cm at 111.7, 203, 301, 390, 493, 499, and 597 C, respectively.

* Not shown in figure.

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35	1125	Powell, R.W., Hickman, M.J., Tye, R.P., and Woodman, M.J.	1962	L, C	73-1273	Armco Iron	99.834 (by difference) Fe, 0.083 Cu, 0.030 Mn, 0.023 S, 0.02 C, 0.006 P, and 0.004 Si; chemical and spectrographic analysis at NPL showed 0.083 Ni in addition to the above; 1 in. rod from American Rolling Mill Co. supplied by BMI in hot-rolled condition; annealed for 30 min. at 1600 F (871 C) in air, followed by furnace cooling; electrical resistivity reported as 1.5, 3.3, 5.3, 7.5, 10.0, 12.5, 15.6, 19.1, 23.0, 27.0, 31.2, 36.3, 41.8, 47.4, 54.0, 61.0, 68.8, 77.2, 86.2, 96.8, 105.2, 109.8, 112.4, 114.1, and 115.8 μohm cm at -200, -150, -100, -50, 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, and 1000 C, respectively.
36	445, 1507	Flynn, D.R.	1963	L	113-913	Armco Iron	99.834 Fe (by difference), 0.083 Cu, 0.030 Mn, 0.023 S, 0.02 C, 0.006 P, and 0.004 Si; specimen 37 cm in length and 2.386 cm in dia; obtained from the American Rolling Mill Co. by Battelle Memorial Institute in the form of 1 in. rod; annealed for 0.5 hr at 1123 K; data taken from smoothed curve.
37	860	Lucks, C.F.	1964		273-873		Cut from the same rod as the above specimen; ends of this specimen marked No. 1 and No. 2, the No. 2 end immediately adjacent to a length sent to NPL.
38	815	Laubitz, M.J.	1963	L	373-1273	Armco Iron	Corrected values for the temp variation on the data (curve 20) of Laubitz, 1960.
39	965	Mikryukov, V.E.	1959		323-673	Armco Iron	Polycrystalline.
40	341	Delle, W.	1964		303-1273		No details reported.
41	984	Moore, J.P., Fulkerson, W., McElroy, D.L., and Kollie, T.G.	1964	R	323-1273		99.41$^+$ Fe, 0.10 Ni, 0.087 O, <0.0507 Al, 0.050 Mn, <0.05 Cr. <0.050 Mo, 0.023 S, <0.02 Si, <0.02 V, 0.013 C, 0.0102 Cu, <0.01 Ti, 0.006 P, 0.005 N, and <0.0001 H; total equivalent carbon (including oxygen): 0.1432 - 0.2002; microstructure snowing oxygen present as a second phase amounting to ~1 vol %; electrical resistivity 10.0, 70.66, 114.69, and 117.95 μohm cm at 0, 600, 900, and 1000 C, respectively.
42	446	Flynn, D.R., Robinson, H.E., and Watson, T.W.	1964		123-473		99.80±0.084 Fe, 0.1 Mn, 0.04 Ni, 0.03 Cu, 0.02 Sr, <0.02 W, 0.01 Cr, 0.01 Mo, <0.01 Co, <0.01 Nb, <0.01 V, 0.006 Ti, and <0.003 Zr; photomicrograph showing an oriented microstructure typical of a cold-worked material; supplied by Redstone Arsenal; electrical resistivity 9.36 μohm cm at 0 C.
43	379	Dunworth, R.J.	1963		673-1373		No details reported.
44	765, 766	Klein, A.H., Shanks, H.R., and Danielson, G.C.	1964	P	273-1373	Armco Iron	Armco iron obtained from BMI; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat using density value 7.874 g cm^{-3} given by Cleaves and Thompson (the Metal-Iron, McGraw Hill, p. 271, 1935).
45	1395	Taylor, R.E.	1962	R	648-1263	Armco Iron	Specimen size 2 in. O.D., 3 in. long with a 0.5 in. center hole.
46	1395	Taylor, R.E.	1962	R	753-1323	Armco Iron	The above specimen measured by using different heat sink.
47	940	Méndez-Peñalosa, R.	1967	R	812-1267	Armco Iron	0.118 Cu, 0.034 Mn, 0.019 S, 0.017 C, 0.004 Si, and 0.003 P; supplied by Great Western Steel Co., Ind; 4.44 cm O.D., 2.54 cm I.D., and 2.54 cm thick.
48	112	Banaev, A.M. and Chekhovskoi, V.Ya.	1965	R	425-773	Armco Iron	99.865 Fe (by difference), 0.07 Mn, 0.04 Si, 0.015 C, and 0.01 Cu; specimen consisted of two central disks, each of 20 mm thickness, included in a stack of similar disks giving a total length to dia ratio of 5-6.

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
49	1068	Pears, C.D.	1965	C	550-811		From BMI round robin stock; 1 in. dia x 1 in. long; stainless steel 316 used as comparative material.
50	1018	Neel, D.S., Pears, C.D., and Oglesby, S., Jr.	1962	R	561, 866		99.941 Fe (by difference), 0.025 S, 0.017 Mn, 0.012 C, 0.005 P, and trace Si; 0.75 in. dia x 0.75 in. long; supplied by Lapham-Hickey Steel Corp; cold-drawn; density 7.53 g cm^{-3}.
51	646, 648	Hust, J.G.	1969	L	6-300	Armco iron; Specimen 2C	99.9 Fe, 0.04 Cu, 0.028 Mn, 0.025 S, 0.015 C, and 0.003 Si; specimen 3.6 mm in dia and 23 cm long; obtained from Battelle Memorial Institute; annealed by the supplier as follows: 0.5 hr at 870 C in a gas-heated air muffle, then in a quartz capsule at 1 x 10^{-6} torr for 1.5 hrs at 875 C, furnace cooled to 150 C, held at 150 C for 24 hrs and furnace cooled to room temp; electrical resistivity reported as 0.6905, 0.6911, 0.6926, 0.6932, 0.6957, 0.6981, 0.7196, 0.7664, 0.8562, 0.9976, 1.191, 1.432, 1.713, 2.028, 2.736, 3.516, 4.340, 5.196, 6.077, 7.918, and 10.970 μohm cm at 6, 8, 10, 14, 18, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 240, and 300 K, respectively; Lorenz function at these temperatures reported as 2.49, 2.53, 2.52, 2.51, 2.51, 2.50, 2.37, 2.16, 1.99, 1.89, 1.87, 1.88, 1.91, 1.96, 2.07, 2.19, 2.30, 2.40, 2.48, 2.61, and 2.72 x 10^{-8} V^2 K^{-2}, respectively.
52	646, 648	Hust, J.G.	1969	L	6-280	Armco iron; Specimen 2C	The above specimen reannealed in the same way as above as indicated by the supplier; electrical resistivity reported as 0.7645, 0.7658, 0.7674, 0.7676, 0.7702, 0.7726, 0.7936, 0.8388, 0.9268, 1.067, 1.259, 1.500, 1.781, 2.096, 2.803, 3.581, 4.404, 5.258, 6.137, 7.978, and 9.971 μohm cm at 6, 8, 10, 14, 18, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 240, and 280 K, respectively; Lorenz function at these temps reported as 2.52, 2.54, 2.55, 2.54, 2.54, 2.53, 2.41, 2.21, 2.04, 1.94, 1.91, 1.91, 1.95, 1.99, 2.10, 2.22, 2.33, 2.42, 2.50, 2.60, and 2.68 x 10^{-8} V^2 K^{-2}, respectively.
53	646, 648	Hust, J.G.	1969	L	6-300	Armco iron; Specimen 4C	Similar to the above specimen except no reannealing applied; electrical resistivity reported as 0.7675, 0.7673, 0.7694, 0.7706, 0.7730, 0.7752, 0.7960, 0.8427, 0.9324, 1.074, 1.267, 1.507, 1.789, 2.104, 2.811, 3.589, 4.412, 5.267, 6.146, 7.986, and 11.04 μohm cm at 6, 8, 10, 14, 18, 20, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 240, and 300 K, respectively; Lorenz function at these temps reported as 2.51, 2.52, 2.53, 2.53, 2.53, 2.52, 2.40, 2.20, 2.04, 1.95, 1.91, 1.92, 1.95, 1.99, 2.10, 2.22, 2.33, 2.43, 2.51, 2.62, and 2.71 x 10^{-8} V^2 K^{-2}, respectively.
54	948	Meyer, R.A. and Koyama, K.	1963	C	349-926	Armco iron	1 in. dia x 0.250 in. thick; Armco iron used as comparative material.
55*	846	Lindenbaum, S.D. and Quimby, S.L.	1962	L	397-636	Armco iron	Specimen supplied by Abeles, B.
56	255	Chang, H. and Blair, M.G.	1969	L	373-973	Armco iron	99.911 Fe, 0.035 Mn, 0.025 C, 0.019 S, 0.006 P, and 0.005 Si; specimen 0.125 in. in dia and 8 in. long; supplied by Armco Steel Co. heat No. 27125 A.
57*	255	Chang, H. and Blair, M.G.	1969		373-973	Armco iron	Similar to the above specimen; measurements obtained under deliberately mismatched guard-sample conditions.

* Not shown in figure.

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
58	1296	Shanks, H.R., Klein, A.H., and Danielson, G.C.	1967	P	1073-1273	Armco Iron; A	0.2 Cu, 0.076 O, 0.04 Ni, 0.035 Mn, 0.023 As, 0.02 Cr, 0.02 S, 0.0119-0.0127 C, 0.012 Sn, 0.0051 N, 0.006 Co, 0.005 Mo, 0.004 Ag, 0.0015 Cl, 0.0015 Ga, 0.001 Sb, 0.001 Zn, 0.0005 Na, 0.0005 K, 0.0003 Ca, 0.00007 Mg, 0.00006 V, 0.00006 Pd, 0.00001 Se, and 0.00001 Nb; specimen 0.25 in. in dia and 3.5 in. long; supplied by Battelle Memorial Institute in the form of round rod of 1 in. in dia; annealed at 870 C for 8 hrs, then annealed at 1020 C for 2 hrs; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 14$; electrical resistivity reported as 0.771, 0.771, 1.32, 1.59, 2.90, 4.96, 9.70, 11.00, 12.30, 15.30, 18.65, 22.45, 26.75, 31.45, 36.55, 42.20, 48.35, 54.85, 61.90, 69.55, 77.80, 86.55, 97.10, 100.85, 105.85, 110.10, 112.85, 112.95, 114.20, and 115.95 μohm cm at -272, -269, -200, -190, -150, -100, 0, 25, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 765, 800, 850, 900, 915, 950, and 1000 C, respectively; apparent Lorenz function reported as 2.69, 2.84, 2.94, 2.99, 2.97, 2.98, 3.05, 3.04, 3.07, 3.10, 3.04, 3.08, 3.13, and 3.18 x 10^{-8} V^2 K^{-2} at 0, 100, 200, 300, 400, 500, 600, 700, 750, 800, 850, 900, 950, and 1000 C, respectively; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat with density 7.874 g cm^{-3} given by Cleaves, H.E. and Thompson, J.G. (The Metal Iron, McGraw-Hill Co., Inc., N.Y., 1935).
59	1296	Shanks, H.R., et al.	1967	P	298-1273	Armco Iron; B	Similar to above except specimen 0.25 in. in dia and 12 in. long, swaged and annealed at 1350 C for 1 hr with apparent Lorenz function reported as 2.69, 2.84, 2.94, 2.99, 2.97, 2.98, 3.05, 3.04, 3.07, 3.10, 3.04, 3.08, 3.13, and 3.18 x 10^{-8} V^2 K^{-2} at 0, 100, 200, 300, 400, 500, 600, 700, 750, 800, 850, 900, 950, and 1000 C, respectively.
60	1018, 1017	Neel, D.S. and Pears, C.D.	1962	R	489-1178	Armco Iron	1 in. dia x 1 in. long.
61*	434	Filippov, L.P.	1966	P	573, 643	Armco Iron	No details reported.
62	1495	Wagner, P. and Dauelsberg, L.B.	1966	P	297-599	Armco Iron	Thermal conductivity values calculated from measured thermal diffusivity data.
63	1563, 1562	Williams, D.R. and Blum, H.A.	1966	L	87-311	Armco Iron	Specimen ~0.4 cm in dia and ~34 cm long; thermal conductivity values calculated from the average of 2 runs.
64	1563, 1562	Williams, D.R. and Blum, H.A.	1966	L	87-311	Armco Iron	Similar to the above except measured by a "no-loss" method.
65	1563, 1562	Williams, D.R. and Blum, H.A.	1966	L	55-147	Armco Iron	Similar to the above curve No. 63.
66	1563, 1562	Williams, D.R. and Blum, H.A.	1966	C	55-147	Armco Iron	Similar to the above except measured by comparative method and Armco iron used as comparative material.
67	1563, 1562	Williams, D.R. and Blum, H.A.	1966	L	55-147	Armco Iron	Similar to the above except measured by the "no-loss" method.
68*	800	Kummer, D.L., Rosenthal, J.J., Lum, D.W., et al.	1965	C	596-812	Armco Iron	1 in. dia x 1 in. thick; 316 stainless steel used as comparative material.
69	999	Moser, J.B. and Kruger, O.L.	1964	P	298.2	Armco Iron	Density 7.86 g cm^{-3} at room temp; thermal conductivity value calculated from measured thermal diffusivity and specific heat capacity.
70*	230	Busch, G. and Steigmeier, E.	1961	L	372-700	Armco Iron	<0.15 Cu, 0.025 Mn, 0.025 S, 0.02 C, 0.008 P, and 0.002 Si; measured in a vacuum of 5 x 10^{-6} torr.

* Not shown in figure.

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
71	1314	Sidles, P.H. and Danielson, C.C.	1960	P	317-1284	Armco Iron	Thin rod specimen; thermal conductivity values calculated from measured thermal diffusivity data using the specific heat capacity data taken from Wallace, D.C. (Thesis, Iowa State University, 1957).
72*	1314	Sidles, P.H. and Danielson, C.C.	1960	P	316-1284	Armco Iron	The above specimen; thermal conductivity values calculated from the same set of thermal diffusivity data as above, using the specific heat capacity data taken from Pallister, P.R. (J. Iron and Steel Inst. (London), 161, 87, 1949).
73*	804	Küster, W., Bode, K.H., and Fritz, W.	1968	L	297-359	Armco Iron	99.8 Fe, 0.065 Cu, 0.035 Ni, 0.028 Mn, 0.02 C, 0.018 Cr, 0.011 P, 0.011 S, and 0.009 Si; 50 mm dia x 70 mm long; density 7.863 g cm^{-3}; measured in a standard apparatus.
74*	804	Küster, W., et al.	1968	L	298-363	Armco Iron	Similar to above.
75*	804	Küster, W., et al.	1968	L	515, 536	Armco Iron	Similar to the above specimen but dimensions 50 mm dia x 90 mm long; measured in another apparatus.
76*	804	Küster, W., et al.	1968	L	389-579	Armco Iron	Similar to above.
77*	804	Küster, W., et al.	1968	L	508	Armco Iron	Similar to above.
78*	804	Küster, W., et al.	1968	L	689	Armco Iron	Similar to above.
79*	239	Carroll, J.M.	1964	C	595-811	Armco Iron	Specimen 1 in. in dia and 1 in. long; stainless steel type 316 used as comparative material.
80*	811, 812	Larsen, D.C.	1968	L	325-365	Armco Iron; Round Robin	0.083 Cu, 0.030 Mn, 0.023 S, 0.02 C, 0.006 P, and 0.004 Si; supplied by Battelle Memorial Institute; heated at 870 C for 0.5 hr; density 7.853 g cm^{-3}; electrical resistivity reported as 0.033, 0.051, 0.073, 0.096, 0.126, 0.158, 0.191, 0.233, 0.275, 0.322, 0.375, 0.432, 0.495, 0.562, 0.631, 0.710, 0.790, 0.877, 0.985, 1.013, 1.031, 1.058. 1.086, and 1.119 μohm m at -150, -100, -50, 0, 50, 100, 150, 200, 250, 300, 350, 400, 450, 500, 550, 600, 650, 700, 750, 762, 764, 780, 800, and 850 C, respectively; Lorenz function reported as 2.61, 2.76, 2.86, 2.90, 2.99, 3.02, and 3.05 x 10^{-8} V^2 K^{-2} at 0, 50, 100, 150, 200, 250, and 300 C, respectively; 1st run.
81*	811, 812	Larsen, D.C.	1968	L	372-489	Armco Iron; Round Robin	The above specimen, 2nd run.
82*	811, 812	Larsen, D.C.	1968	L	408-552	Armco Iron; Round Robin	The above specimen, 3rd run.
83*	811, 812	Larsen, D.C.	1968	L	375-467	Armco Iron; Round Robin	The above specimen, 4th run.
84*	811, 812	Larsen, D.C.	1968	L	322-348	Armco Iron; Round Robin	The above specimen, 5th run.
85	977	Moak, D.P. (Compiler)	1966	C	107-1006	Armco Iron	99.9 pure; 0.75 in. dia x 5.00 in. long; measured in vacuum; Armco iron used as comparative material.
86	977	Moak, D.P. (Compiler)	1966	C	1048-1329	Armco Iron	99.9 pure; 3.00 in. dia x 1.00 in. thick; measured in argon atmosphere; type 347 stainless steel used as comparative material.

* Not shown in figure.

TABLE 82. THERMAL CONDUCTIVITY OF ARMCO IRON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
87*	1376	Sugawara, A.	1968	L	273-773	Armco Iron	Specimen 30.2 mm in dia and ~196 mm long; annealed at 700 C for ~3 hrs.
88*	1566	Williams, T. L. and Pate, J. L.	1968	C	423-923	Armco Iron	Armco iron used as comparative material.
89*	1566	Williams, T. L. and Pate, J. L.	1968	C	573-973	Armco Iron	Similar to above.
90*	1566	Williams, T. L. and Pate, J. L.	1968	C	398-886	Armco Iron	Similar to above.
91	1566	Williams, T. L. and Pate, J. L.	1968	C	493-886	Armco Iron	Similar to above.
92*	1566	Williams, T. L. and Pate, J. L.	1968	C	753.2	Armco Iron	Similar to above.
93	978	Moeller, C. E. and Wilson, D. R.	1960	R	593-1391	Armco magnetic ingot iron	99.828 Fe (by difference), 0.100 Cu, 0.022 Mn, 0.021 C, 0.020 S, 0.007 P, and 0.002 Si; specimen 2.875 in. O. D. x 0.875 in. I. D. x 5.5 in. long consisted of 11 disks; transition point (α-γ) 1183 K.
94	1060	Pak, M. I. and Osipova, V. A.	1967	→	482-1243	Armco Iron	Specimen made of cylindrical discs 40 mm in dia and 70 mm overall height; measured in a vacuum of 5 x 10^{-2} N m^{-2} by a quasi-steady-state method; Curie point 780 C; transition point (α-γ) 928 C; 1st heating.
95	1060	Pak, M. I. and Osipova, V. A.	1967	→	479-884	Armco Iron	The above specimen; second heating.
96	1060	Pak, M. I. and Osipova, V. A.	1967	→	476-1243	Armco Iron	The above specimen after repeated heating and cooling.
97	245	Cason, J. L., Jr.	1967	L	80-313	Armco Iron	Obtained from Battelle Memorial Institute; 3 mm dia x 19 mm long.
98*	272	Danielson, G.C., Chiotti, P., and Carlson, O.N.	1956	P	336-1269	Armco Iron	Thermal conductivity values calculated from the measured data of thermal diffusivity using specific heat data of Darkin, L.S. and Smith, R.P. (Ind. Engr. Chem., 43, p. 1815, 1951) and the density of 7.867 g cm^{-3}.

* Not shown in figure.

Krypton

The thermal conductivity of krypton in each of the physical states is discussed separately below.

Solid

The thermal conductivity of solid krypton has been experimentally studied by White and Woods [1552] from about 3 to 80 K and by Krupskii [792] from 25 to 100 K. Calculations were made by Julian [696] and the [1552] values served as a basis for a book review graph [752].

The two different [1552, 792] sets of experimental data agree only to a moderate extent. The most disturbing difference is the trend of the [792] data to much higher values, at temperatures lower than about 70 K, than the [1552] data. This is claimed [792] as being due to impurities in the [1552] material. Such a change to higher values is indeed reasonable from a purity viewpoint. However, other effects may also occur and it is felt that a critical experimental investigation is highly desirable. Moreover, if the [792] values are used as base, no means exists for determining values for temperatures at and below those at which the thermal conductivity reaches a maximum. The White and Woods [1552] values have therefore been retained as the basis for the recommended values, obtained from a smooth curve-fit of the original [1552] values. Considerable uncertainty in the recommended values exist. Possibly a forty percent uncertainty above 25 K is a reasonable estimate. No reliable estimate is felt possible at lower temperatures.

Saturated Liquid

Data for the thermal conductivity of liquid krypton have been reported by Keyes [748] and by Ikenberry and Rice [654]. The former source reports three data points from 123 to 162 K while the latter reports data for temperatures from 126 to 200 K. In both cases, apparently, no values at exactly saturation conditions were obtained and extrapolation to saturation pressure is necessary. In general, this was simple. However, some error could occur with the highest temperature [654] data.

While the accord between the two sets of data is usually good, the highest temperature point of Keyes, for 162 K, is suspect. Keyes has confirmed in private communication that this point is in error. He was unable to supply a revised figure as some of his original notebooks were destroyed by fire. Possibly partial vaporization of the sample could have produced the apparently very low value.

For temperatures below 190 K most experimental data do not deviate significantly from a straight line relationship and the recommended values were calculated from the equation

$$k\ (\mathrm{mW\ cm^{-1}\ K^{-1}}) = 1.69375 - 6.573 \cdot 10^{-3}\,T$$

which fitted the data to about 0.25 percent. However, the accuracy is more probably about two percent. For temperatures above 190 K the critical thermal conductivity estimate of Owens and Thodos [1058] was used with a graphical plot to obtain the recommended values. The uncertainty increases rapidly above 190 K and can be assessed at about ten percent to 205 K and possibly twenty percent at the critical point.

Saturated Vapor

No measurements of the thermal conductivity of saturated krypton vapor were located or vapor phase measurements sufficiently close to saturation to enable an estimate of the saturation conditions to be made. The correlation of Owens and Thodos [1058] was used and it was found that this gave a value at the normal boiling point some three percent higher than that obtained from extrapolation of the atmospheric pressure curve. Accordingly, the values so obtained were reduced by percentages which varied linearly with temperature from three percent at the normal boiling point to zero at the critical point. These adjusted values are presented as the recommended values.

In the absence of any experimental values, no departure plot is given. It can be estimated that the probable accuracy of the recommended values is some five percent below 150 K, ten percent at 200 K and possibly twenty percent at the critical point.

Gas

In the original analysis, thirteen data points from 131 to 579 K were located, due to [305, 403, 705, 748, 808, 1499]. Only two of these [705, 748] covered any appreciable temperature range. Based on these data recommended values to 700 K were generated [843, 844, 608, 1420].

Since then, Shäfer [1255] reported data from 273 to 1373 K using the hot wire method and Schramm [1270] from 276 to 1086 K, while the column method was used by Saxena and Saxena [1251] from 350 to 1500 K, and by Umanskii and Timrot [1448] from 796 to 1263 K. Values to 5000 K [287] were deduced from heat transfer rates in reflected shock waves. Other measurements over less extensive ranges also have been made [472]. In addition, several other analyses have appeared. Hanley and Childs [585] in 1967 used the Lennard-Jones 6–17 potential to calculate values from 100 to 1000 K and Kestin and Wakeham [743] analyzed viscosity and thermal conductivity data to produce values from 300 to 1500 K, using the Lennard-Jones 6–13 potential. Svehla [138] used the Lennard-Jones 6–12 potential to calculate values to 5000 K.

In the present analysis, the criterion of Klein [586] was used that the precise form of the potential is very difficult to determine in the Lennard-Jones 6–12 potential for reduced temperatures from 2 to 5. This implies roughly a temperature range of 400 to 1000 K. For reduced temperatures above 10, the collision integrals can be approximated by power law functions of temperatures, implying that the thermal conductivity varies as temperature to the powers 0.652, 0.642, and 0.610 for the 6–12, 6–13, and 6–17 potentials. None of these approach the 0.695 power cited by Collins and Menard. There is thus a systematic discrepancy between the theoretical and shock wave values.

For this reason, the recommended values were curtailed to 2000 K, at which point the discrepancy is already about eight percent.

The recommended values below 250 K were taken from the original analysis and from 700 to 2000 K were generated as a mean of the different theoretical predictions. Values between 250 and 700 K were produced by extrapolation of the values at lower and higher temperatures, respectively. It would appear from the departure plot that the recommended values should be accurate to about two percent up to 600 K, five percent from 600 to 1500 K, and possibly uncertain to as much as ten percent at 2000 K, due to the discrepancy noted above.

TABLE 83. Recommended thermal conductivity of krypton

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
				120	0.0406*
		116	0.931	125	0.0429*
1	0.4*	120	0.905	130	0.0452*
1.5	0.8*	125	0.872	135	0.0476*
2	1.3*	130	0.839	140	0.0501*
2.5	2.0*	135	0.806	145	0.0527*
3	2.7	140	0.773	150	0.0554*
3.5	3.5	145	0.740	155	0.059*
4	4.4	150	0.708	160	0.062*
4.5	5.4	155	0.675	165	0.065*
5	6.5	160	0.642	170	0.070*
6	8.9	165	0.609	175	0.074*
7	10.7	170	0.576	180	0.079*
8	14.4	175	0.543	185	0.085*
9	16	180	0.510	190	0.093*
10	17	185	0.477	195	0.101*
12	16	190	0.444	200	0.112*
14	15	195	0.408	205	0.135*
16	14	200	0.366	210	0.21*‡
18	13	205	0.31*		
20	12	210	0.21*‡		
25	9.8				
30	8.3				
35	7.1				
40	6.2				
45	5.6				
50	5.1				
60	4.3				
70	3.8				
80	3.4				
90	3.1				
100	2.8				
110	2.6				
116	2.5				

*Extrapolated or estimated.
‡Pseudo-critical value.

TABLE 83. Recommended thermal conductivity of krypton—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas (At 1 atm)					
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		500	0.147	900	0.227
		510	0.149	910	0.228
120	0.0405	520	0.151	920	0.230
130	0.0437	530	0.154	930	0.231
140	0.0469	540	0.156	940	0.233
150	0.0501	550	0.158	950	0.235
160	0.0533	560	0.160	960	0.237
170	0.0562	570	0.162	970	0.239
180	0.0593	580	0.165	980	0.240
190	0.0623	590	0.167	990	0.242
200	0.0653	600	0.169	1000	0.244
210	0.0683	610	0.171	1050	0.252
220	0.0713	620	0.173	1100	0.260
230	0.0742	630	0.176	1150	0.268
240	0.0772	640	0.178	1200	0.276
250	0.0802	650	0.180	1250	0.284
260	0.0830	660	0.182	1300	0.291
270	0.0860	670	0.184	1350	0.299
280	0.0891	680	0.186	1400	0.306
290	0.0920	690	0.188	1450	0.313
300	0.0949	700	0.190	1500	0.320
310	0.0978	710	0.192	1550	0.327
320	0.1007	720	0.194	1600	0.334
330	0.1035	730	0.196	1650	0.341
340	0.1063	740	0.198	1700	0.347
350	0.1090	750	0.200	1750	0.353
360	0.1118	760	0.201	1800	0.359
370	0.1145	770	0.203	1850	0.365
380	0.1173	780	0.205	1900	0.371
390	0.1199	790	0.207	1950	0.377
400	0.1226	800	0.209	2000	0.382
410	0.1252	810	0.211		
420	0.1278	820	0.212		
430	0.1302	830	0.214		
440	0.1329	840	0.216		
450	0.1355	850	0.218		
460	0.1380	860	0.220		
470	0.1405	870	0.221		
480	0.1430	880	0.223		
490	0.1450	890	0.225		

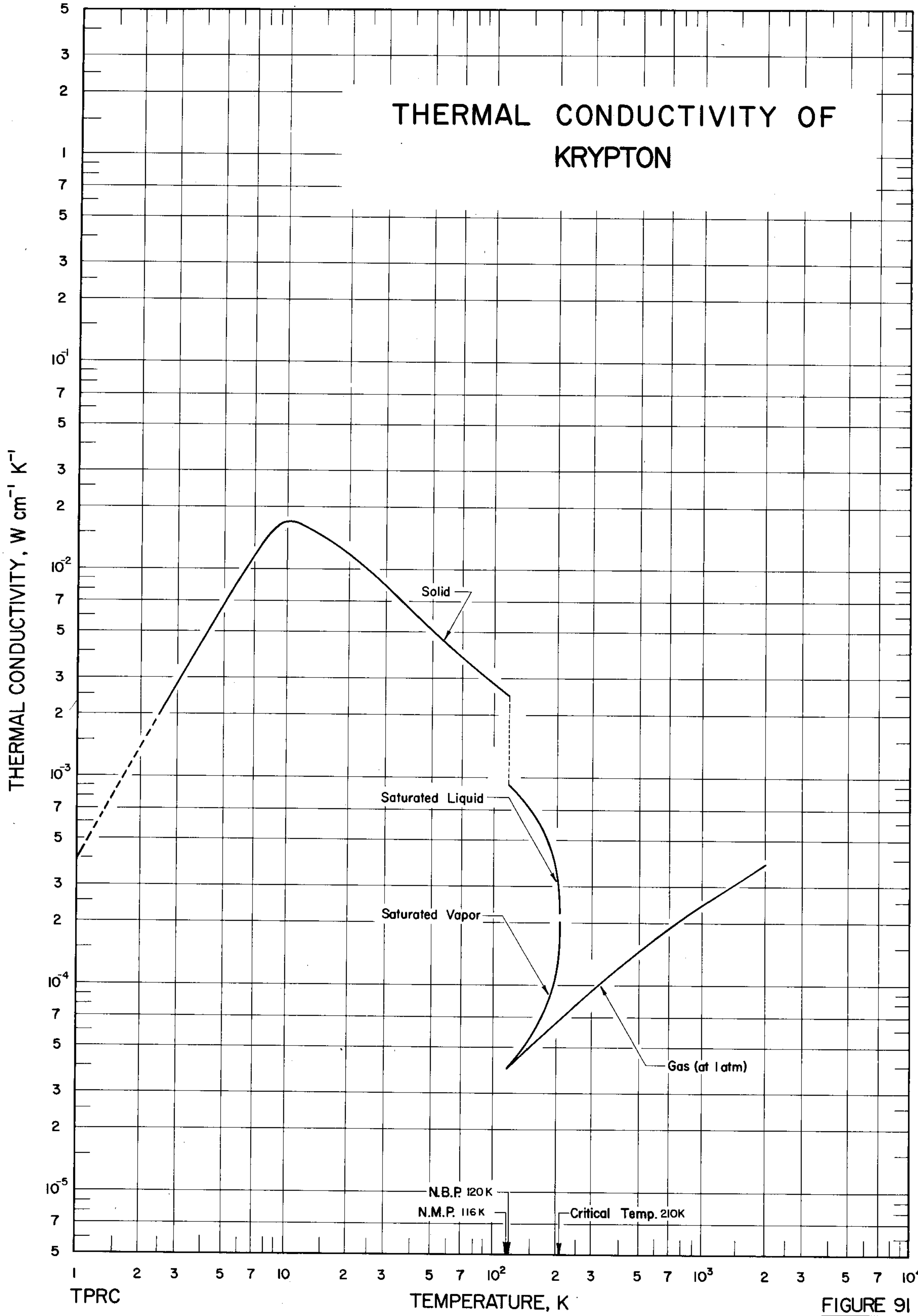
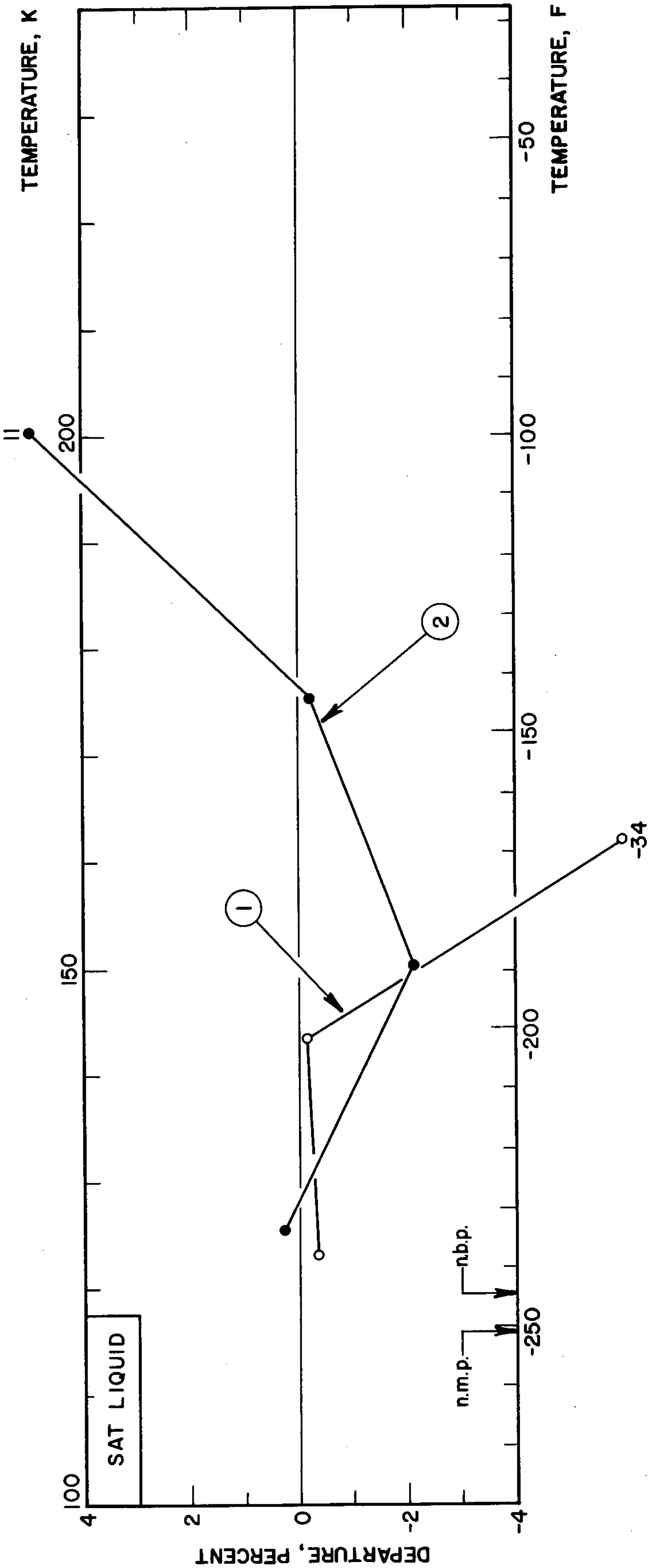

THERMAL CONDUCTIVITY OF
KRYPTON
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Solid
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.B.P. 120 K
N.M.P. 116 K
Critical Temp. 210K
TPRC

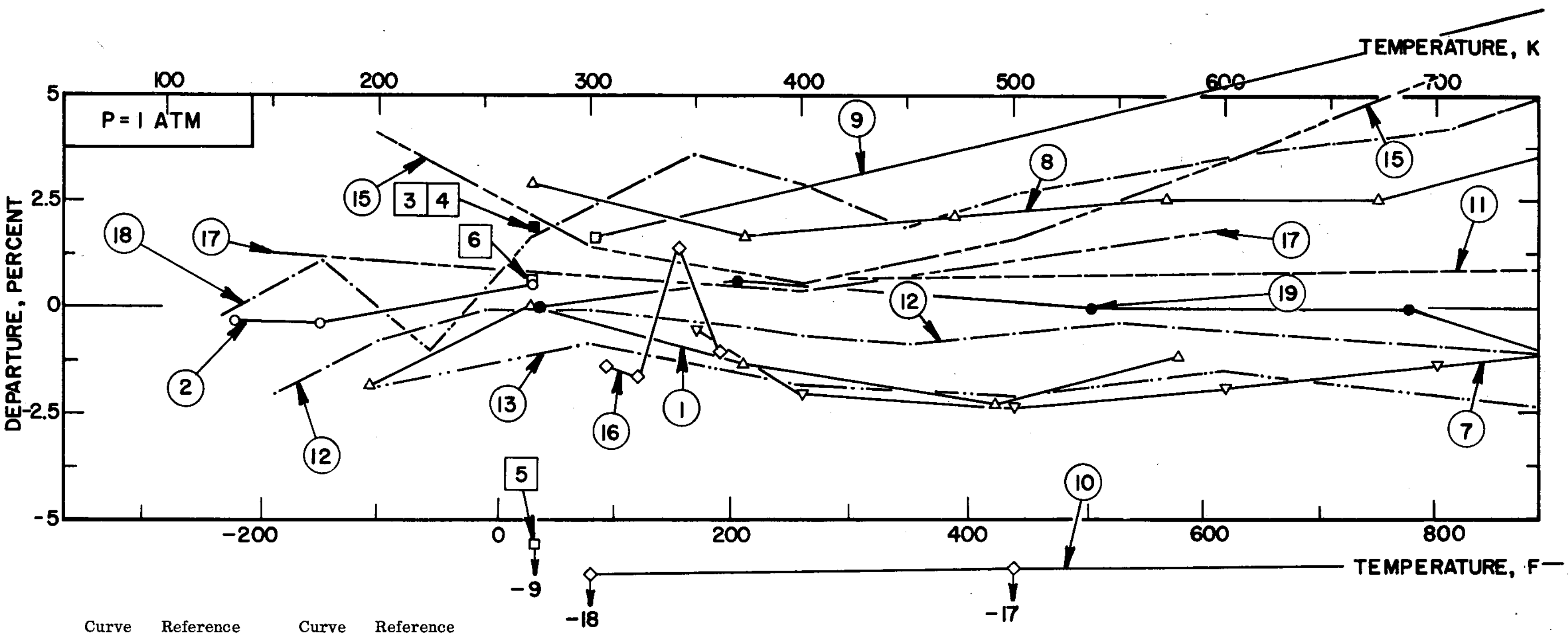
FIGURE 91

FIGURE 92. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID KRYPTON



Curve	Reference
1	748
2	654

FIGURE 93. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS KRYPTON



Curve	Reference	Curve	Reference
1	705	11	743
2	748	12	585
3	1499	13	1381
4	305	14	55
5	808	15	1473
6	403	16	472
7	1251	17	1417
8	1255	18	1474
9	1490	19	1270
10	287	20	1448

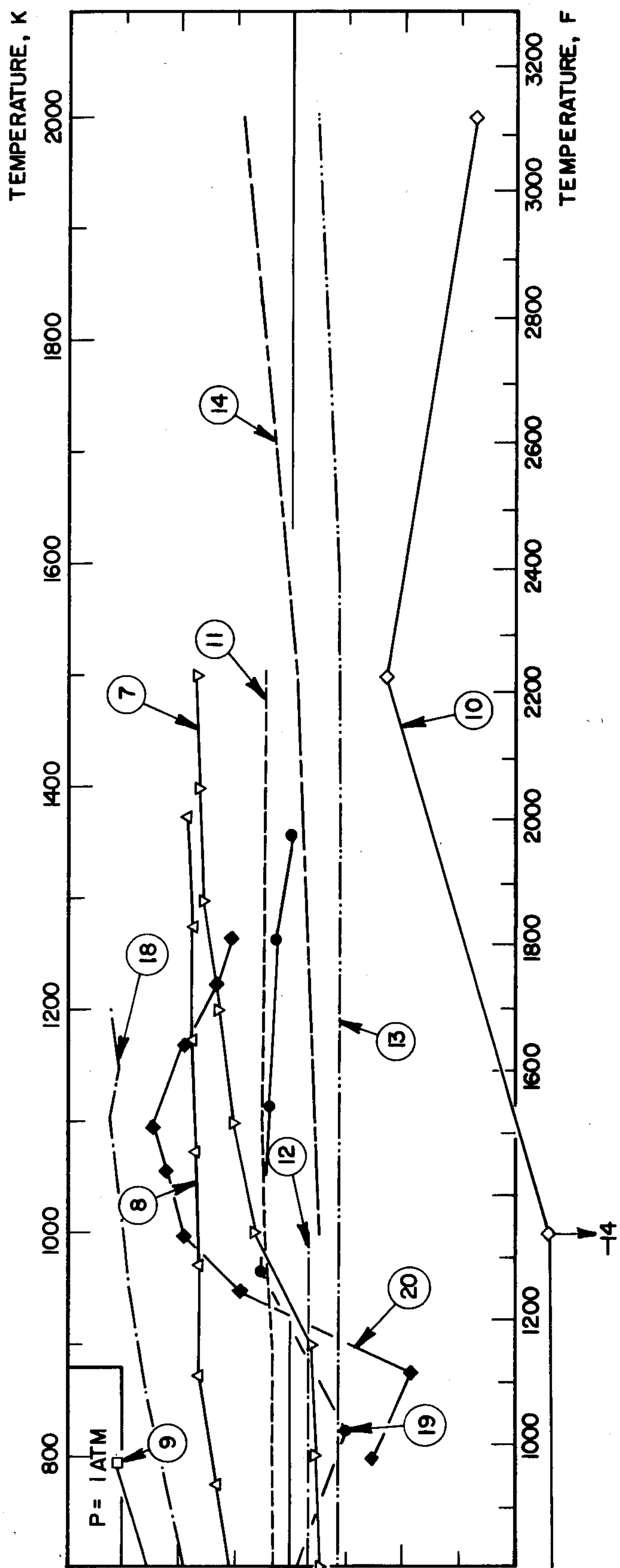


FIGURE 93. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS KRYPTON (continued)

Curve	Reference
7	1251
8	1255
9	1490
10	287
11	743
12	585
13	1381
14	55
18	1474
19	1270
20	1448

Lanthanum

Two groups of workers, Rosenberg [1220] (curve 1) and Mamiya, Fukuroi, and Tanuma [878] (curves 2–5) have been responsible for thermal conductivity determinations on lanthanum at low temperatures. The sample used by Rosenberg, although stated to have been of 99.94 percent purity, gave values which were lower by about an order of magnitude and which could be extrapolated to link on with the higher temperature data of Golubkov, Devyatkova, Zhuze, Sergeeva, and Smirnov [515] (curve 8) at about 85 K with no evidence of a low-temperature maximum. The higher values of Mamiya, et al. [878] (curve 5) on the other hand could be extrapolated to yield a maximum at about 14 K, followed by a minimum at about 63 K. This last serves as the provisionally recommended curve, which, over the range 83 to 450 K, has been drawn parallel to, but about 5 percent above, the mean curve through the data of Golubkov, et al. [515] on account of the fact that the purity of the sample is low. At room temperature the curve satisfies the mean of the three sets of available data and has been extrapolated to higher temperatures by using the electrical resistivities reported by Kaye and Laby [723], the theoretical Lorenz function, and a lattice component given by AT^{-1} where A is 6.84, as derived from the room temperature data of Jolliffe, Tye, and Powell [690] (curve 7).

Lanthanum has a phase transformation at 583 K, so there is the possibility of a discontinuity at this temperature. Since at temperatures below 583 K, lanthanum has a double close-packed hexagonal structure, over the temperature range already studied and up to 583 K the conductivity is likely to exhibit anisotropy. Measurements on single-crystal samples which would determine the extent of any anisotropy have yet to be made. No information is available for the molten state.

The values above 80 K are recommended values and below 80 K are provisional values. The recommended values have a probable uncertainty of ±5 percent within ±100 K of room temperature and ±10 to ±15 percent at other temperatures. The provisional values above 10 K are very uncertain, and those below 10 K should be good to ±15 percent. The values below 50 K are applicable only to a sample having a residual electrical resistivity of 1.29 μΩ cm.

TABLE 84. Recommended thermal conductivity of lanthanum†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline					
T	k	T	k	T	k
0	0	30	0.121	350	0.142
1	0.0250*	35	0.108	373.2	0.145
2	0.0468	40	0.101	400	0.149
3	0.0674	45	0.0969*	473.2	0.158*
4	0.0875	50	0.0943*	500	0.162*
5	0.107	60	0.0927*	573.2	0.175*
6	0.124	70	0.0929*	600	0.179*
7	0.140	80	0.0941*	673.2	0.192*
8	0.154	90	0.0958	700	0.196*
9	0.166	100	0.0978	773.2	0.207*
10	0.176	123.2	0.103	800	0.211*
11	0.183	150	0.109	873.2	0.219*
12	0.188	173.2	0.116	900	0.222*
13	0.191	200	0.118	973.2	0.227*
14	0.192	223.2	0.122	1000	0.229*
15	0.191	250	0.127	1073.2	0.232*
16	0.188	273.2	0.131	1100	0.232*
18	0.179	298.2	0.134		
20	0.168	300	0.135		
25	0.141	323.2	0.138		

†The values are for well-annealed high-purity lanthanum, and those below 50 K are applicable only to a specimen having $\rho_0 = 1.29$ μΩ cm. The values below 50 K are provisional.

*Extrapolated or interpolated.

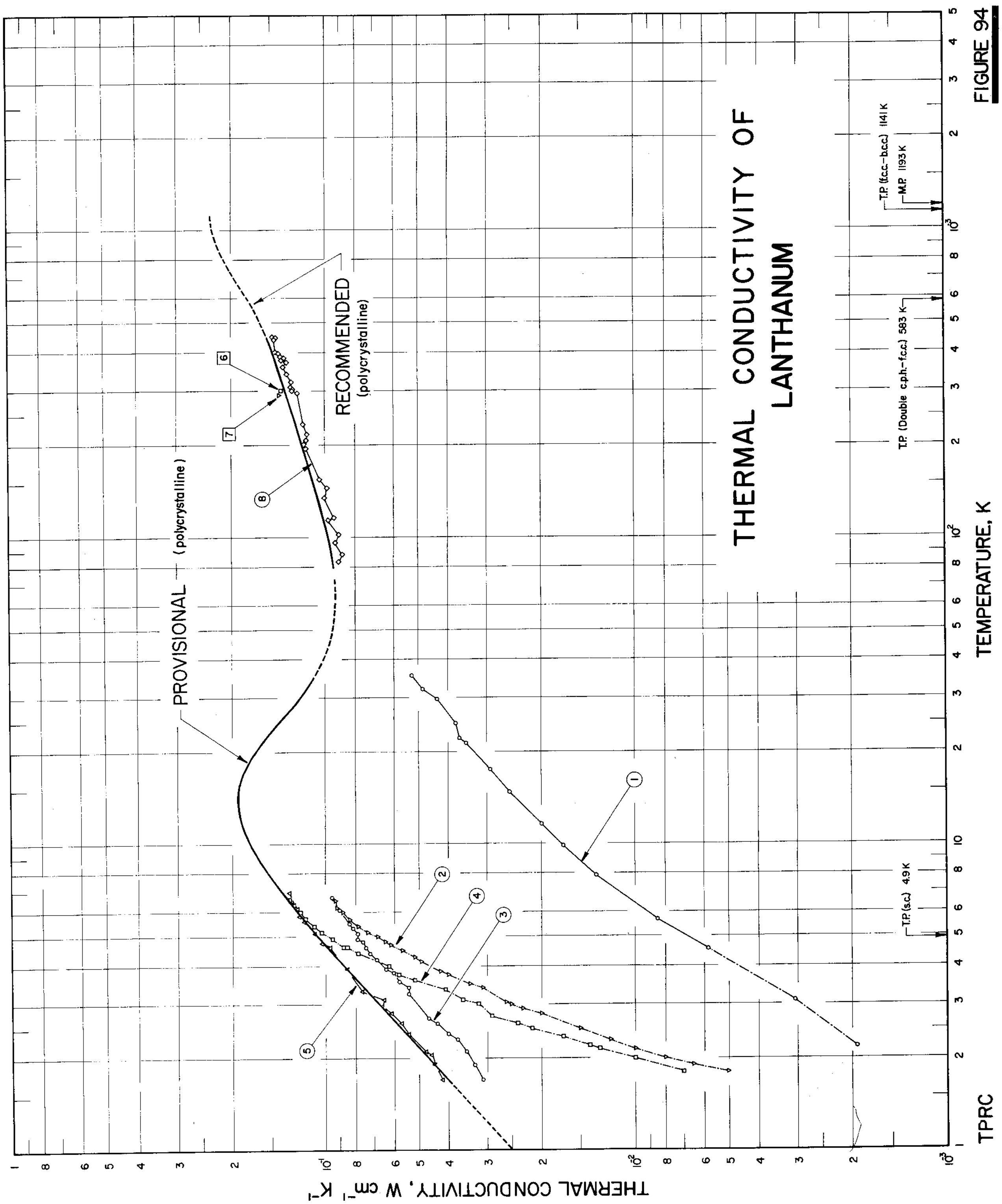

THERMAL CONDUCTIVITY OF
LANTHANUM
RECOMMENDED
(polycrystalline)
PROVISIONAL
(polycrystalline)
T.P. (f.c.c.-b.c.c.) 1141 K
M.P. 1193 K
T.P. (Double c.p.h.-f.c.c.) 583 K
T.P. (s.c.) 4.9 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 94

TABLE 85. THERMAL CONDUCTIVITY OF LANTHANUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1220	Rosenberg, H.M.	1955	L	2.2-36	La I	99.94 pure; Ca and Be as major impurities; polycrystalline; electrical resistivity ratio $\rho(293K)/\rho(20K) = 3.71$; superconducting below 4.7 K; author thinks values below 4.7 K may apply to an intermediate state if magnetic field was too weak.
2	878	Mamiya, T., Fukuroi, S., and Tanuma, S.	1965	L	1.8-6.6	La I	99.99 nominal purity; polycrystalline rod, of f.c.c. form; 5 cm long, 0.4 cm in dia; supplied by H. Fleishman Ltd.; annealed at 600 C for 24 hrs; residual electrical resistivity $\rho(4.2K)$ 1.72 μohm cm; electrical resistivity ratio $\rho(293K)/\rho(4.2K) = 32.4$; specimen in superconducting state below the transition point of 6.04 K (determined magnetically); x-ray analysis showed a trace of h.c.p. phase dispersed in the f.c.c. phase.
3	878	Mamiya, T., et al.	1965	L	1.7-6.7	La I	The above specimen measured in a magnetic field of 6600 gauss; specimen in normal conducting state; Lorenz number $L_0 = 2.79 \times 10^{-2}\ V^2\ K$.
4	878	Mamiya, T., et al.	1965	L	1.8-6.6	La II	Similar to the above except annealed at 600 C for 106 hrs; residual electrical resistivity $\rho(4.2K) = 1.29$ μohm cm; electrical resistivity ratio $\rho(293K)/\rho(4.2K) = 44.0$; specimen in superconducting state below the transition point of 6.04 K (determined magnetically); x-ray analysis showed a trace of h.c.p. phase dispersed in the f.c.c. phase.
5	878	Mamiya, T., et al.	1965	L	1.7-7.0	La II	The above specimen measured in a magnetic field of 6600 gauss; specimen in normal conducting state; Lorenz number $L_0 = 2.83 \times 10^{-8}\ V^2\ K^{-2}$.
6	831	Legvold, S. and Spedding, F.H.	1954		301.2		No details given.
7	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	C	291		<0.01 rare earth metals, ~0.02 base metals; polycrystalline specimen 1 cm in dia and 1.2 cm long; electrical resistivity 61 μohm cm at 291 K; data point derived by the authors from measurements by 2 different thermal comparators.
8	515	Golubkov, A.V., Devyatkova, E.D., Zhuze, V.P., Sergeeva, V.M., and Smirnov, I.A.	1966	L	83~450	La I	0.1 O, 0.01 Ce, 0.008 Fe, 0.005 Cu, 0.005 Nd, and 0.005 Pr; hexagonal polycrystalline; electron-beam refined; electrical resistivity reported as 28.5, 37.3, 46.6, 53.9, 60.6, 66.1, 69.4, and 73.1 μohm cm at 98, 151, 199, 251, 300, 351, 397, and 447 K, respectively; measured in a vacuum of 10^{-4}~10^{-5} mm Hg.

Lawrencium

No information is available for the thermal or electrical conductivity of lawrencium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidences show that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of lawrencium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Lead

There are 156 curves available for the thermal conductivity of lead. In the low temperature region, the measurements (curve 56) of Wolff [1574] for an annealed pure single crystal enriched with lead isotopes yield the highest thermal conductivity in the normal state. The curve for which recommended values are tabulated is based on his measurements. The recommended values below 3 K were obtained by calculation using a β value of 0.0353 derived from his data. From 3 to 7 K the curve follows closely curve 56 and from 7 to 35 K lies close to curves 17 and 6. The former is by Mendelssohn and Rosenberg [937] for a 99.998 percent pure single crystal and the latter by deHaas and Rademakers [339] for a high-purity single crystal. These recommended values are of course only applicable to a sample having $\rho_o = 0.000862$ $\mu\Omega$ cm.

At normal and higher temperatures the thermal conductivity of lead is of particular interest owing to its early use as a standard by Shelton and Swanger [1302] (curve 2) (the same results were later published by Van Dusen and Shelton [1464]. The sample used was the NBS melting-point lead as available in the 1930's, having a freezing point of 327.4 C.*

A recent publication on the thermal conductivity of lead is by Lucks [861] (curves 140, 141). He used a similar comparative method to that just mentioned but with Armco iron as the standard material. It was Lucks who organized a round-robin investigation of the thermal conductivity of this same stock of Armco iron and he used the mean values as reported by four other measuring laboratories. He has studied two NBS Pyrometric Standard Lead samples, one of their most recent, with a freezing point of 327.417 C and an earlier grade with a freezing point of 327.31 C. The tabulated smooth values of Lucks for the earlier of these two samples and those of Van Dusen and Shelton agreed exactly over the common range of 50 to 150 C, and extrapolation leads to complete agreement from 0 to 300 C. For the later and purer sample, Lucks' values at 50 C is greater by about 1.8 percent, and at 150 C by about 4.3 percent, whilst at 300 C the extrapolated difference is nearly 9 percent.

Lucks concludes "These data are believed significant and indicate the data of Van Dusen and Shelton should not be used for NBS Pyrometric Standard Lead having a freezing point of 0.1 C difference."

Support for Lucks' higher set of values is forthcoming from the recently published values of Dauphinee, Armstrong, and Woods [317] (curves 137, 138). These workers had carried out their measurements several years previously by an absolute longitudinal heat-flow method on a very pure lead that was stated to be 99.999 percent or better purity. Their temperature range was about —50 to 300 C. Two independent sets of measurements gave results that agreed to within 1 percent but fitted straight lines of differing slope. Lucks' values at 50 C for the higher-freezing-point sample are in close agreement and his extrapolated value at 300 C is greater than the mean value of Dauphinee, et al. by only 1.5 percent. Thus both of Lucks' curves receive independent support from other workers and the recommended curve for moderate and high temperatures has been drawn to fit closely with these two recent determinations. The derived Lorenz function is of the order of 2.5×10^{-8} V^2 K^{-2} and is thus in fairly good agreement with the earlier values of Lees [830] (curve 19) and of Jaeger and Diesselhorst [664] (curve 8). Nevertheless the divergence of the thermal conductivity curves with increase in temperature for these two grades of lead is sufficiently unusual to warrant further independent investigation. Furthermore, it is surprising that Lucks and Gibbs [865] found no corresponding change in the electrical resistivity of these two grades of lead, which were found to have almost identical electrical resistivity at 200 C at which their thermal conductivity values differ by about 6 percent. The 3 to 4 percent higher thermal conductivity data of Powell and Tye [1137] (curve 139) were obtained on smaller and less suitable samples and these data which were thought to have an uncertainty of ±3 percent, have been ignored as likely to be too high. The many earlier determinations are considered low, probably due to the use of less pure lead.

The recommended curve for moderate and high temperatures and that for a specific sample at low temperatures having $\rho_o = 0.000862$ $\mu\Omega$ cm were extrapolated to join smoothly together and the resulting curve in the

* The freezing point of this lead was quoted as 327.3 C by Lucks [861].

subnormal temperature region lies above the curve of Lees [830] (curve 19) by about 2 percent. It is steadily decreasing with increase in temperature.

For molten lead there are eleven sets of data available and the values differ by about 60 percent and also in the sign of the temperature coefficient. The recommended values are based upon the data of Dutchak and Panasyuk [383] (curve 136) and of Powell and Tye [1131] (curve 9), and are in close agreement with values derived from the electrical resistivity and the theoretical value of the Lorenz function. The specimen of Powell and Tye in the molten state was from the same supply as the specimen measured in the solid state. The values of Filippov [434, 435] (curves 135, 143) and of Yurchak and Filippov [1591, 1592] (curves 144, 88) as derived by them from thermal diffusivity determinations are almost independent of temperature up to 1355 K, and indicate a Lorenz function at that temperature which is of the order of 30 percent below the theoretical value. These results are in need of independent confirmation, and have been discussed in more detail in [1122].

At the melting point the ratio of the recommended thermal conductivity for the solid lead to that for the molten lead is 2.02, which is close to the value of 1.94 obtained by Roll and Motz [1217] for the corresponding electrical conductivity ratio. The thermal conductivity of molten lead will reach a maximum at a certain high temperature and then start to decrease gradually to a very low value at the critical temperature around 5400 K.

Curves for superconducting lead below 7.193 K (the transition temperature) are also shown in figure 95, but no recommendations are at present made for the superconducting state.

The recommended values are thought to be accurate to within ±3 percent of the true values at moderate temperatures, ±5 percent at high temperatures, and ±10 percent at low temperatures and for molten below 800 K. The values above 800 K are provisional. The low-temperature values below 30 K are only for lead having $\rho_0 = 0.000862\ \mu\Omega$ cm.

TABLE 86. Recommended thermal conductivity of lead†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	k	T	k
0	0	60	0.425
1	27.9	70	0.416
2	44.6	80	0.409
3	35.8	90	0.403
4	22.2	100	0.397
5	13.8	123.2	0.389
6	8.10	150	0.379
7	4.86	173.2	0.372
8	3.20	200	0.367
9	2.30	223.2	0.365
10	1.78	250	0.360
11	1.46	273.2	0.356
12	1.23	298.2	0.353
13	1.07	300	0.353
14	0.944	323.2	0.350
15	0.845	350	0.347
16	0.772	373.2	0.344
18	0.661	400	0.340
20	0.591	473.2	0.330
25	0.507	500	0.328
30	0.477	573.2	0.318
35	0.462	600	0.314
40	0.451	600.652	0.314
45	0.442		
50	0.436		

Liquid

T	k	T	k
600.652	0.155	873.2	0.201
673.2	0.170	900	0.205
700	0.175	973.2	0.212
773.2	0.187	1000	0.215
800	0.192		

†The recommended values are for well-annealed high-purity lead, and those below 30 K are applicable only to lead in the normal state having $\rho_0 = 0.000862$ $\mu\Omega$cm. The values above 800 K are provisional.

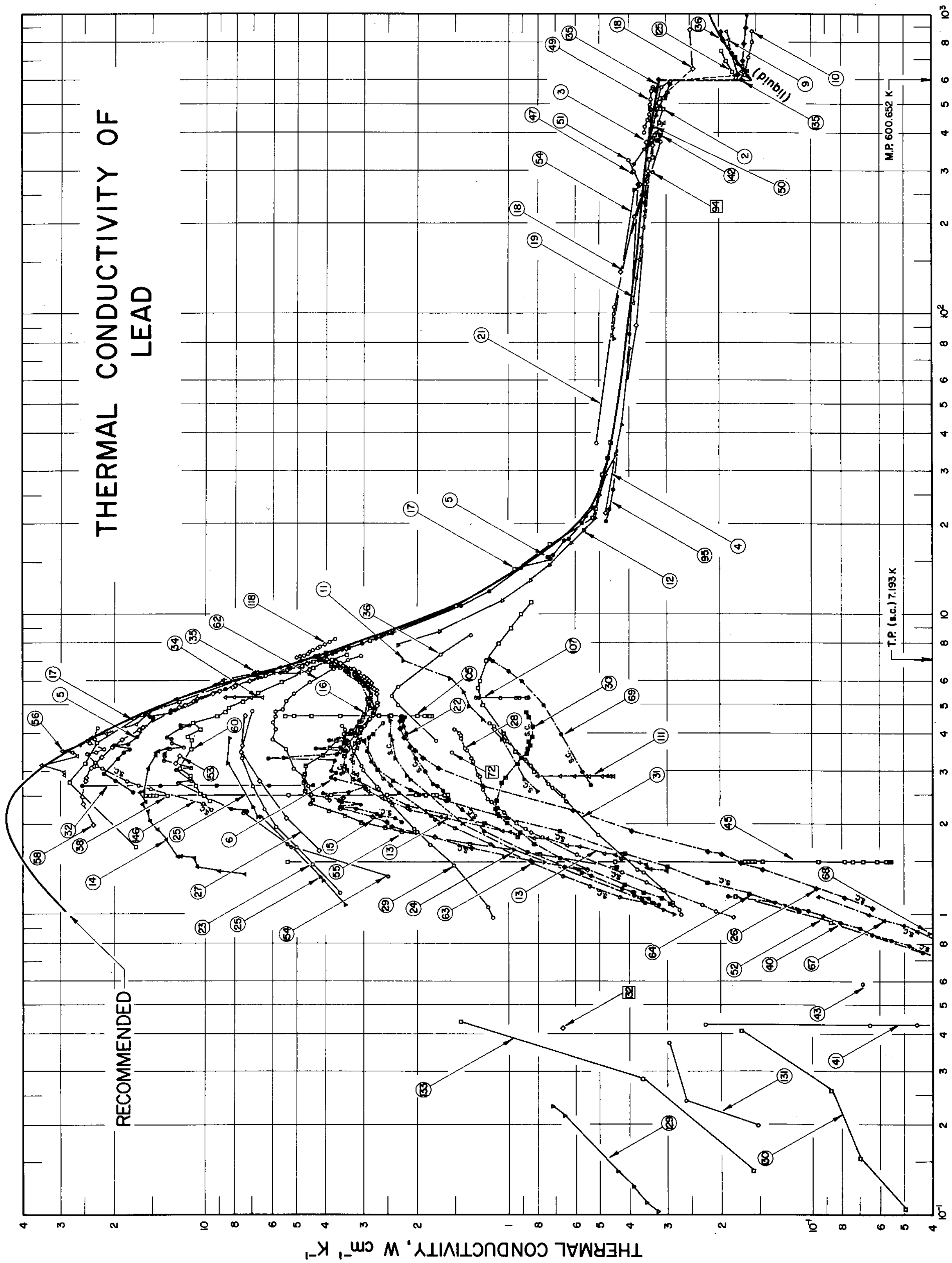

THERMAL CONDUCTIVITY OF LEAD
RECOMMENDED
(liquid)
T.P. (s.c.) 7.193 K
M.P. 600.652 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 95

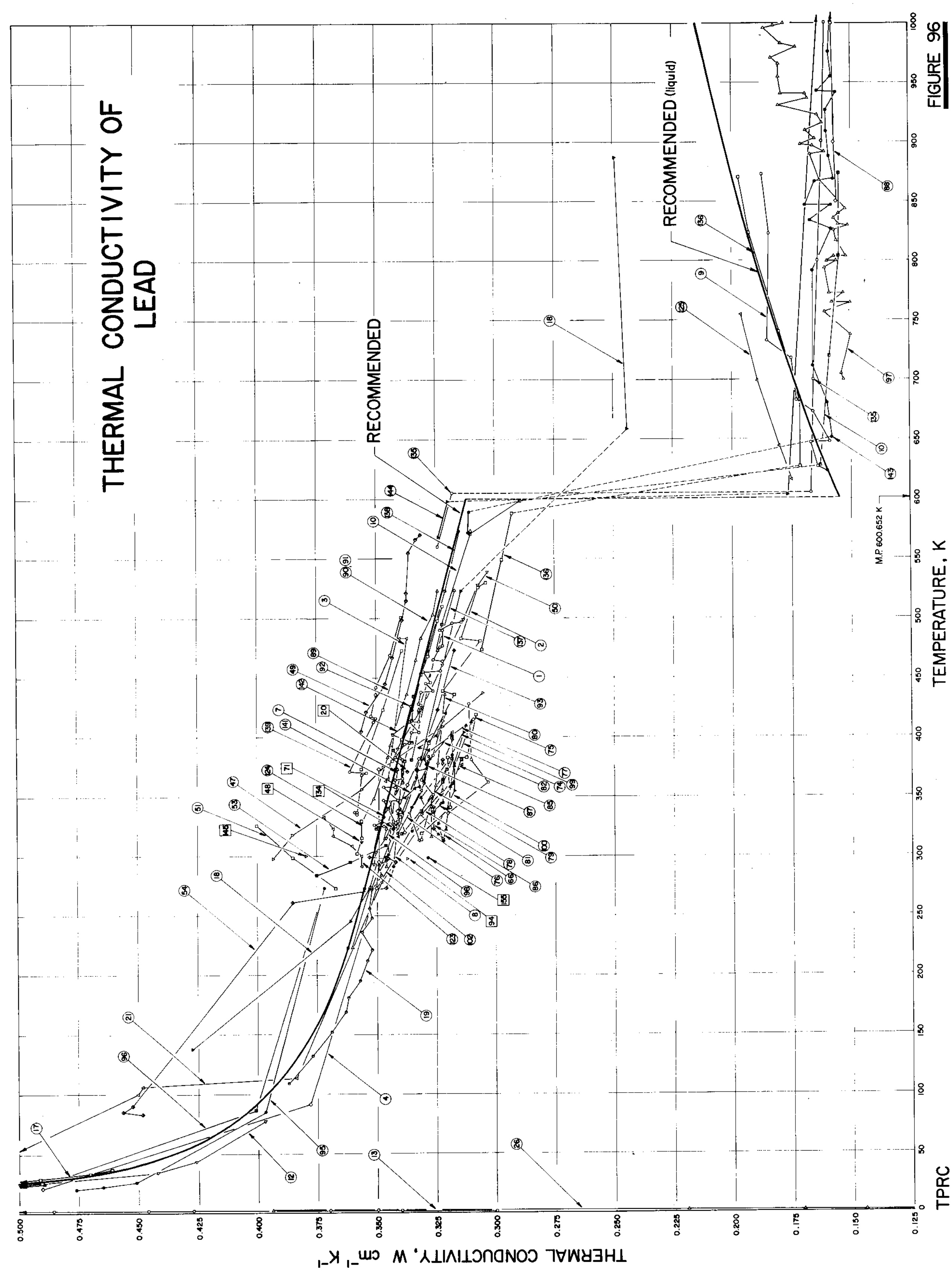

THERMAL CONDUCTIVITY OF LEAD
RECOMMENDED
RECOMMENDED (liquid)
M.P. 600.652 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 96

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	458	Francl, J. and Kingery, W. D.	1954	C	326–497		Specimen of 1 in. cube; cut and machined from a bar of melting-point lead supplied by NBS (sample No. 49c); all surfaces carefully lapped; nickel used as comparative material.
2	1302, 1464	Shelton, S. M. and Swanger, W. H.	1933	C	273–530	L. S.	Bureau of Standards melting point standard lead; purity indicated by freezing point of 327.4 C; specimen 15 cm long, 2 cm in dia; melted in graphite and cast in bottom feed cast iron mold; all data referred to the value 0.352 W cm^{-1} K^{-1} at 0 C taken from International Critical Tables, Volume IV, p. 221, McGraw Hill, 1929.
3	761	King, R. W.	1918	P	363–483		Pure; "squirted" wire, 3.1 mm in dia; thermal conductivity values calculated from measured data of thermal diffusivity and the specific heat values taken from literature.
4	920	Meissner, W.	1915	E	22–374		99.998 pure; specimen 6.24 cm long, 0.2996 cm in dia; electrical resistivity reported as 19.26 and 20.68 μohm cm at 0 and 18 C, respectively.
5	339	deHaas, W. J. and Rademakers, A.	1940	L	2.6–23		Single crystal, pure lead obtained from Adam Hilger Ltd. (H. S. brand); melted in high vacuum, filtered through a narrow glass opening, pressed in nitrogen into a glass tube of the desired shape then cooled slowly to make a specimen of 15 cm long, 2.5 mm in dia; transition point ~7.13 K; thermal conductivity data in normal state below transition point obtained by applying a transverse magnetic field of strength 472–810 gauss.
6	339	deHaas, W. J. and Rademakers, A.	1940	L	2.0–7.1		The above specimen in superconducting state.
7	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 273		99.95 Pb (by difference), <0.05 total Cu, Bi, Fe, and Ni; 1.8028 cm dia x 27.0 cm long; density 11.32 g cm^{-3} at 18 C; electrical conductivity reported as 4.84 and 3.64 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
8	664	Jaeger, W. and Diesselhorst, H.	1900	L	291, 273		Same material as the above specimen; drawn into a wire; electrical conductivity reported as 4.80 and 3.61 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
9	1131	Powell, R. W. and Tye, R. P.	1957	C	623–873	Lab No. 5873	99.995^+ pure; molten specimen contained in a thin-walled tube; electrical resistivity reported as 95.0, 97.2, 99.5, 102.0, 104.4, and 106.8 μohm cm at 350, 400, 450, 500, 550, and 600 C, respectively; 0.8% carbon steel used as comparative material.
10	778	Konno, S.	1919	L	381–874		Cylindrical specimen.
11	201	Bremmer, H. and deHaas, W. J.	1936	L	2.6–7.1		In superconducting state.
12	201	Bremmer, H. and deHaas, W. J.	1936	L	7.9–77		No details reported.
13	1164	Rademakers, A.	1949	L	1.4–3.8	Pb II	High purity; single crystal; specimen 3.8 mm in dia obtained from Adam Hilger Ltd. (H. S. brand); in superconducting state.
14	1164	Rademakers, A.	1949	L	1.4–3.9	Pb II	The above specimen in normal state; measured in a longitudinal magnetic field of 850 oersteds.
15	1164	Rademakers, A.	1949	L	1.4–2.5	Pb III	Similar to the above specimen but 4.0 mm in dia; in superconducting state.
16	937, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	1.8–6.7	Pb I	99.998 pure; Tadanac lead; single crystal; 0.0264 cm^2 x 3.02 cm; in superconducting state.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17	937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	1.7-38	Pb I	The above specimen in normal state.
18	159	Bidwell, C.C.	1940	L	138-887		No details reported.
19	830	Lees, C.H.	1908	L	109-299		Turned from a bar of pure lead supplied by Messr. Baxendale, Manchester; density 11.29 g cm^{-3} at 25 C; electrical resistivity reported as 6.71, 9.71, 12.9, 15.7, 18.5, and 20.9 μohm cm at -170, -129.4, -89.2, -51.8, -14.0, and 17.4 C, respectively.
20	1523	Weeks, J.L. and Seifert, R.L.	1952	L	317.2		Specimen cut from melting point standard lead supplied by NBS; 1.75 x 0.1875 x 0.1875 in.; measured in vacuo.
21	161	Bidwell, C.C. and Lewis, E.J.	1929	F	37-378		No details reported.
22	931, 981	Montgomery, H.	1958	L	1.1-4.6	Pb 1	99.99 pure; monocrystal; obtained from Johnson, Matthey and Co., Ltd. (No. 560); specimen ~7 cm long, 3 mm in dia; grain size 0.5 mm; annealed in vacuo for several days at a few degrees below the melting point; residual electrical resistivity 0.008 μohm cm; in superconducting state.
23	931, 981	Montgomery, H.	1958	L	1.2-4.8	Pb 1	The above specimen in normal state; measured in a transverse magnetic field of 1000 gauss.
24	981	Montgomery, H.	1958	L	1.0-4.6	Pb 2	99.99 pure; polycrystal; obtained from Johnson, Matthey and Co., Ltd. (No. 560); grain size 0.5 mm; specimen 7 cm long, 3 mm in dia; annealed in vacuo for several hrs at a few degrees below the melting point; residual electrical resistivity 0.008 μohm cm; in superconducting state.
25	981	Montgomery, H.	1958	L	1.1-3.9	Pb 2	The above specimen in normal state; measured in a transverse magnetic field of 1000 gauss.
26	981	Montgomery, H.	1958	L	1.1-4.6	Scroll	Pure; hollow cylindrical specimen 3 cm in dia made from lead foil 0.070 mm thick; annealed in vacuo for 5 days at a few degrees below the melting point; in superconducting state.
27	981	Montgomery, H.	1958	L	1.6-4.6	Scroll	The above specimen in normal state; measured in a magnetic field of 1000 gauss.
28	981	Montgomery, H.	1958	L	0.98-4.2	PbBi 0.02	99.98 Pb, 0.02 Bi; polycrystal with long crystals; specimen ~7 cm long, 3 mm in dia; annealed in vacuo for several hrs at a few degrees below the melting point; residual electrical resistivity 0.021 μohm cm; in superconducting state.
29	981	Montgomery, H.	1958	L	0.98-4.3	PbBi 0.02	The above specimen in normal state; measured in a magnetic field of 1000 gauss.
30	981	Montgomery, H.	1958	L	1.1-4.8	PbBi 0.1	99.899 Pb (by difference), 0.101 Bi; polycrystal; grain size 0.3 mm; specimen ~7 cm long, 3 mm in dia; annealed in vacuo for several hrs at a few degrees below the melting point; residual electrical resistivity 0.092 μohm cm; in superconducting state.
31	981	Montgomery, H.	1958	L	1.0-4.4	PbBi 0.1	The above specimen in normal state; measured in a magnetic field of 1000 gauss.
32	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.7	Pb 1	99.998 pure; single crystal; measured in transverse magnetic fields of strength ranging from 0.70 to 3.90 kilooersteds.
33*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.7	Pb 1	The above specimen measured in longitudinal magnetic fields of strength ranging from 0.87 to 3.94 kilooersteds.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
34	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	5.3	Pb 1	The above specimen measured in transverse magnetic fields of strength ranging from 1.86 to 3.94 kilooersteds.
35	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	6.4	Pb 1	The above specimen measured in transverse magnetic fields of strength ranging from 0.52 to 3.94 kilooersteds.
36	201	Bremmer, H. and deHaas, W. J.	1936	L	3.8-8.6		Measured in a magnetic field of 764 gauss.
37*	201	Bremmer, H. and deHaas, W. J.	1936	L	6.39		The above specimen measured in a magnetic field of 765 gauss.
38	1511	Webber, R. T. and Spohr, D. A.	1951	L	2.5		99.998 pure; 0.5 cm dia x 10 cm long; measured in transverse magnetic fields of strength ranging from 0 to 921 gauss.
39*	1511	Webber, R. T. and Spohr, D. A.	1951	L	2.5		The above specimen measured in transverse magnetic fields of decreasing strength ranging from 685 to 0 gauss.
40	1052	Olsen, J. L. and Renton, C. A.	1952	L	0.40-1.2		Single crystal; in superconducting state.
41	1052	Olsen, J. L. and Renton, C. A.	1952	L	0.43		The above specimen measured in magnetic fields with increasing strength ranging from 0 to 100% of the critical magnetic field.
42*	1052	Olsen, J. L. and Renton, C. A.	1952	L	0.43		The above specimen measured in magnetic fields with decreasing strength ranging from 82 to 0% of the critical magnetic field.
43	1052	Olsen, J. L. and Renton, C. A.	1952	L	0.59		The above specimen measured in magnetic fields with increasing strength ranging from 0 to 100% of the critical magnetic field.
44*	1052	Olsen, J. L. and Renton, C. A.	1952	L	0.59		The above specimen measured in magnetic fields with decreasing strength ranging from 72 to 37% of the critical magnetic field.
45	1052	Olsen, J. L. and Renton, C. A.	1952	L	1.5		The above specimen measured in magnetic fields with increasing strength ranging from 0 to 86% of the critical magnetic field.
46*	1052	Olsen, J. L. and Renton, C. A.	1952	L	1.5		The above specimen measured in magnetic fields with decreasing strength ranging from 69 to 0% of the critical magnetic field.
47	970	Mikryukov, V. E. and Tyapunina, N.A.	1956	E	298-437		Nominally pure; electrical conductivity reported as 4.4, 4.25, 3.6, 3.05, 2.65, and 2.45 x 10^4 ohm^{-1} cm^{-1} at 37, 50, 100, 150, 200, and 230 C, respectively.
48	1463	Van Dusen, M. S.	1922	C	313.2		Pure lead specimen 3 cm long and 3 cm in dia; zinc used as comparative material.
49	969	Mikryukov, V. E. and Rabotnov, S. N.	1944	E	405-570		Pure; single crystal; electrical resistivity reported as 29.67, 34.01, 39.68, 42.01, and 47.16 μohm cm at 405.1, 445.1, 499.1, 521.1, and 570.1 K, respectively.
50	969	Mikryukov, V. E. and Rabotnov, S. N.	1944	E	390-540		Pure; polycrystal; electrical resistivity reported as 30.1, 38.16, 42.44, and 46.88 μohm cm at 390.1, 461.8, 499.0, and 539.9 K, respectively.
51	1048	O'Day, M. D.	1924	E	273-326		Pure (supposed to be Kahlbaum's); 25 cm long, cross sectional area 0.439 cm^2.
52	1603	Zavaritski, N. V.	1960	L	0.16-1.2	1	99.999 pure; single crystal; specimen 0.13 cm in dia, ~5.0 cm long; in superconducting state.
53	1072	Peczalski, T.	1917	R	285-310		Commercially pure (major impurity probably tin); specimen composed of 2 hollow hemispheres of 3.65 cm internal radius and 7 cm external radius.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54	872	Macchia, P.	1907	C	83-300		Pure specimen (Kahlbaum lead) 32.85 mm in dia and 7 cm long; copper used as comparative material.
55	1474	Wolff, C. L.	1961	L	1.4-7.5	E	99.9$^+$ Pb (by difference), <0.1 metallic impurities; single crystal; enriched in isotopes of lead; specimen 1.54 cm long, 0.186 cm in dia; cast in high vacuum (10^{-5} mm Hg); annealed in vacuum for 5 hrs at 260 C; in superconducting state.
56	1474	Wolff, C. L.	1961	L	2.9-7.3	E	The above specimen measured in a longitudinal magnetic field of 900 gauss; in normal state.
57*	1474	Wolff, C. L.	1961	L	1.5-7.7	D	99.95 Fe (by difference), 0.05 metallic impurities; specimen 2.40 cm long, 0.123 cm in dia; same fabrication method as the above specimen; in superconducting state.
58	1474	Wolff, C. L.	1961	L	2.0-7.6	D	The above specimen measured in a longitudinal magnetic field of 900 gauss; in normal state.
59*	1474	Wolff, C. L.	1961	L	2.4-7.6	B	Similar to the above specimen but 2.26 cm long and 0.123 cm in dia; in superconducting state.
60	1474	Wolff, C. L.	1961	L	2.4-7.3	B	The above specimen measured in a longitudinal magnetic field of 900 gauss; in normal state.
61*	1474	Wolff, C. L.	1961	L	2.4-7.7	C	Similar to the above specimen but 2.05 cm long and 0.123 cm in dia; in superconducting state.
62	1474	Wolff, C. L.	1961	L	2.4-7.3	C	The above specimen measured in a longitudinal magnetic field of 900 gauss; in normal state.
63	930, 1228	Mendelssohn, K.; Rowell, P. M.	1958	L	1.0-4.4		99.99 pure; single crystal; straight wire; annealed at 270 C for 3 days; in superconducting state.
64	930, 1228	Mendelssohn, K.; Rowell, P. M.	1958	L	1.0-4.0		The above specimen bent at 4.2 K and annealed at 90 K; in superconducting state.
65*	930, 1228	Mendelssohn, K.; Rowell, P. M.	1958	L	1.1-4.4		The above specimen annealed at 290 K; in superconducting state.
66	773	Koenig, J. H.	1953	C	313-429	55 Nl-1	NBS melting point standard lead; Inconel used as comparative material.
67	936	Mendelssohn, K. and Renton, C. A.	1955	L	0.41-1.2		From Messrs. Goodlass, Wall and Lead Industries, Ltd.; the same specimen as used for curve No. 16, 99.998 pure Tadanac lead; single crystal; measured without magnetic shielding; in superconducting state.
68	936	Mendelssohn, K. and Renton, C. A.	1955	L	0.30-0.87		The above specimen measured with magnetic shielding; in superconducting state.
69	928, 934	Mendelssohn, K.	1950	L	2.7-7.2		99.98 Pb (by difference), 0.02 Bi; in superconducting state.
70*	928, 934	Mendelssohn, K.	1950	L	2.5-11		The above specimen in normal state; measured in a magnetic field.
71	1327	Smith, A. W.	1925	L	327.2		Baker's analyzed metal; total impurities <0.03; rod 1.9 cm in dia and 10 cm long; electrical conductivity 4.76 ohm^{-1} cm^{-1} at 22 C.
72	201	Bremmer, H. and deHaas, W. J.	1936	L	3.47		Measured in a magnetic field of 1006 gauss.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
73*	201	Bremmer, H. and deHaas, W. J.	1936	L	4.4, 4.6		The above specimen measured in a magnetic field of 956 gauss.
74	233	Koenig, J. H.	1953	C	322-414	55 M-1	NBS melting point standard lead; specimen 0.350 in. in dia and 0.510 in. long; copper used as the comparative material.
75	233	Koenig, J. H.	1953	C	319-419	55 P-1	Similar to the above specimen but 0.450 in. in dia and 0.509 in. long.
76	233	Koenig, J. H.	1953	C	319-385	55 J-1	Similar to the above specimen but 0.250 in. in dia and 0.265 in. long.
77	233	Koenig, J. H.	1953	C	321-416	55 K-1	Similar to the above specimen but 0.250 in. in dia and 0.528 in. long.
78	233	Koenig, J. H.	1953	C	316-398	55 L-1	Similar to the above specimen but 0.300 in. in dia and 0.502 in. long.
79	233	Koenig, J. H.	1953	C	319-400	55 N-1	Similar to the above specimen but 0.410 in. in dia and 0.489 in. long.
80	233	Koenig, J. H.	1953	C	316-436	55 N-2	Similar to the above specimen but 0.410 in. in dia and 0.487 in. long.
81	233	Koenig, J. H.	1953	C	322-401	55 Q-1	Similar to the above specimen but 0.500 in. in dia and 0.500 in. long.
82	233	Koenig, J. H.	1953	C	314-405	55 Q-2	Similar to the above specimen but 0.500 in. in dia and 0.476 in. long.
83*	928, 933	Mendelssohn, K. and Olsen, J. L.	1950	L	2.6-9.4		99.9 Pb, 0.1 Bi; in normal state; measured in a magnetic field.
84*	928, 933	Mendelssohn, K. and Olsen, J. L.	1950	L	2.7-6.4		The above specimen in superconducting state.
85	1233	Ruh, E.	1954	C	314-381	55 B-1	Accurately ground specimen 0.500 ± 0.001 in. in dia and 0.500 ± 0.005 in. long; electrolytic deposited pure copper used as a comparative material; reference data of copper taken from International Critical Tables, Vol. 5, McGraw Hill, p. 221, 1929.
86	1233	Ruh, E.	1954	C	324-401	55 B-2	Second run of the above specimen.
87	1233	Ruh, E.	1954	C	314-414	55 B-3	Third run of the above specimen.
88	1592	Yurchak, R. P. and Filippov, L. P.	1965	P	850-1250		Molten specimen in a tantalum crucible made from 2 coaxial tubes with dia of 23.8 and 8 mm, each tube 0.12 mm thick; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat, and values of density taken from Slavinskii, M. P. (Physicochemical Properties of Elements (in Russian), 1952).
89	1380	Suzuki, H., Kuwayama, N., and Yamauchi, T.	1956	L	373-473	H	99.997$^+$ pure electrolytic lead; specimen 20 mm in dia and 40 mm long.
90	1380	Suzuki, H., et al.	1956	L	328-523	B	Similar to the above specimen.
91*	1380	Suzuki, H., et al.	1956	L	328-523	P	Ractangular specimen of the same purity as the above specimen; size 22 x 22 x 40 mm.
92	1380	Suzuki, H., et al.	1956	L	358-510	A	Similar to the above specimen but 20 mm in dia and 50 mm long.
93	1380	Suzuki, H., et al.	1956	L	373-473	L	Similar to the above specimen but only 40 mm long.
94	869	Lussana, S.	1918	L	298.0		Specimen radius 0.675 cm; furnished by "Erba."
95	1268	Schott, R.	1916	L	20-273		Lead (technical) specimen 0.5 cm in dia and 5 cm long; electrical conductivity reported as 173.57 and 5.09 x 10^4 ohm^{-1} cm^{-1} at 20.4 and 273 K, respectively.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
96	1268	Schott, R.	1916	L	21-273		Pure Kahlbaum lead specimen 0.5 cm in dia and 5 cm long.
97	1036	Nikol'skii, N. A., Kalakutskaya, N. A., Pchelkin, I. M., Klassen, T. V., and Vel'tishcheva, V. A.	1959	L	700-1130		In liquid state; melting point 327.4 C; measured in a vacuum of 5 x 10^{-4} mm Hg.
98	1402	Tewfik, O. E., Eckert, E. R. G., and Jurewicz, L. S.	1961	E	293-347		99.99 pure; size 0.184 x 2 x 6 in.; specimen cut from a prefabricated sheet.
99	1337	Smoke, E. J., Illyn, A. V., Eichbaum, B. R., Snyder, N. H., Lass, G., and Nussbaum, T.	1955	C	319-411		NBS melting point standard lead; data obtained by using 28 gauge iron-constantan thermocouples with OFHC copper used as comparative material.
100	1337	Smoke, E. J., et al.	1955	C	328-405		The above specimen measured by using 30 gauge copper constantan thermocouples.
101*	1337	Smoke, E. J., et al.	1955	C	317-376		The above specimen measured by using 24 gauge copper constantan thermocouples.
102	859	Lorenz, L.	1881	L	273, 373		23.7 cm long; electrical conductivity reported as 5.141 and 3.602 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively; (the author reported as 5.141 and 3.602 x 10^5 ohm^{-1} cm^{-1}, obviously a typographical error).
103*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.7		99.998$^+$ pure (by difference), impurity <0.002; cylindrical specimen prepared from Johnson, Matthey H. S. lead; measured in longitudinal magnetic fields of increasing strength ranging from 0 to 1000 gauss.
104*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.7		The above specimen measured in magnetic fields of decreasing strength ranging from 1000 to 0 gauss.
105	932	Mendelssohn, K. and Olsen, J. L.	1950	L	4.6		The above specimen measured in magnetic fields of increasing strength ranging from 0 to 1000 gauss.
106*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	4.6		The above specimen measured in magnetic fields of decreasing strength ranging from 610 to 33 gauss.
107	932	Mendelssohn, K. and Olsen, J. L.	1950	L	5.29		Above 99.98 Pb (by difference), 0.02 Bi; cylindrical specimen prepared from Johnson, Matthey H. S. lead (impurity <0.002%); measured in longitudinal magnetic fields of increasing strength 0 to 1000 gauss.
108*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	5.29		The above specimen measured in longitudinal magnetic fields of decreasing strength ranging from 1000 to 45 gauss.
109*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	5.40		The above specimen measured in transverse magnetic fields of increasing strength ranging from 0 to 1000 gauss.
110*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	5.40		The above specimen measured in transverse magnetic fields of decreasing strength ranging from 996 to 0 gauss.
111	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.89		The above specimen measured in transverse magnetic fields of increasing strength ranging from 0 to 1000 gauss.
112*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.89		The above specimen measured in transverse magnetic fields of decreasing strength ranging from 1000 to 0 gauss.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
113*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.92		The above specimen measured in longitudinal magnetic fields of increasing strength ranging from 0 to 1000 gauss.
114*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.92		The above specimen measured in longitudinal magnetic fields of decreasing strength ranging from 1000 to 0 gauss.
115*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.6-21		The above specimen measured in a magnetic field greater than the critical field; in normal state.
116*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.8-7.2		The above specimen measured before applying the magnetic field; in superconducting state.
117*	932	Mendelssohn, K. and Olsen, J. L.	1950	L	2.7-3.9		The above specimen measured after applying the magnetic field; in superconducting state.
118	1505, 1506	Watson, J. H. P. and Graham, G. M.	1963	L	7.2-8.3		Lead specimen grade 69 of the Consolidated Mining and Smelting Co.; single crystal; 0.25 in. in dia and 3 in. long; zone refined.
119*	1505, 1506	Watson, J. H. P. and Graham, G. M.	1963	L	6.4-8.3		The above specimen measured in a magnetic field of 600 gauss; in normal state; data corrected to zero field.
120*	1505, 1506	Watson, J. H. P. and Graham, G. M.	1963	L	6.3-8.3		The above specimen measured in a magnetic field of 680 gauss; in normal state; data corrected to zero field.
121*	1505, 1506	Watson, J. H. P. and Graham, G. M.	1963	L	6.2-7.3		The above specimen measured in a magnetic field of 800 gauss; in normal state; data corrected to zero field.
122*	1505, 1506	Watson, J. H. P. and Graham, G. M.	1963	L	5.5-7.2		The above specimen in superconducting state.
123	1093	Plott, R. F. and Raeth, C. H.	1945	L	291-333	NBS sample 49b	Calibration specimen for freezing point determination.
124*	1093	Plott, R. F. and Raeth, C. H.	1945	L	302-330	NBS sample 49b	The above specimen remeasured with a slightly different method of balancing thermocouples to avoid radial heat losses.
125	1223	Rosenthal, M. W.	1953	C	617-755		<0.10 foreign non-volatile matter, <0.001 Ag, and <0.001 other foreign metals; in molten state; produced by Mallinckrodt Chemical Works; test cylinder 3 in. in dia; Armco iron used as comparative material; data taken from smoothed curve, corrected for the effect of transients.
126*	1033	Nicol, J.	1952	L	0.13-0.29		99.998$^+$ pure; provided by Johnson, Matthey and Co., Ltd. (Batch No. 3620); specimen size 8 x 2.1 x 25 mm; warm up number 1; in superconducting state.
127*	1033	Nicol, J.	1952	L	0.18-0.36		The above specimen, warm up number 2.
128*	1033	Nicol, J.	1952	L	0.19-0.38		The above specimen, warm up number 3.
129	882	March, R. H. and Symko, O. G.	1965	L	0.015-0.23		99.999 pure (nominal); supplied by Koch-Light Laboratories Ltd. (Colnbrook, England); wire 5 cm long and 0.5 mm in dia; measured in a longitudinal magnetic field of 1000 gauss; in normal state.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
130	1190	Reese, W. and Steyert, W.A., Jr.	1962	L	0.11-0.41		99.999 pure; polycrystalline; material obtained from Central Research Laboratories, American Smelting and Refining Co.; ratio of specimen cross-sectional area to length 3.47×10^{-3} cm; cut and rolled from a lead bar of the mentioned purity; annealed at room temp for many weeks; measured in a longitudinal magnetic field of 900 gauss; in normal state.
131	1190	Reese, W. and Steyert, W.A., Jr.	1962	L	0.20-0.38		The above specimen measured in a transverse magnetic field of 3000 gauss.
132	1190	Reese, W. and Steyert, W.A., Jr.	1962	L	0.42		The above specimen measured in a transverse magnetic field of 2000 gauss.
133	1190	Reese, W. and Steyert, W.A., Jr.	1962	L	0.14-0.44		The above specimen measured in a transverse magnetic field of 1000 gauss.
134	74	Angell, M.F.	1926	R	323.2		Specimen in the form of a long hollow cylinder.
135	434	Filippov, L.P.	1966	P	560-1355		Molten lead filled the space between two coaxial thin walled tubes of tantalum of 24 and 8 mm dia, respectively, with a number of thin horizontal tantalum plates placed in the metal as partitions; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat; measured in both solid and liquid states.
136	383	Dutchak, Ya.I. and Panasyak, P.V.	1966	C	474-870		Molten specimen placed in a hole 21 mm in dia drilled in an asbestos cement cylinder 30 mm in height; 1 Kh18 N9T steel used as comparative material.
137	317	Dauphinee, T.M., Armstrong, L.D., and Woods, S.B.	1966	L	223-573		Lead specimen cut from bar 99.999 pure or better; supplied by Dept. of Mines and Technical Surveys, Ottawa; smoothed values (experimental point deviations less than 1.5%).
138	317	Dauphinee, T.M., et al.	1966	L	223-573		Lead specimn cut from the same bar as above and measured by another apparatus with modifications of the thermal shielding.
139	1137	Powell, R.W. and Tye, R.P.	1967	L	335-602		99.995^{+} Pb, 0.001 Cd, 0.0005 Cu, 0.0005 Ag, and 0.0003 Bi; 7 mm dia x 15 cm long; supplied by Johnson, Matthey and Co.; electrical resistivity reported as 19.3, 23.4, 27.5, 31.8, 36.3, 40.8, and 45.7 μohm cm at 0, 50, 100, 150, 200, 250, and 300 C, respectively.
140*	861	Lucks, C.F.	1967	C	316-420	Pyrometric standard lead 49c	0.03 Bi, 0.002 Cd, 0.002 Ag, 0.001 Fe, 0.001 Ni, 0.001 Si, 0.001 Te, 0.0005 Cu, 0.0005 Sn, and 0.0001 Mg; electrical resistivity reported as 0.394, 0.735, 4.84, and 21.31 μohm cm at 20, 25, 77, and 298 K, respectively; M.P. 327.3 C; Armco iron used as comparative material.
141	861	Lucks, C.F.	1967	C	323-434	Pyrometric standard lead 49e	0.001 Fe, 0.001 Ni, 0.001 Si, <0.001 Te, 0.0005 Ag, 0.0005 Bi, 0.0005 Cu, <0.0005 Cd, <0.0005 Sn, and 0.0001 Mg; electrical resistivity reported as 0.366, 0.685, 4.83, and 21.25 μohm cm at 20, 25, 77, and 298 K, respectively; M.P. 327.417 C; Armco iron used as comparative material.
142	1338	Snyder, N.H., Smoke, E.J., Wisely, H R., and Ruh, E.	1949	L	338-399		No details reported.
143	435	Filippov, L.P.	1968	P	572-1255		In both solid and liquid states; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat.

* Not shown in figure.

TABLE 87. THERMAL CONDUCTIVITY OF LEAD - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
144	1591	Yurchak, R. P. and Filippov, L. P.	1964	P	564-1107		In solid and liquid states; electrical resistivity reported as 21.4, 30.8, 34.2, 42.4, 43.5, 44.3, 47.0, 97.6, 99.5, 102.6, 105.0, 107.0, 112.6, and 117.8 μohm cm at 20, 138, 172, 255, 260, 280, 300, 350, 375, 425, 460, 509, 600, and 701 C, respectively; thermal conductivity values calculated from measured thermal diffusivity data with specific heat data taken from Klinkhard, H. (Ann. Physik, 84, 167-200, 1927) and density data taken from Slavinskii, M. P. ("Physico-chemical Properties of Elements," Moscow, 1952).
145	1080	Perron, J. C.	1961	P	300		Specimen 3 cm long; measured by Angström's method.
146	1432	Tseng, T. P.	1954	L	2.2–4.2	A	99.999 pure; polycrystalline; obtained from Johnson, Matthey and Co.; 4.7 x 0.241 x 0.0226 cm; cold worked; measurements made on the segment from the bath to the middle block; in superconducting state.
147*	1432	Tseng, T. P.	1954	L	2.4–4.3	A	Similar to the above specimen; measured on the segment from the middle block to the heater; in superconducting state.
148*	1432	Tseng, T. P.	1954	L	1.3–4.2	B	Similar to above but specimen dimensions 10.4 x 0.406 x 0.0457 cm; measured on the bath to middle block segment; in superconducting state.
149*	1432	Tseng, T. P.	1954	L	1.5–4.3	B	Similar to the above specimen but dimensions 8.03 x 0.406 x 0.0457 cm; measured on the middle block to heater segment; in superconducting state.
150*	1432	Tseng, T. P.	1954	L	1.4–4.2	C	Similar to above but specimen 0.220 x 0.0437 cm in cross section with the form factors 1.78 x 10^{-3} cm for the bath to middle block segment and 1.72 x 10^{-3} cm for the middle block to heater segment; in superconducting state.
151*	1432	Tseng, T. P.	1954	L	3.7, 3.9	C	The above specimen measured in a magnetic field of 793 gauss; in normal state.
152*	1432	Tseng, T. P.	1954	L	3.61	C	The above specimen measured in a magnetic field of 800 gauss; in normal state.
153	1432	Tseng, T. P.	1954	L	3.2, 3.4	C	The above specimen measured in a magnetic field of 828 gauss; in normal state.
154	1432	Tseng, T. P.	1954	L	1.3–4.3	C	The above specimen measured in a magnetic field of 865 gauss; in normal state.
155	1336	Smith, N. D., Fun, F., and Visoky, R. M.	1967	C	298.2		Specimen ~1 in. in dia and 0.5 cm long; aluminum used as comparative material, assume measured at room temp.
156*	51	Allison, W. L.	1951	C	706		Molten lead filled in a cavity created by a sleeve connecting two similar Armco iron cylinders; cavity dimension 2.89 in. in dia and 2.0 in. in length; Armco iron used as comparative material.

* Not shown in figure.

Lithium

At low temperatures the particular curve for which recommended values are tabulated is based on the higher of the two sets of measurements by MacDonald, White, and Woods [873] (curve 2). This curve below 1.5 T_m was calculated with $m = 2.25$, $n = 2.00$, $\alpha'' = 0.0000774$, and $\beta = 1.52$ and is only applicable to a sample having $\rho_0 = 0.0372$ $\mu\Omega$ cm. It continues to follow curve 2 from 1.5 T_m to 121 K, and has been tentatively continued so as to fall at a decreasing rate to the melting point. This portion of the curve is however very uncertain, lithium being another metal for which further determinations are required in the immediate subnormal temperature region. Indeed, for this metal these measurements should cover the approximate range 90 to 450 K. The measurements of Bidwell [157] (curve 1) and Meissner [921] (curve 14) provide the only data that span this temperature range. The former yield a sharp minimum at 293 K but these results may be for a very impure sample since the electrical resistivity at this temperature exceeds the mean of Rosenberg's two values by 6.3 percent. Meissner's sample was also rather impure since the electrical conductivity at 0 C is only 1.3 percent higher than Bidwell's value. Nearer the melting point thermal conductivity values derived from the electrical resistivity data of Tepper, Zalenak, Roehlich, and May [1401] and the theoretical Lorenz function lie close to Bidwell's values. The tentatively proposed curve decreases gradually to this region, but ignores the possibility of a minimum.

More attention has been devoted to the thermal conductivity of the liquid state and, at the low-temperature end at about 500 K the five available sets of experimental data all agree that the conductivity is within about 10 percent of 0.43 W cm^{-1} K^{-1}. They differ very strongly however as regards the variation of thermal conductivity with temperature, two indicating large negative coefficients, one a small positive coefficient, and two large positive coefficients. These last receive support as regards the initial temperature variation from the several workers who have made estimates based on assumed values for the Lorenz function and measured or assumed values for the electrical resistivity. Notably among these is Grosse [545] (curve 16), whose estimated values for the thermal conductivity of liquid lithium extend to 4150 K, his predicted critical temperature, although he admits to more uncertainty in this prediction than in that made for the other alkali metals.

Several sets of experimental data for the electrical resistivity of liquid lithium are available. Those of Rigney, Kapelner, and Cleary [1201], Kapelner [711], and of Tepper, et al. are all higher than the resistivity values of Freedman and Robertson [461], the extreme difference being of the order of 10 percent, whereas those of Shpil'rain and Savehenko [1309] agree to ±3 percent. Although the values of Freedman and Robertson were only made to 830 K, these are the data on which Grosse has chosen to base the lower-temperature values which determined the equilateral hyperbola that he regarded as fitting to the critical temperature his plot of reduced electrical conductivity against reduced temperature. He comments that the more recent and more extensive measurements represented to 1703 K by the equation of Rigney, Kapelner, and Cleary could not be fitted in this way. The difference between this assumed curve and the measured values becomes large with increase in temperature and at 1700 K, about the upper limit of the experiments of Rigney, Kapelner, and Cleary, the estimated resistivity of Grosse appears to be greater than the measured value by about 45 percent.

The other parameter that introduces uncertainty is the Lorenz function. Grosse and Tepper, et al. both chose to use the theoretical value so the difference in these two curves results from the electrical resistivity differences. Kapelner chose an 11.5 percent lower value of 2.16×10^{-8} V^2 K^{-2}, since this value yielded thermal conductivities in agreement with three unpublished thermal conductivity values due to C. T. Ewing at temperatures of 556.5, 636.0, and 796.0 K. Rigney, Kapelner, and Cleary, on the other hand, chose 2.29×10^{-8} V^2 K^{-2}, which was the mean value that they obtained from their own electrical resistivities and the thermal conductivity values of Cooke [294] (curves 10, 11) for the range 588.8 to 810.9 K. They assumed this same value to hold to 1703 K, despite the expected increase and the fact that Cooke's smooth curve, as fitted to his admittedly more scattered results at higher temperatures, would, with their observed electrical resistivity at 1073 K, give a Lorenz function of 2.46×10^{-8} V^2 K^{-2}.

Cooke when discussing his experimental results estimated that at the critical temperature the thermal conductivity of the saturated vapor should be about 0.002 W cm^{-1} K^{-1} and that by this temperature the thermal conductivity of the liquid should fall, to merge smoothly to this same value. On the basis of what would seem to be a low estimate of 2966 K for the critical temperature, Cooke thought it probable that the thermal conductivity of molten lithium would pass through a maximum of about 0.78 W cm^{-1} K^{-1} at about 1973 K. According to Grosse's estimate a maximum value of 0.59 W cm^{-1} K^{-1} occurs at 1150 K.

Some further experimental evidence is available from 623 to 1273 K. Rudnev, Lyashenko, and Abramovich [1232] (curve 19) employed a method of the Angström type to determine the thermal diffusivity of a 99 percent lithium sample and from these data and literature values of the density and specific heat they calculated the thermal conductivity. The values so obtained are seen to be definitely increasing at their upper temperature limit and give no indication of a maximum at 1150 K as required by Grosse's treatment.

Thus, judging from the available experimental evidence for both the electrical resistivity and the thermal conductivity of molten lithium, this metal appears to be one for which the derivation method devised by Grosse is proving somewhat deficient. Unfortunately, there is at present no satisfactory modification or alternative.

The curve drawn in the figure as the most probable lies between the experimental data of Cooke and of Rudnev, et al. and a little below the derived curve of Tepper, et al. At 1700 K, the highest temperature to which the electrical resistivity has been measured, it passes through a value derived from the measurement of Rigney, et al. but assuming a Lorenz function of 2.443×10^{-8} and not 2.29×10^{-8} V^2 K^{-2}.

At higher temperatures the course of the curve is clearly very conjectural. It has been continued with a maximum at about 1800 K and an increasing rate of fall to a value of about 0.002 W cm^{-1} K^{-1} at 4150 K, the critical temperature as estimated by Grosse.

The recommended values are believed to be accurate to within about ±5 percent for the solid state and for molten lithium to about 700 K. The uncertainty increases to about ±10 percent by 1600 K and continues to increase at higher temperatures. The values above 1800 K are provisional. The tabulated values for temperatures below 150 K are of course only for lithium having $\rho_0 = 0.0372$ $\mu\Omega$ cm.

TABLE 88. Recommended thermal conductivity of lithium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	k	T	k	T	k	T	k
0	0	60	1.75	453.7	0.428*	1900	0.707*
1	0.658*	70	1.40	473.2	0.434	1973.2	0.706*
2	1.32	80	1.20	500	0.443	2000	0.705*
3	1.97	90	1.10	573.2	0.467	2073.2	0.703*
4	2.62	100	1.04	600	0.476	2173.2	0.698*
5	3.29	123.2	0.986	673.2	0.500	2200	0.696*
6	3.86	150	0.949	700	0.509	2273.2	0.690*
7	4.56	173.2	0.925	773.2	0.533	2400	0.676*
8	5.15	200	0.901	800	0.541	2473.2	0.666*
9	5.67	223.2	0.887	873.2	0.564	2600	0.645*
10	6.13	250	0.871	900	0.572	2673.2	0.630*
11	6.51	273.2	0.859	973.2	0.593	2800	0.602*
12	6.82	298.2	0.848	1000	0.600	2873.2	0.581*
13	7.09	300	0.847	1073.2	0.619	3000	0.543*
14	7.25	323.2	0.839	1100	0.625	3073	0.516*
15	7.38	350	0.828	1173.2	0.641	3200	0.467*
16	7.40	373.2	0.818	1200	0.647	3273	0.437*
18	7.39	400	0.804	1273.2	0.661	3400	0.383*
20	7.20	453.7	0.772*	1300	0.665	3473	0.351*
25	6.30			1373.2	0.676	3600	0.293*
30	5.20			1400	0.680	3673	0.257*
35	4.22			1473.2	0.688	3800	0.193*
40	3.43			1500	0.691	3873	0.155*
45	2.81			1573.2	0.697	4000	0.086*
50	2.35			1600	0.699	4073	0.045*
				1673.2	0.703	4150	0.002*
				1700	0.704		
				1773.2	0.706		
				1800	0.707*		
				1873.2	0.707*		

†The values are for well-annealed high-purity lithium, and those below 150 K are applicable only to a specimen having residual electrical resistivity of 0.0372 $\mu\Omega$ cm. The values above 1800 K are provisional.

*Extrapolated or estimated.

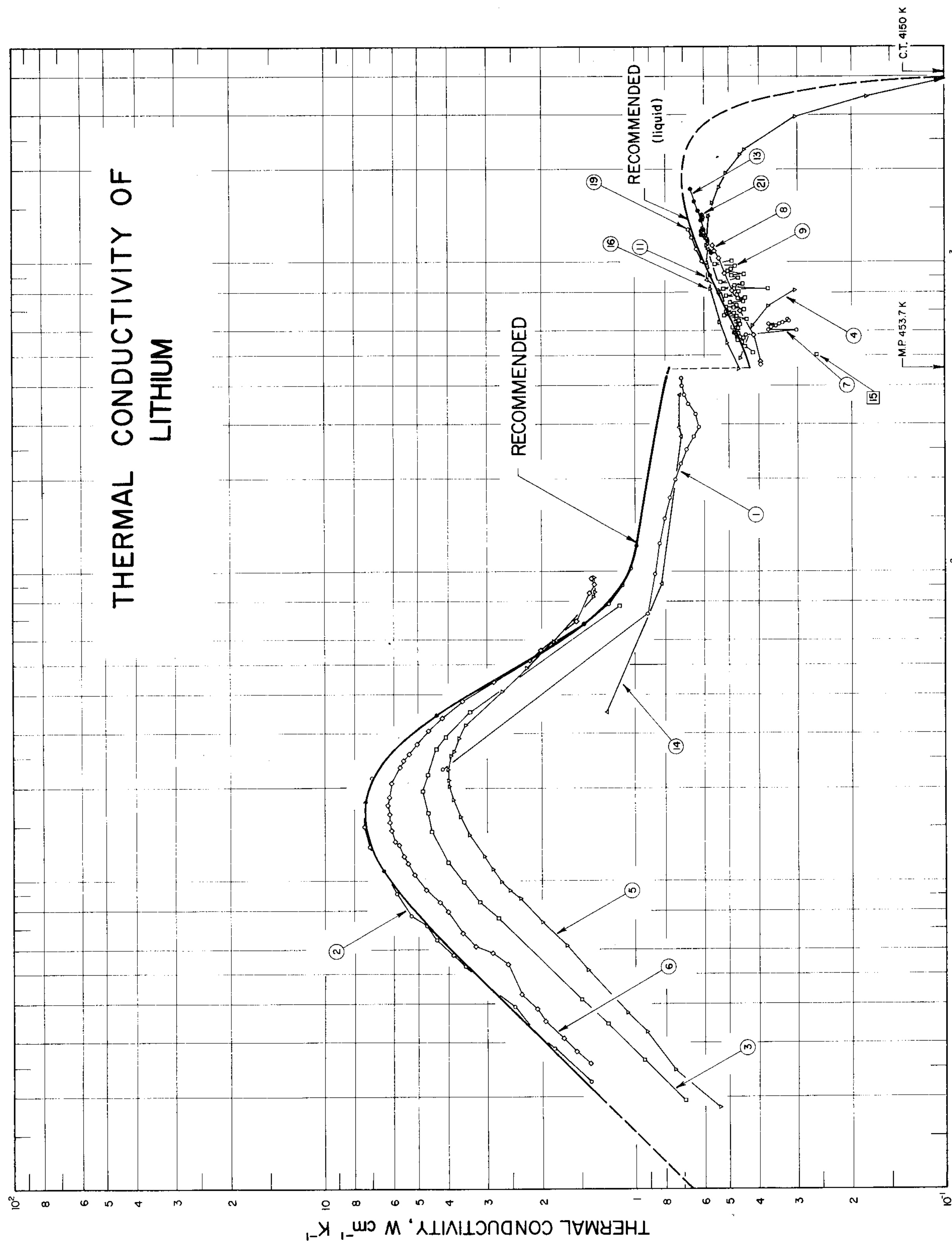

THERMAL CONDUCTIVITY OF LITHIUM
RECOMMENDED
RECOMMENDED (liquid)
M.P. 453.7 K
C.T. 4150 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 97

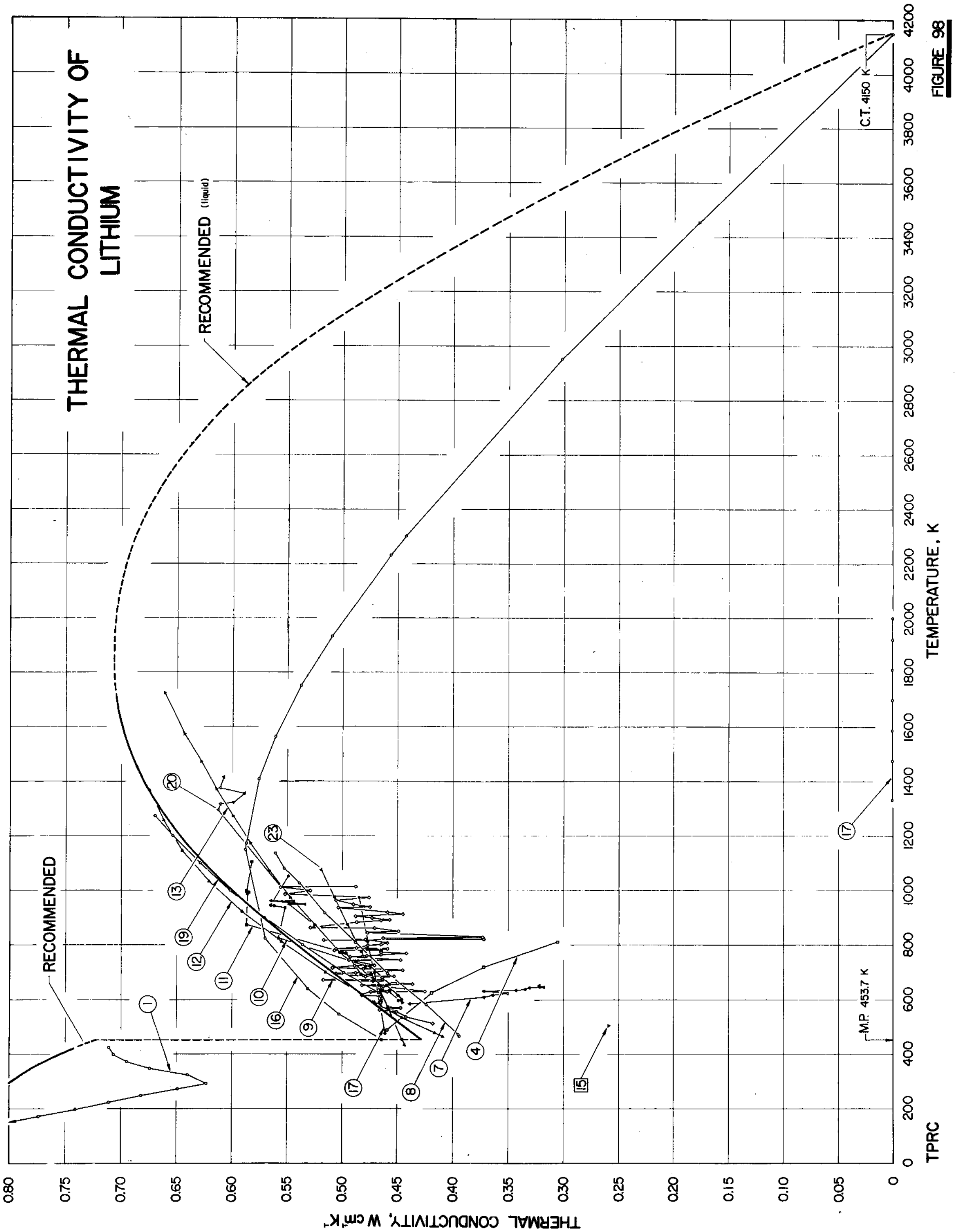

THERMAL CONDUCTIVITY OF
LITHIUM
RECOMMENDED (liquid)
RECOMMENDED
C.T. 4150 K
M.P. 453.7 K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE, K
TPRC
0 0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45 0.50 0.55 0.60 0.65 0.70 0.75 0.80
0 200 400 600 800 1000 1200 1400 1600 1800 2000 2200 2400 2600 2800 3000 3200 3400 3600 3800 4000 4200
1 4 7 8 9 10 11 12 13 15 16 17 19 20 23

FIGURE 98

TABLE 89. THERMAL CONDUCTIVITY OF LITHIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	157	Bidwell, C.C.	1926	F	23-423		Pure; 1.10 cm dia and 25 cm long; extruded; electrical conductivity reported as 1050, 116, 57.8, 36.1, 26.9, 21.1, 17.5, 15.00, 12.85, 11.55, 10.35, 9.44, 8.70, 8.13, 7.57, and 7.14 x 10^4 ohm^{-1} cm^{-1} at 23, 73, 98, 123, 148, 173, 198, 223, 248, 273, 293, 323, 348, 373, 398, and 423 K, respectively.
2	873	MacDonald, D.K.C., White, G.K., and Woods, S.B.	1956	L	2.2-121	Li 2	High purity; 1.4 mm dia; supplied by A.D. Mackay (New York); extruded; electrical resistivity ratio $\rho(295K)/\rho_0$ = 254 (using Gunty and Broniewski's value $\rho(295K)$ = 9.44 μohm cm).
3	873	MacDonald, D.K.C., et al.	1956	L	2.0-78	Li 3	High purity; 1.4 mm dia; supplied by New Metals and Chemical Ltd. (London); $\rho(295K)/\rho_0$ = 137 (using Gunty and Broniewski's value $\rho(295K)$ = 9.44 μohm cm).
4	1510	Webber, H.A., Goldstein, D., and Fellinger, R.C.	1955	C	489-812		99.8 Li, 0.06 Ca, 0.03 N, 0.03 (Al + Fe), 0.02 Na, 0.015 Si, 0.003 Cl, and 0.09 heavy metals; specimen in liquid state; supplied by Maywood Chemical Works; 1.999 in. dia; Armco iron used as comparative material.
5	1221	Rosenberg, H.M.	1956	L	1.9-96	Li 1	High purity; possibly contaminated with Cu; 0.83 mm dia; distilled; electrical resistivity 8.98 μohm cm at room temp and 0.084 μohm cm at 0 K; electrical resistivity ratio ρ(room temp)/ρ_0 = 100.
6	1221	Rosenberg, H.M.	1956	L	2.6-95	Li 2	Similar to the above specimen but no Cu contamination; electrical resistivity 9.17 μohm cm at room temp; residual electrical resistivity 0.0485 μohm cm; ρ(room temp)/ρ_0 = 200.
7	1583	Yaggee, F.L. and Untermyer, S.	1950	L	583-652		Composition before test: 99.52$^+$ Li (by difference), 0.1 Ca, 0.1 Si, <0.1 Hg, <0.1 P, <0.01 Al, <0.01 B, <0.01 Cr, <0.01 Cu, <0.01 Fe, <0.01 K, <0.01 Na, and <0.01 Ni; after test: 99.22$^+$ Li (by difference), 0.2 B, 0.1 Al, 0.1 Ca, <0.1 Hg, <0.1 P, <0.1 Na, 0.04 Cu, 0.02 Cr, <0.01 K, and <0.01 Ni; specimen in liquid state; 0.684 in. dia; supplied by Maywood Chemical Co.; M.P. 186 C.
8	280, 711	Kapelner, S.M.	1961	→	467-1138		99.9 Li (min), 0.03 Na, 0.01 Ca, 0.01 N, 0.01 Ni, 0.01 K, 0.005 Fe, 0.002 Cr, and 0.002 Cl nominal composition; post test: 0.23 N, 0.04 Na, 0.013 Cr, 0.012 Fe, and 0.004 Ni; specimen in liquid state; 0.59 in. dia; electrical resistivity reported as 25.6, 25.8, 29.7, 33.1, 35.9, 38.5, 41.2, 42.5, and 43.8 μohm cm at 193.6, 199.2, 309.4, 422.2, 535.0, 644.4, 753.6, 808.3, and 864.4 C, respectively; data calculated from Wiedemann-Franz-Lorenz relationship using L = 2.16 x 10^{-8} V^2 K^{-2}, this value being based on unpublished thermal conductivity values of 0.416, 0.428, and 0.496 W cm^{-1} K^{-1} at 283.3, 362.8, and 522.8 C that had been obtained from C.T. Ewing of the Naval Research Lab., Washington.
9	805	Kutateladze, S.S., Borishanskii, V.M., Novikov, I.I., and Fedynskii, O.S.	1958	L	511-1012		In liquid state; M.P. 186 C; measured in a vacuum of ~4 x 10^{-4} mm Hg.
10	292, 293, 294	Cooke, J.W.	1964	C	596-1052		Composition before test: 99.82 Li (by difference), 0.06 K, 0.04Cl, 0.015 Na, 0.012 N, 0.0063 N_2, 0.0027 Fe, <0.0015 Cr, <0.0015 Ni, 0.001 Si, <0.0010 Ti, 0.0005 Al, 0.0003 O_2, 0.0001 Ca, and 0.025 others; after test: values assumed to remain the same except 99.81 Li (by difference), 0.0058 Si, 0.0022 Ni, <0.001 Cr, <0.002 Mn, and 0.0024 Fe; in liquid state; supplied by the Foote Mineral Co.; measured in a vacuum of 3 x 10^{-6} mm Hg; type 347 stainless steel used as comparative material; data calculated by comparing to the top reference material (between heater and specimen).

TABLE 89. THERMAL CONDUCTIVITY OF LITHIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
11	292, 293, 294	Cooke, J. W.	1964	C	631-1103		Data of the above specimen calculated by comparing with the bottom reference material (Armco iron, between specimen and heat sink).
12	1212, 1401	Tepper, F., Zalenak, J., Roehlich, F., and May, V.	1965	→	463-1366		Density reported as 0.4992, 0.4898, 0.4724, 0.4654, 0.4581, 0.4440, and 0.4289 g cm^{-3} at 615.8, 714.3, 862.7, 940.4, 1054, 1157, and 1311 K, respectively; electrical resistivity reported as 12.16, 13.36, 14.73, 15.54, 26.54, 28.30, 30.39, 31.02, 32.10, 33.40, 34.90, 35.99, 37.53, 38.61, 39.97, 41.53, 42.68, 46.05, 48.21, 48.96, and 49.67 μohm cm at 360, 394, 432, 451, 487, 536, 597, 604, 655, 698, 764, 815, 878, 918, 983, 1045, 1104, 1246, 1319, 1342, and 1372 K, respectively; thermal conductivity values calculated from measured electrical resistivity data using the Lorenz number 2.45×10^{-8} V^2 K^{-2}.
13	1201	Rigney, D. V., Kapelner, S. M., and Cleary, R. E.	1965	→	589-1723		0.0490 O, 0.0130 Na, <0.0010 Fe, <0.0010 Ni, <0.0010 N, <0.0005 Nb, and <0.0005 Zr; post test impurities 0.24 O, <0.01 Fe, <0.01 Nb, <0.0030 N, <0.0010 Ni, <0.0010 Zr, and <0.0002 C; molten specimen contained in a Nb-1 Zr alloy capsule; electrical resistivity reported as 27.2, 29.9, 32.7, 35.4, 38.1, 40.8, 43.5, 46.1, 48.6, 51.2, 53.7, 56.1, and 59.1 μohm cm at 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, and 1430 C, respectively; data calculated from the measured electrical resistivity data and the Lorenz number 2.29×10^{-8} V^2 K^{-2}, this value being based on measured thermal conductivity data of Cooke, J. W. (J. Chem. Phys., 40(7), 1902-9, 1964).
14	921	Meissner, W.	1920	E	20-374		Electrical conductivity 11.7×10^4 ohm^{-1} cm^{-1} at 0 C; electrical resistivity ratio $\rho(273K)/\rho(20.4K) = 137$; Lorenz function 0.63, 1.34, 2.21, 2.29, and 2.64×10^{-8} V^2 K^{-2} at 20.42, 90.90, 273.15, 292.84, and 374.35 K, respectively; thermal conductivity values calculated from measured electrical resistivity at 0 C and from given thermal conductivity ratio k(T)/k(0C) at various temps.
15	881	Manson, S. V.	1950		503		Thermal conductivity value calculated from electrical conductivity using Wiedemann-Franz-Lorenz equation.
16	546, 548	Grosse, A. V.	1964		454-4150		Thermal conductivity calculated from semiempirically calculated electrical conductivity values using Wiedemann-Franz law and the theoretical Lorenz number of 2.443×10^{-8} V^2 K^{-2}; electrical conductivity calculation based on the data of Kapelner, S. M. (Pratt & Whitney Aircraft Corp. Rept. PWAC-349, June 30, 1961) and of Freedman, J. F. and Robertson, W. D. (J Chem. Phys., 34, 769-80, 1961); melting point 453.7 K and critical point 4150 K.
17	1509	Weatherford, W. D., Jr., Tyler, J. C. and Ku, P. M.	1961		599-971		Liquid state; recommended values based on the measurements of Oak Ridge National Laboratory and on curve 9 of this table.
18*	1509	Weatherford, W. D., Jr., et al.	1961		1344-1888		Saturated vapor; calculated from the frozen specific heat and the viscosity of saturated vapor assuming a constant Prandtl number of 0.73.

* Not shown in figure.

TABLE 89. THERMAL CONDUCTIVITY OF LITHIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
19	1232	Rudnev, I. I., Lyashenko, V. S., and Abramovich, M. D.	1961	P	623-1273		0.27 Na, 0.19 Fe, 0.18 Mg, 0.08 C, 0.06 Cu, 0.052 Ni, 0.05 Cr, 0.032 Pb, 0.023 Sn, 0.016 Ti, 0.01 Co, <0.01 Sb, <0.01 Zn, 0.006 Ba, 0.0058 Mo, 0.0046 Ca, 0.0044 N, 0.0042 V, 0.0037 Al, 0.003 K, 0.0029 Mn, 0.002 Bi, <0.001 Be, <0.001 Cd, <0.001 In, and <0.0003 Ag; molten specimen filtered through a capillary of inside dia 1.5 mm, poured in a vacuum of ~1×10^{-2} mm Hg into a thin walled tube made of steel 1Kh 18N9T with length 230 mm, dia 8.6 mm, and wall thickness 0.2 mm; measured in high vacuum; thermal conductivity data derived from the results of the measurements on thermal diffusivity, the density data was taken from "Thermal and Physical Properties of Metals," Gosenergoizdat, Moscow, 1956, and the specific heat data taken from Douglas, T., et al. (J. Amer. Chem. Soc., 77(8), 2144, 1955); thermal conductivity given by equation $\lambda = 0.072 + 0.01271 \times 10^{-2} t - 0.00039 \times 10^{-4} t^2$, where λ in cal $cm^{-1} C^{-1}$ and t in C.
20	1043	Novikov, I. I., Gruzdev, V. A., Kraev, O. A., Odintzov, A. A., and Roshchunkin, V. V.	1969	L	763-1413		99.33 Li; before test: 0.052 K, 0.037 Na, 0.022 Fe, 0.011 each of Al, N, and Si, and 0.0041 Ca; after test: 0.052 K, 0.037 Na, 0.034 Fe, 0.011 Al, 0.011 Si, and 0.0041 Ca; liquid specimen contained in an Armco iron cell 20 mm in dia and 170-200 mm long; density 0.5082 g cm^{-3} at 271.
21	1043	Novikov, I. I., et al.	1969	L	556-1413		The above specimen measured at decreasing temps.
22*	1043	Novikov, I. I., et al.	1969	L	724-1057		Similar to the above specimen.
23	1308	Shpil'rain, E. E. and Krainova, I. F.	1969		454-1073		In liquid state; thermal conductivity values calculated from the given equation $k = 36.2 + 0.0106 T$ (T in C and k in k cal $m^{-1} hr^{-1} C^{-1}$).

* Not shown in figure.

Lutetium

Since lutetium has a close-packed hexagonal structure, the thermal conductivity of a single crystal is expected to be anisotropic. Boys and Legvold [192] (curves 3 and 4) have recently made thermal conductivity measurements over the range 5 to 300 K on single crystals of lutetium which have shown the conductivity parallel to the *c*-axial direction to be much greater than that perpendicular to this direction. At 300 K the ratio of the thermal conductivities for these two directions is 1.68, and this ratio increases with decrease in temperature, becoming 2.74 at about 6.5 K.

The curves of Boys and Legvold have been provisionally accepted as representing the thermal conductivity of lutetium for these two main crystal directions, and these curves have been extrapolated to lower temperatures, assuming the temperature variation to be closely that found by Aliev and Volkenshtein [46] and Volkenshtein had published values for the range 2.7 to 100 K but for a polycrystalline sample of lower purity. The electrical resistivity ratio, $\rho_{293}/\rho_{4.2}$, of 6.43 which they obtained for this sample can be compared with values of the order of 43 and 28 found for the parallel and perpendicular directions of the single crystals. The lower purity could account for the lower thermal conductivity values obtained by Aliev and Volkenshtein.

One other thermal conductivity determination has been reported for lutetium, that of Jolliffe, Tye, and Powell [690] (curve 2) for a polycrystalline sample at room temperature. The electrical resistivity of this sample at room temperature was reported as 59 $\mu\Omega$ cm, and was intermediate between the values of Boys and Legvold of 34.5 and 76.4 $\mu\Omega$ cm for the respective parallel and perdendicular directions but considerably below the 79 $\mu\Omega$ cm of the sample studied by Aliev and Volkenshtein. The thermal conductivity value of Jolliffe, et al. of 0.162 W cm^{-1} K^{-1} is also in reasonable agreement with the values of 0.166 and 0.156 W cm^{-1} K^{-1} derived for a polycrystal from the single crystal data of Boys and Legvold according to whether the conductivities are considered to be arranged in a series or parallel manner. Taking a mean, as was done in the case of gallium, yields of 0.161 W cm^{1-} K^{-1}, and the curve obtained in this way for the range 1 to 300 K is provisionally proposed for the thermal conductivity of polycrystalline lutetium.

Until thermal conductivity measurements are available to higher temperatures, or information above room temperature becomes available on the electrical resistivity, the proposed curves have a high-temperature limit of 300 K.

The values are thought to be accurate to within ±15 percent of the true values at temperatures above 100 K and ±20 percent from 10 to 100 K. Those below 10 K are very uncertain. At temperatures below 100 K the values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having ρ_o = 0.76, 2.65, and 1.45 $\mu\Omega$ cm, respectively.

TABLE 90. Provisional thermal conductivity of lutetium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1}K^{-1})

	Solid		
T	‖ to *c*-axis *k*	⊥ to *c*-axis *k*	Poly-crystalline *k*
0	0	0	0
1	0.0155*	0.00510*	0.00757*
2	0.0496*	0.0165*	0.0244*
3	0.0984*	0.0328	0.0484
4	0.160*	0.0532	0.0786
5	0.217*	0.0742	0.108
6	0.262*	0.0934	0.134
7	0.295*	0.110	0.155
8	0.322	0.124	0.173
9	0.343	0.136	0.188
10	0.359	0.145	0.199
11	0.372	0.153	0.208
12	0.383	0.160	0.216
13	0.391	0.166	0.223
14	0.397	0.171	0.229
15	0.402	0.175	0.233
16	0.406	0.179	0.237
18	0.408	0.185	0.243
20	0.406	0.188	0.245
25	0.384	0.191	0.242
30	0.353	0.188	0.233
35	0.330	0.182	0.223
40	0.317	0.178	0.216
45	0.308	0.175	0.212
50	0.303	0.173	0.209
60	0.296	0.169	0.204
70	0.290	0.166	0.200
80	0.285	0.163	0.197
90	0.280	0.161	0.194
100	0.277	0.160	0.192
123.2	0.267	0.155	0.186
150	0.260	0.152	0.182
173.2	0.255	0.149	0.179
200	0.249	0.146	0.175
223.2	0.245	0.144	0.173
250	0.240	0.142	0.170
273.2	0.236	0.140	0.167
298.2	0.232	0.138	0.164
300	0.232	0.138	0.164

†The provisional values are for well-annealed high-purity lutetium, and those below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having ρ_o=0.76, 2.65, and 1.45 $\mu\Omega$ cm, respectively.
*Extrapolated.

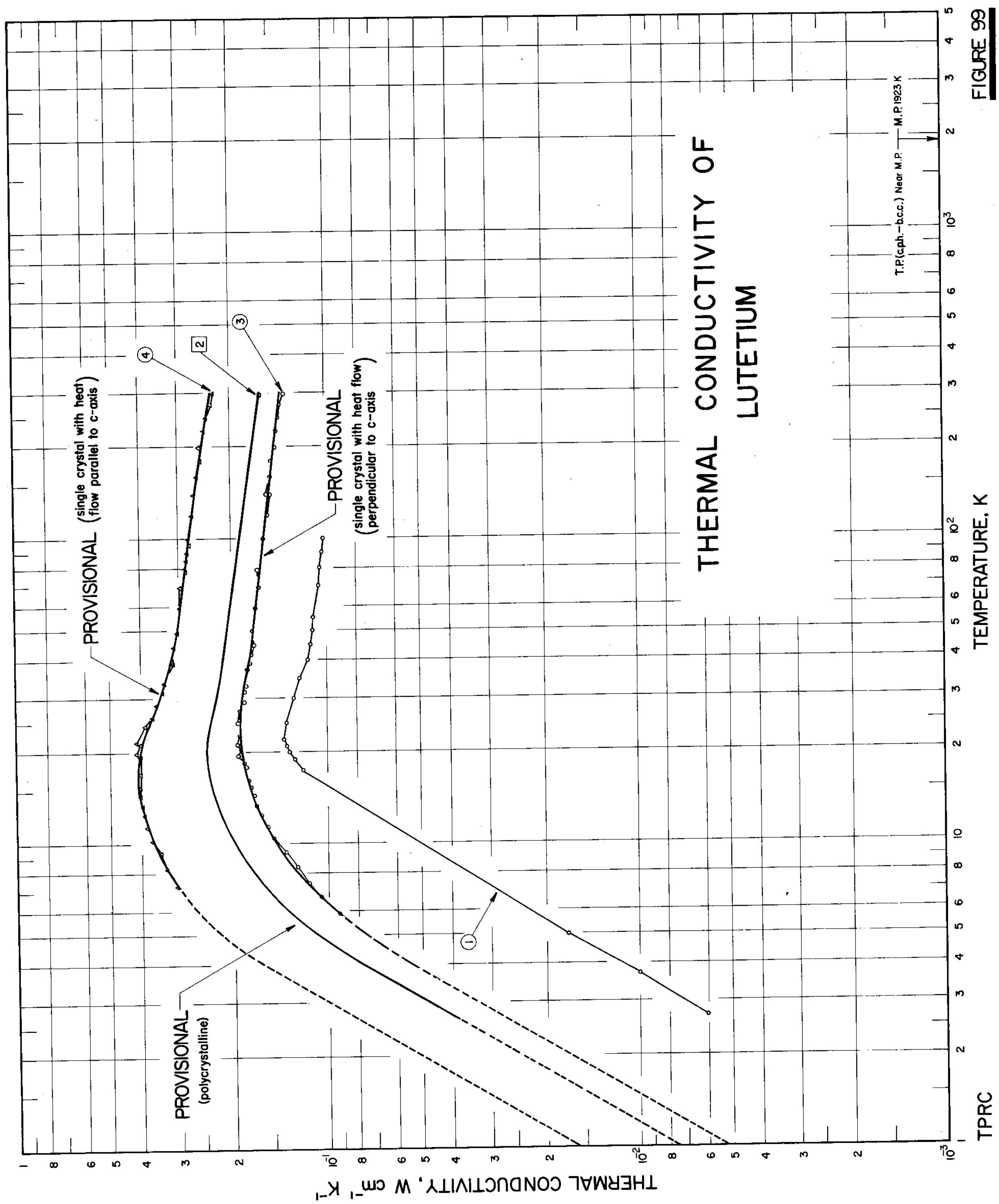

THERMAL CONDUCTIVITY OF
LUTETIUM
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
PROVISIONAL (polycrystalline)
T.P.(c.p.h.–b.c.c.) Near M.P.
M.P. 1923 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 99

TABLE 91. THERMAL CONDUCTIVITY OF LUTETIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	46	Aliev, N.G. and Volkenshtein, N.V.	1965	L	2.7-100		99.99 pure; polycrystalline; strip specimen 0.25 mm thick; annealed in stream of helium vapor at 600 C for 3 hrs; electrical resistivity reported at 4.2 and 293 K, respectively as 12.3 and 79 μohm cm; data from smoothed curve; Lorenz function reported as 3.40 x 10^{-8} V^2 K^{-2} in the residual resistance region.
2	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	C	291		<0.1 rare earth metal; ~0.5 Ta, ~0.05 base metals; polycrystalline specimen 1.2 x 1.2 x 0.31 cm; electrical resistivity 59 μohm cm at 291 K; data proposed by the author from measurements of 2 different thermal comparators.
3	192	Boys, D.W. and Legvold, S.	1967	L	5.9-300		0.0600 Yb, <0.0200 Ta, 0.0128 O, <0.0100 Er, <0.0100 Y, <0.0030 Fe, 0.0025 N, <0.0020 Ca, <0.0010 each of Al, Cr, Cu, Mg, Ni, Si, and Tm, and <0.0005 Sc; single crystal; 8.18 x 1.53 x 1.40 cm; grown from arc-melted buttons using the strain anneal method; <10$\bar{1}$0> direction (b-axis) along the specimen axis; electrical resistivity reported as 2.650, 2.650, 2.652, 2.652, 2.663, 2.703, 2.924, 3.313, 4.103, 5.818, 9.089, 12.981, 18.864, 22.779, 28.478, 36.422, 44.358, 52.232, 62.593, and 76.517 μohm cm at 1.3, 2.4, 3.3, 4.2, 7.0, 9.9, 14.6, 18.8, 24.0, 32.4, 44.4, 57.5, 77.5, 90.9, 111.0, 139.7, 169.6, 199.9, 240.3, and 297.5 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 28.9$; residual electrical resistivity 2.65 μohm cm; Lorenz function reported as 4.31, 3.46, 3.33, 3.44, 3.70, 3.89, 4.00, 4.00, 3.93, 3.77, 3.60, and 3.52 x 10^{-8} V^2 K^{-2} at 5.5, 14.7, 21.4, 30.1, 45.4, 67.4, 97.8, 114.6, 150.2, 207.3, 267.1, and 300.0 K, respectively; heat flow along b-axis.
4	192	Boys, D.W. and Legvold, S.	1967	L	7.3-299		0.0200 Tm, <0.0200 Ta, <0.0200 Ti, <0.0100 W, <0.0100 Y, 0.0099 O, <0.0030 Fe, <0.0010 each of Al, Ca, Cr, Cu, Er, Mg, Ni, and Se, 0.0008 N, <0.0005 Sc, and <0.0005 Yb; single crystal; 17.96 x 2.18 x 2.14 mm; grown from arc-melted buttons using the strain-anneal method; <0001> direction along the specimen axis; electrical resistivity reported as 0.759, 0.759, 0.761, 0.761, 0.770, 0.798, 0.852, 0.941, 1.069, 1.374, 1.842, 2.861, 4.709, 6.253, 8.630, 11.811, 15.178, 18.849, 21.581, 26.250, and 34.793 μohm cm at 1.2, 2.4, 3.3, 4.2, 7.0, 10.0, 13.0, 16.0, 19.0, 24.0, 30.0, 40.6, 56.1, 70.3, 92.6, 120.8, 150.0, 180.0, 200.8, 240.0, and 298.6 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 45.7$; residual electrical resistivity 0.76 μohm cm; Lorenz function reported as 3.37, 2.66, 2.33, 2.22, 2.19, 2.26, 2.46, 2.56, 2.58, 2.61, and 2.61 x 10^{-8} V^2 K^{-2} at 5.5, 12.2, 18.4, 24.8, 30.7, 45.2, 58.9, 68.1, 77.6, 158.3, and 300.0 K, respectively; heat flow along c-axis.

Magnesium

There are 39 curves available for the thermal conductivity of magnesium, which include six determinations for samples of magnesium powder at room temperature. At low temperatures eleven sets of data yield curves having maxima and these can all be reasonably well fitted by the same straight line. Two authors, Rowe [1227] (curves 31 and 32) and Bogaard [177] (curves 36–39) have included single crystal samples for each of the two main crystal directions. These data do not yield consistent differences from those for the polycrystalline samples studied, and the purest samples were of polycrystalline magnesium. The curve for which recommended values are tabulated has been derived with $m = 2.10$, $n = 2.00$, $\alpha'' = 0.0000627$, and $\beta = 0.101$ to fit the highest set of data for a sample examined by Bogaard [177] (curve 35). This curve at low temperatures is only for a sample having $\rho_0 = 0.00261$ $\mu\Omega$ cm.

At higher temperatures this curve joins others by Bogaard and above about 90 K follows that of the previous report [607] discussed below.

The majority of the workers that have made thermal conductivity determinations on magnesium in the range 273 to 729 K have included electrical resistivity values for the same samples. The resultant values of the Lorenz function at about 373 K range from 2.16×10^{-8} to 2.48×10^{-8} V^2 K^{-2} and it seems significant that in only one work is the theoretical value exceeded. These highest values are due to Mannchen [880] who published values due to Staebler [1358], a worker whose data have been criticized and are thought to be uncertain (see Kempf, Smith, and Taylor [740] and Powell [1110]). The values for the Lorenz function obtained by Schofield [1267], Powell [1110], and Powell, et al. [1124] are in fair accord and indicate that this quantity probably increases slowly with increase in temperature and has values of 2.27, 2.31, 2.33, 2.35, 2.36, 2.37, and 2.38×10^{-8} V^2 K^{-2} at temperatures of 273, 373, 473, 573, 673, 773, and 923 K, respectively.

From these values and the electrical resistivity of pure magnesium the most probable thermal conductivity curve has been derived. The electrical resistivity at 273 K has been taken as 3.95 $\mu\Omega$ cm with values of 5.61, 7.28, 9.00, 10.76, 12.51, and 15.2 $\mu\Omega$ cm at 373, 473, 573, 673, 773, and 923 K. Increasing uncertainty arises as the melting point, 923 K, is approached. The above value at 923 K is based on that of Roll and Motz [1217] of 15.4 $\mu\Omega$ cm for magnesium of 99.8 percent purity, but it should be noted that measurements by Horn [634] indicate a strong upturn as the melting point is approached, his value at 923 K being greater by about 10 percent.

Since no thermal conductivity determinations have been made on molten magnesium, a provisional value can be derived from the electrical resistivity, ρ, by means of the equation proposed by Powell [1120]. Roll and Motz [1217] have reported values for ρ which lead to thermal conductivity values at 923 K and 1173 K respectively of 0.79 and 0.96 W cm^{-1} K^{-1}.

The recommended values are considered accurate to within ±3 percent of the true values at moderate temperatures, ±10 percent for low temperatures and as the melting point is approached, and ±15 percent for the liquid state within some 200 K of the melting point. The values for molten magnesium are provisional. At temperatures below 100 K the values are only applicable to magnesium having $\rho_0 = 0.00261$ $\mu\Omega$ cm.

TABLE 92. Recommended thermal conductivity of magnesium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline				Liquid	
T	k	T	k	T	k
0	0	123.2	1.63	923.2	0.790*
1	9.86	150	1.61	973.2	0.826*
2	19.6	173.2	1.60	1000	0.844*
3	29.0	200	1.59	1073.2	0.893*
4	37.6	250	1.57	1100	0.911*
5	45.0	273.2	1.57	1173.2	0.961*
6	50.8	298.2	1.56	1200	0.978*
7	54.7	300	1.56		
8	56.7	323.2	1.55		
9	57.0	350	1.54		
10	55.8	373.2	1.54		
11	53.7	400	1.53		
12	50.9	473.2	1.52		
13	47.8	500	1.51		
14	44.4	573.2	1.50		
15	41.1	600	1.49		
16	37.9	673.2	1.48		
18	32.2	700	1.47		
20	27.2	773.2	1.46*		
25	18.3	800	1.46*		
30	12.9	873.2	1.45*		
35	9.45	900	1.45*		
40	7.19	923.2	1.45*		
45	5.70				
50	4.65				
60	3.27				
70	2.49				
80	2.02				
90	1.78				
100	1.69				

†The values are for well-annealed high-purity magnesium, and those below 100 K are applicable only to a specimen having $\rho_0 =$ 0.00261 $\mu\Omega$ cm. The values for molten magnesium are provisional

*Extrapolated or estimated.

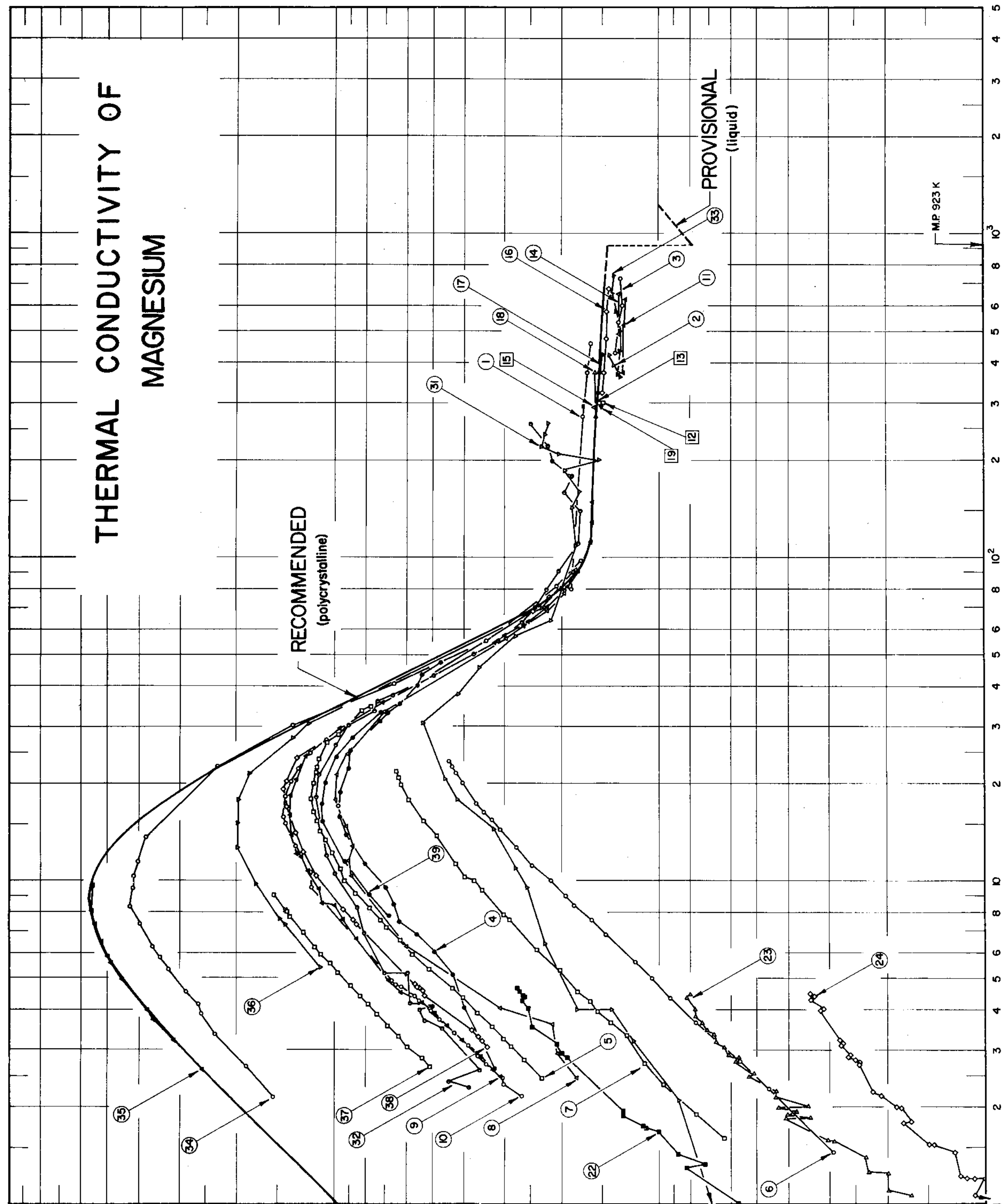

THERMAL CONDUCTIVITY OF MAGNESIUM
RECOMMENDED (polycrystalline)
PROVISIONAL (liquid)
M.P. 923 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 100

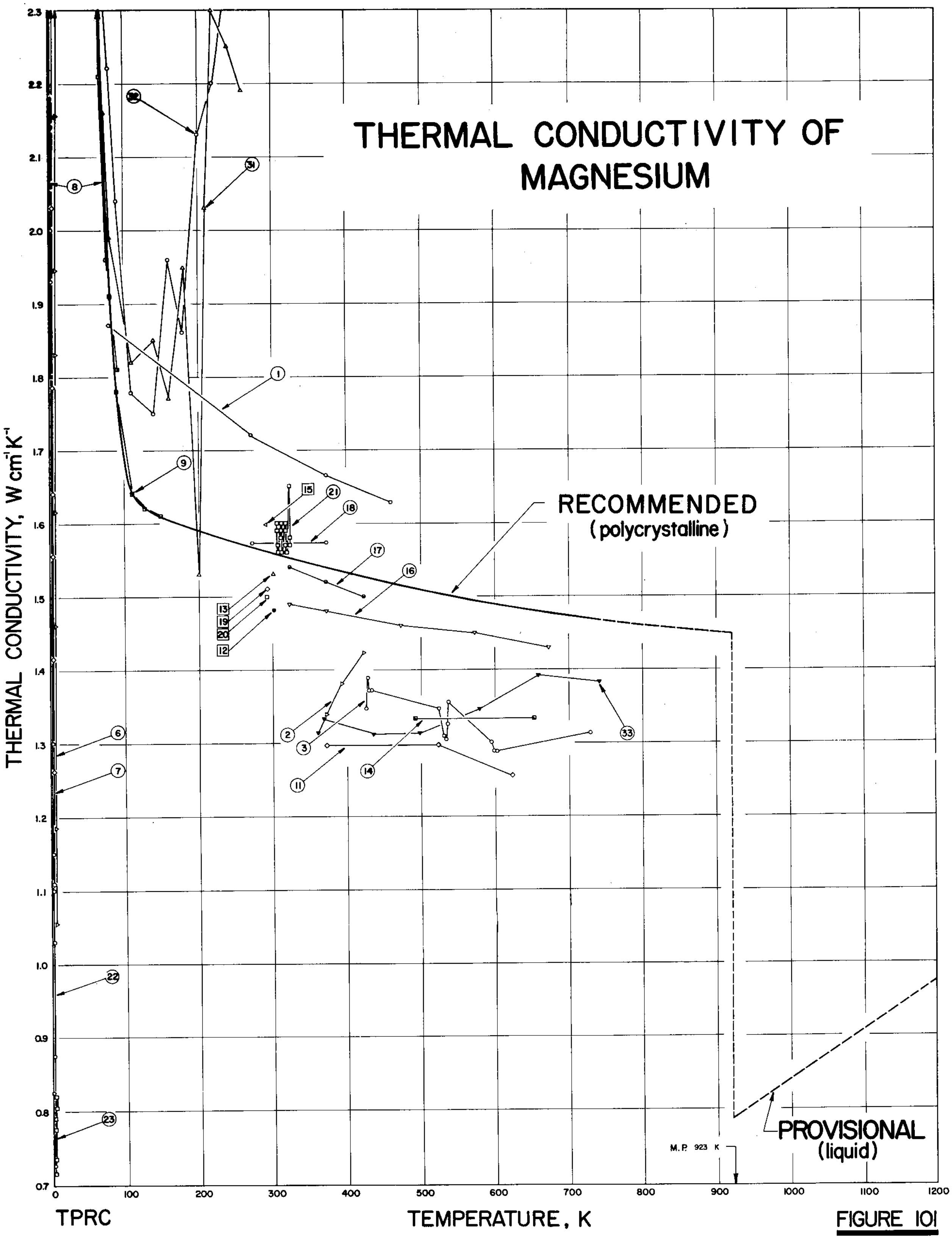

THERMAL CONDUCTIVITY OF MAGNESIUM
RECOMMENDED
(polycrystalline)
PROVISIONAL
(liquid)
M.P. 923 K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 101

TABLE 93. THERMAL CONDUCTIVITY OF MAGNESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	880 1358	Staebler, J. Mannchen, W.	1929	L	80–460		Pure; 3 cm x 1.23 cm^2; electrical resistivity reported as 0.82, 3.91, 5.56, and 7.27 μohm cm at 80, 273, 373, and 460 K, respectively.
2	524	Grand, C. and Villey, J.	1927	E	373–423		Commercially pure.
3	1267	Schofield, F. H.	1925	L	430–729		99.6 pure; 0.75 in. rod; obtained from Magnesium Co. Ltd.; extruded, then annealed for 6 hrs at 360 C; density (at 21 C) 1.75 g cm^{-3}; electrical resistivity reported as 4.59, 6.19, 8.13, 10.35, 11.13, and 13.74 μohm cm at 20.0, 101.2, 199.4, 314.0, 348.3, and 480.1 C, respectively.
4	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.6–47	JM 1703; Mg 1	99.95 pure; polycrystalline; 1 to 2 mm in dia and 5 cm long; obtained from Johnson, Matthey and Co.
5	1219	Rosenberg, H. M.	1954	L	2.5–35	JM 1703; Mg 2	99.99^+ Mg, 0.03 Mn, 0.0075 Fe, and 0.004 Al; 15 mm dia specimen made from Johnson, Matthey standardized rod; annealed in vacuo at 500 C for 6 hrs.
6	1351	Spohr, D. A. and Webber, R. T.	1957	L	1.5–24	Mg (Mn)	99.95^+ Mg, 0.043 Mn, 0.0048 Zn, 0.0012 Ca, 0.0011 Pb, 0.0011 Sn, 0.0010 Fe, 0.001 Si, 0.0002 Al, 0.0001 Cu, and 0.0001 Ni; polycrystalline; 3.2 mm dia x 9 cm long; prepared by Dow Chemical Co.; annealed; electrical resistivity reported as 0.1479, 0.1270, 0.1196, 0.1187, and 0.1217 μohm cm at 1, 5, 10, 14.5, and 20 K, respectively.
7	1351	Spohr, D. A. and Webber, R. T.	1957	L	1.6–22	Mg (Fe)	99.98^+ Mg, 0.013 Fe, 0.0023 Mn, 0.0013 Pb, traces of Al, Ca, Cu, Si, Ag, and Na; polycrystalline; 3.2 mm dia x 9 cm long; prepared from a Johnson, Matthey spectrographic rod; electrical resistivity reported as 0.06624, 0.06438, 0.0655, 0.0679, and 0.0727 μohm cm at 1, 5, 10, 15, and 20 K, respectively.
8	739	Kemp, W. R. G., Sreedhar, A. K., and White, G. K.	1953	L	2.5–91	JM 1848; Mg 1	99.98^+ Mg, 0.013 Fe, 0.0023 Mn, 0.0013 Pb, traces of Ca, Cu, Si, Ag, and Na; 3 mm dia rod drawn by Johnson, Matthey from a sample JM 1848.
9	739	Kemp, W. R. G., et al.	1953	L	2.5–149	JM 1848; Mg 2	The above specimen annealed in vacuo for 3 hrs at 350 C.
10	739	Kemp, W. R. G., et al.	1953	L	2.2–27	JM 1848; Mg 3	Similar to the above specimen Mg 2.
11	805	Maybrey, H. J.	1928	L	373–623		0.031 Si, 0.012 Cu, and 0.014 total Fe and Al; 1 in. dia x 12 in. long; annealed for 5 hrs at 530 C before machining.
12	896	Masumoto, H.	1925	E	302.2	Mg	0.175 Si, 0.052 Al, and 0.014 Fe; 3 mm dia x 20 cm long; chill-cast; electrical resistivity 4.52 μohm cm at 29 C.
13	896	Masumoto, H.	1925	E	301.2	Mg	The above specimen annealed for 30 min at 450 C; electrical resistivity 4.42 μohm cm at 29 C.
14	908	McCreight, L. R.	1952		493, 653		Extruded powder specimen; density 98-100% of theoretical value.
15	758	Kikuchi, R.	1932	E	291.3		Pure; electrical conductivity 2.31 x 10^5 ohm^{-1} cm^{-1} at 18.1 C.
16	1124	Powell, R. W., Hickman, M. J., and Tye, R. P.	1964	L, C	323–673	Mg 1	99.95 Mg, 0.033 Al, and 0.012 Zn; 1.9 cm in dia and 30 cm long; supplied by the Metallurgy Division of the National Physical Laboratory; forged and stabilizing heat treated; electrical resistivity reported as 4.5, 5.01, 5.85, 7.57, 9.30, and 11.04 μohm cm at 293, 323, 373, 473, 573, and 673 K, respectively.

TABLE 93. THERMAL CONDUCTIVITY OF MAGNESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17	1124	Powell, R.W., Hickman, M.J., and Tye, R.P.	1964	L, C	323-423	Mg 2	99.98 Mg, 0.017 Al, and 0.004 Zn; 0.635 cm dia and 10 cm long; supplied by Messrs. Johnson, Matthey and Co., Ltd.; electrical resistivity reported as 4.34, 4.85, 5.70, and 6.51 μohm cm at 293, 323, 373, and 423 K, respectively.
18	859	Lorenz, L.	1881	L	273, 373		Electrical conductivity reported as 24.47 and 17.5 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively.
19	1389	Taylor, R.	1965	P	293.2		Spectrographically pure; specimen 1.27 cm long; thermal conductivity values calculated from measured thermal diffusivity data.
20	1389	Taylor, R.	1965	P	293.2		Similar to the above specimen, but 0.635 cm long.
21	1363	Stephenson, A.E.	1963	L	307-324		Specimen 4.025 in. in dia and 1.015 in. thick.
22	1298	Sharkoff, E.G.	1953	L	1.0-4.7	Sample #765	99.98^+ Mg, 0.01 Mn, 0.003 Zn, 0.0012 Pb, 0.001 Ca, <0.001 Si, <0.001 Sn, 0.0008 Fe, 0.0002 Al, <0.0001 Cu, and <0.0001 Ni; specimen 9.03 cm long and 0.310 cm in dia; electrical resistivity reported as 0.048, 0.042, 0.04, 0.037, 0.04, 0.042, 0.047, and 0.058 μohm cm at 1.0, 3.0, 5.0, 10.0, 15.0, 20.0, 25.0, and 30 K, respectively.
23	1298	Sharkoff, E.G.	1953	L	1.1-4.4	Sample #767	99.95 Mg, 0.043 Mn, 0.0048 Zn, 0.0012 Ca, 0.0011 Pb, 0.0011 Sn, 0.0010 Fe, <0.001 Si, 0.0002 Al, <0.0001 Cu, and <0.0001 Ni; specimen 8.93 cm long and 0.307 cm in dia; electrical resistivity reported as 0.153, 0.144, 0.136, 0.123, 0.120, 0.127, and 0.137 μohm cm at 1.0, 3.0, 5.0, 10, 15, 20, and 25 K, respectively.
24	1298	Sharkoff, E.G.	1953	L	1.0-4.5	Sample #370	99.87^+ Mg, 0.12 Mn, 0.0036 Zn, 0.0014 Pb, 0.0011 Fe, <0.001 Si, <0.001 Sn, 0.0006 Ca, 0.0002 Al, <0.0002 Ni, and 0.0001 Cu; specimen 9.35 cm long and 0.305 cm in dia; electrical resistivity reported as 0.365, 0.34, 0.32, 0.29, 0.275, 0.30, and 0.37 μohm cm at 1.0, 3.0, 5.0, 10, 20, 30, and 40, respectively.
25*	1382	Swift, D.L.	1966	P	298.2		Spherical grains supplied by Valley Metallurgical Processing Co.; specimen contained in a 0.75 in. dia x 2 in. long cylindrical cell; mesh size -100 +200; thermal conductivity measured by the transient line source method; measured in Freon-12 under a pressure of ~100 psig.
26*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in argon under a pressure of ~100 psig.
27*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in nitrogen under a pressure of ~100 psig.
28*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in methane under a pressure of ~100 psig.
29*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in helium under a pressure of ~100 psig.
30*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in hydrogen under a pressure of ~100 psig.
31	1227	Rowe, V.A.	1967	L	0.8-260		99.99 pure; single crystal; specimen cross-sectional area 0.0483 cm^2 and 6.98 cm long; supplied by Aremco Products, Briarcliff Manor, N.Y.; electrical resistivity ratio $\rho(297K)/\rho(4.2K) = 24$; heat flow perpendicular to c-axis; measured in a vacuum of 5 x 10^{-6} mm Hg.

* Not shown in figure.

TABLE 93. THERMAL CONDUCTIVITY OF MAGNESIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
32	1227	Rowe, V.A.	1967	L	2.3-260		Similar to the above specimen except cross-sectional area 0.0509 cm^2 and 6.60 cm long; electrical resistivity ratio $\rho(297K)/\rho(4.2K) = 65$; heat flow parallel to c-axis.
33	493	Giuliani, S.	1967	C	361-741	Magnox	99.95 Mg, 0.0070~0.0200 Fe, 0.0040~0.0080 Si, 0.0020~0.0070 Zn, 0.0030~0.0050 Al, 0.0030~0.0050 Mn, <0.0050 Pb, <0.0020 Cu, <0.0010 Nb, and <0.0010 Sn; 1.2 to 1.3 cm in dia and 1.8 to 2.5 cm long; Armco iron used as comparative material.
34	177	Bogaard, R.H.	1970	L	2.2-98	Mg 1	Polycrystalline; 1.95 mm wide, ~2 mm thick, and ~25 mm long; prepared by melting vapor deposited magnesium in an induction furnace; electrical resistivity ratio $\rho(r.t.)/\rho(1.4\ K) = 1200$.
35	177	Bogaard, R.H.	1970	L	2.6-9.7	Mg 2	Similar to the above specimen but the width 1.13 mm and electrical resistivity ratio $\rho(r.t.)/\rho(1.4K) = 1700$.
36	177	Bogaard, R.H.	1970	L	5.4-90	MgC 10	0.0250 O, ~0.0115 Fe, 0.0035 Zn, 0.0025 Cl, 0.0018 S, 0.0015 Ca, 0.0014 Al, and 0.0007 N (calculated composition); single crystal; 1.40 mm wide, ~2 mm thick, and ~25 mm long; supplied by AREMCO Products, Inc.; electrical resistivity ratio $\rho(r.t.)/\rho(4.2K) = 330$; heat flow along the c-axis.
37	177	Bogaard, R.H.	1970	L	2.7-9.0	MgC 11	Cut from the same ingot as the above specimen; heavily etched to 0.55 mm in width; heat flow along the c-axis.
38	177	Bogaard, R.H.	1970	L	3.1-75	MgC 3	Single crystal; 3.02 mm wide, ~2 mm thick, and ~25 mm long; electrical resistivity ratio $\rho(r.t.)/\rho(4.2K) = 210$; heat flow along the c-axis.
39	177	Bogaard, R.H.	1970	L	7.8-34	MgA 1	Single crystal; 3.21 mm wide, ~2 mm thick, and ~25 mm long; electrical resistivity ratio $\rho(r.t.)/\rho(4.2K) = 160$; heat flow along the a-axis.

Manganese

Manganese is a metal for which much more information for both thermal and electrical conductivities is required. The reported values for the electrical conductivity at room temperature cover a wide range. Only one measurement of thermal conductivity has been reported at room temperature, none above room temperature, and four at lower temperatures.

A smooth curve has been drawn through the highest set (curve 3) of the low temperature values, those of White and Woods [1241] for the range 2 to 78 K. This curve is for a sample having $\rho_0 = 11.3\ \mu\Omega$ cm. It rises at a gradually decreasing rate and appears to extrapolate to the value of Jolliffe, Tye, and Powell [690] (curve 5) at 293 K. The data of White and Woods had been for a sample for which the ratio ρ_{295}/ρ_0 was only 13.3 and the typical low-temperature maximum did not occur. It is clear that measurements on a sample of higher purity and perfection are required for the full range of temperature. The large number of phase transitions of manganese should add interest to these measurements.

The provisional values are for well-annealed high-purity manganese, and those below 200 K are applicable only to a specimen having a residual electrical resistivity of 11.3 $\mu\Omega$ cm. While the values are thought to be accurate to within ±20 percent, the accuracy of those values around room temperature may be slightly better.

TABLE 94. Provisional thermal conductivity of manganese†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	k	T	k	T	k
2	0.00645*	15	0.0205	80	0.0526
3	0.00813	16	0.0213	90	0.0555
4	0.00956	18	0.0227	100	0.0579*
5	0.0109	20	0.0241	123.2	0.0624*
6	0.0121	25	0.0274	150	0.0663*
7	0.0132	30	0.0304	173.2	0.0691*
8	0.0143	35	0.0332	200	0.0717*
9	0.0153	40	0.0358	223.2	0.0735*
10	0.0163	45	0.0382	250	0.0754*
11	0.0172	50	0.0406	273.2	0.0768*
12	0.0180	60	0.0450	298.2	0.0781
13	0.0188	70	0.0491	300	0.0782*
14	0.0196				

†The values are for well-annealed high-purity manganese, and those below 200 K are applicable only to a specimen having $\rho_0 = 11.3$ $\mu\Omega$ cm.

*Extrapolated or interpolated.

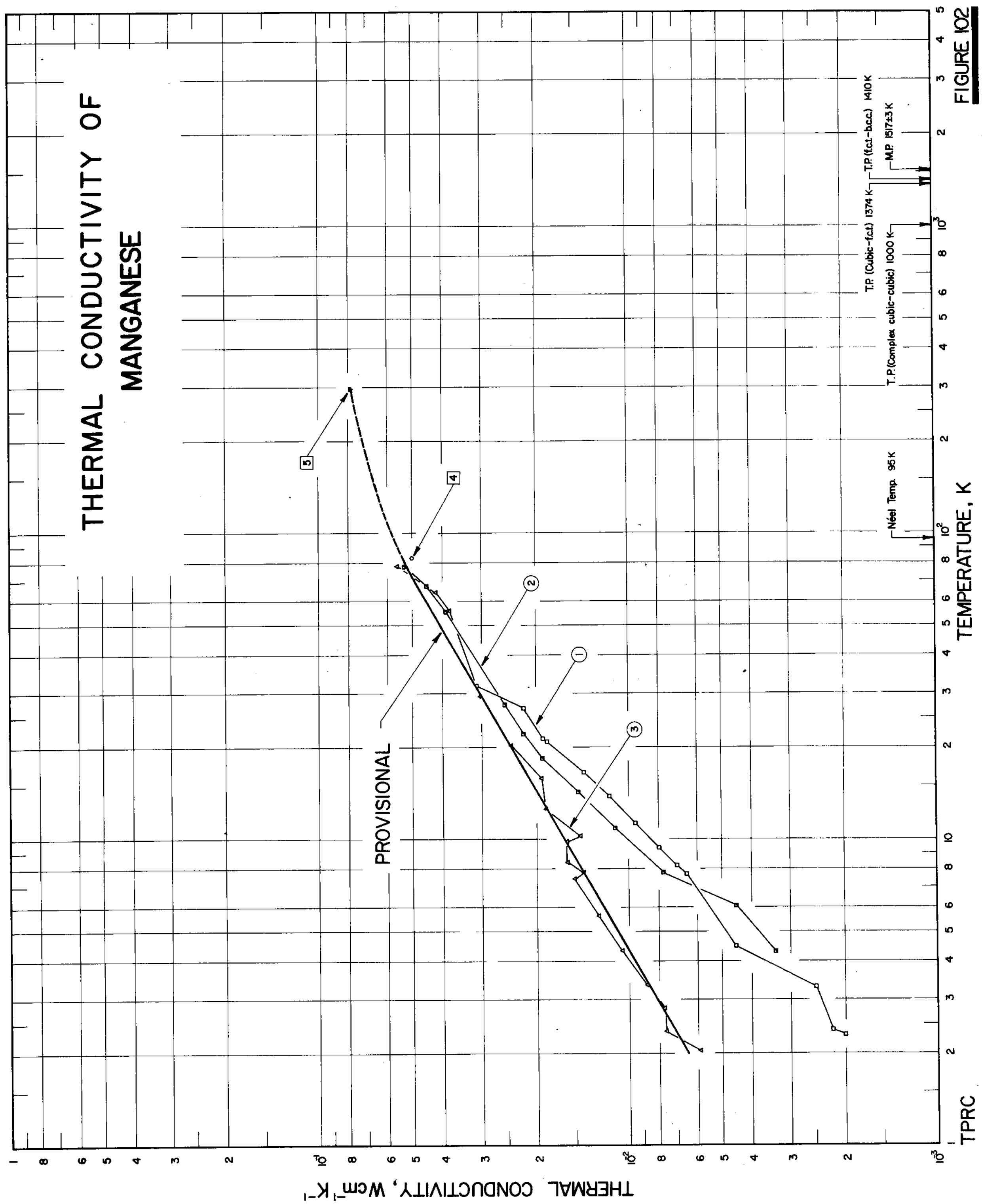

THERMAL CONDUCTIVITY OF
MANGANESE
PROVISIONAL
TPRC
T.P. (Cubic-f.c.t.) 1374 K
T.P. (f.c.t.-b.c.c.) 1410 K
M.P. 1517±3 K
T.P. (Complex cubic-cubic) 1000 K
Néel Temp. 95 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, $W cm^{-1} K^{-1}$

FIGURE 102

TABLE 95. THERMAL CONDUCTIVITY OF MANGANESE - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-32	JM 2472; Mn 1	99.99 pure; polycrystalline; supplied by Johnson, Matthey and Co., Ltd; annealed; electrical resistivity ratio $\rho(293K)/\rho(20K) = 1.47$.
2	1546	White, G. K. and Woods, S. B.	1959	L	4.3-91	Mn 2	99.99 Mn and 0.001 Mg; α-manganese; cross section 3 x 1.1 mm; as received; JM 10792 from Johnson, Matthey and Mallory, Ltd.; electrical resistivity reported as 330 and 375 μohm cm at 4.2 K and room temp, respectively; Lorenz number 30×10^{-8} V^2 K^{-2} at 4.2 K.
3	1546	White, G. K. and Woods, S. B.	1959	L	2.1-78	Mn 3	Similar to the above specimen except cross section ~3.3 x 1.4 mm and annealed in vacuum at 600 C; electrical resistivity 150 μohm cm at room temp; residual electrical resistivity 11.3 μohm cm; Lorenz number 3×10^{-8} V^2 K^{-2} at 4.2 K.
4	1188	Reddemann, H.	1935	L	83.2		β-manganese; approx 16 mm long, 5 mm dia; electrical resistivity 110 μohm cm at -190 C.
5	690	Jolliffe, B. W., Tye, R. P., and Powell, R. W.	1966	C	293	JM 810	Pure α-manganese with impurities Ca, Mg, and <0.01 S; some gaseous impurity expected; specimen a small irregular-shaped flake ~0.1 cm thick from Johnson, Matthey and Co., Ltd; electrolytically prepared; high-alloy steel, titanium alloy, and an alumina based ceramic used as comparative materials.

Mendelevium

No information is available for the thermal or electrical conductivity of mendelevium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidences show that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of mendelevium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Mercury

Until recently the thermal conductivity of liquid mercury was very uncertain. Recent work has, however, led to the availability of three sets of data carried out in the USA by Ewing, et al. [416] (curve 17), in the USSR by Vel'tischeva, et al. [1036, 1483] (curves 61–63), and in Great Britain by Powell and Tye [1133] (curves 56, 64–71), which agree to within about 10 percent at 350 K and more closely at higher temperatures. The most recent data of Duggin [373, 375] (curves 87 and 88) are slightly lower than the above.

In the case of liquid mercury it is again possible to refer to the predicted values of Grosse [546] (curve 90). For this metal the electrical conductivity has been determined by Birch [163] and decreases with increase of temperature along a smooth curve to a value of about 10 Ω^{-1} cm^{-1} at the critical point of 1733 K indicated by this experiment. In this instance, Grosse used a value of the Lorenz function of 2.60×10^{-8} V^2 K^{-2} as found by others for the range 373 to 570 K. He appears to have used this value together with the electrical conductivities of Birch right to the critical temperature. Part of Grosse's thermal conductivity curve derived in this way is shown as curve 90. A maximum value is indicated at about 760 K, followed by a fall at an increasing rate to meet the estimated saturated vapor of about 0.00045 W cm^{-1} K^{-1} at the critical temperature.

The difference between Grosse's predicted thermal conductivity curve and the measured values at the highest measurement temperature is about 8 percent. Whilst there are uncertainties regarding the true values of ρ and L, the general form of the curve derived by Grosse seems sound. Hence, the recommended curve has been drawn as the mean through the experimental data of the three aforementioned groups of workers, which is seen to agree well with Grosse's curve in the extrapolated low-temperature region and up to about 600 K. However, from 600 to 800 K the recommended curve has been increasingly biased toward that of Grosse.

Support for the electrical conductivity measurements by Birch has since come from an investigation by Kikoin and Sanchenkov [757], who stated that their resistivity values were in extremely good agreement with the results of Birch in the range up to 1300 C. They found the critical temperature to be 1753 ±10 K, which exceeds that of Birch by 20 K, or twice their stated uncertainty.

In the solid phase, since mercury has a rhombohedral crystal structure, its thermal conductivity is dependent on the crystal orientation. The available data for solid mercury are very scarce. In the range from about 80 to 200 K, the curves for the thermal conductivity of mercury single crystal in the directions parallel and perpendicular to the trigonal axis have been based on the data of Reddemann [1186] (curves 28–43), and that for the polycrystalline sample is derived from $k_{poly}\ \frac{1}{3}\ (k_{\parallel} + 2k_{\perp})$. At temperatures around 4 K the curve for the polycrystalline sample has been drawn through the data of Watson and Graham [1506] (curves 73, 74), and this section of curve around 4 K and that derived for the range from 80 to 200 K have been tentatively extended to be smoothly joined together around 9 K. The values for the single crystal samples below 80 K have been derived from those for the polycrystalline sample by assuming linear variations of anisotropy and taking $k_{\parallel}/k_{\perp} = 1.376$ and 1.292 at 86 K and 196 K, respectively, according to the data of Reddemann [1186].

The values for the solid state above 80 K and for the liquid state below 1000 K are recommended values, and are thought to be accurate to within ±10 percent of the true values at temperatures from 80 K to the melting point, ±5 percent from the melting point to 700 K, and ±10 percent from 700 to 1000 K. The values above 1000 K are provisional; the uncertainty increases with temperature and up to ±20 percent at the highest temperatures. The values below 80 K are merely typical values.

TABLE 96. Recommended thermal conductivity of mercury†

(Temperature, T, K; Thermal Coneuctivity, k, W cm^{-1} K^{-1})

Solid				Liquid	
	∥ to triagonal axis	⊥ to triagonal axis	Poly-crystal-line		
T	k	k	k	T	k
0	0	0	0	234.288	0.0697
1	82.4*	57.2*	65.6*	250	0.0732
2	21.5*	14.9*	17.1	273.2	0.0782
3	6.34*	4.40*	5.05	298.2	0.0830
4	2.84*	1.97*	2.26*	300	0.0834
5	1.66*	1.15*	1.32*	323.2	0.0874
6	1.11*	0.770*	0.882*	350	0.0915
7	0.834*	0.581*	0.665*	373.2	0.0947
8	0.691*	0.481*	0.551*	400	0.0984
9	0.615*	0.429*	0.491*	473.2	0.107
10	0.576*	0.400*	0.460*	500	0.110
11	0.559*	0.387*	0.445*	573.2	0.117
12	0.547*	0.382*	0.437*	600	0.120
13	0.538*	0.377*	0.432*	673.2	0.126
14	0.532*	0.373*	0.427*	700	0.127
15	0.527*	0.369*	0.422*	770	0.1283
16	0.522*	0.366*	0.418*	773	0.128
18	0.512*	0.360*	0.410*	800	0.128
20	0.504*	0.354*	0.404*	873.2	0.126
25	0.488*	0.343*	0.392*	900	0.124*
30	0.474*	0.334*	0.382*	973.2	0.119*
35	0.462*	0.327*	0.373*	1000	0.117*
40	0.452*	0.320*	0.365*	1073.2	0.111*
45	0.444*	0.315*	0.359*	1100	0.108*
50	0.437*	0.311*	0.354*	1173.2	0.101*
60	0.424*	0.304*	0.345*	1200	0.0984*
70	0.413*	0.297*	0.337*	1273.2	0.0904*
80	0.404	0.293	0.330*	1300	0.0872*
90	0.396	0.288	0.324	1373.2	0.0773*
100	0.390	0.285	0.320	1400	0.0732*
123.2	0.374	0.279	0.310	1473.2	0.0610*
150	0.360	0.271	0.301	1500	0.0559*
173.2	0.349	0.268	0.295	1573.2	0.0407*
200	0.340	0.264	0.289	1600	0.0345*
223.2	0.332	0.260	0.285	1673.2	0.0164*
234.288	0.329	0.259	0.282	1700	0.0094*
				1733	0.00045*

†The values are for high-purity mercury. Those for liquid mercury above 1000 K are provisional and those for solid mercury below 80 K are merely typical values.

*Extrapolated or estimated.

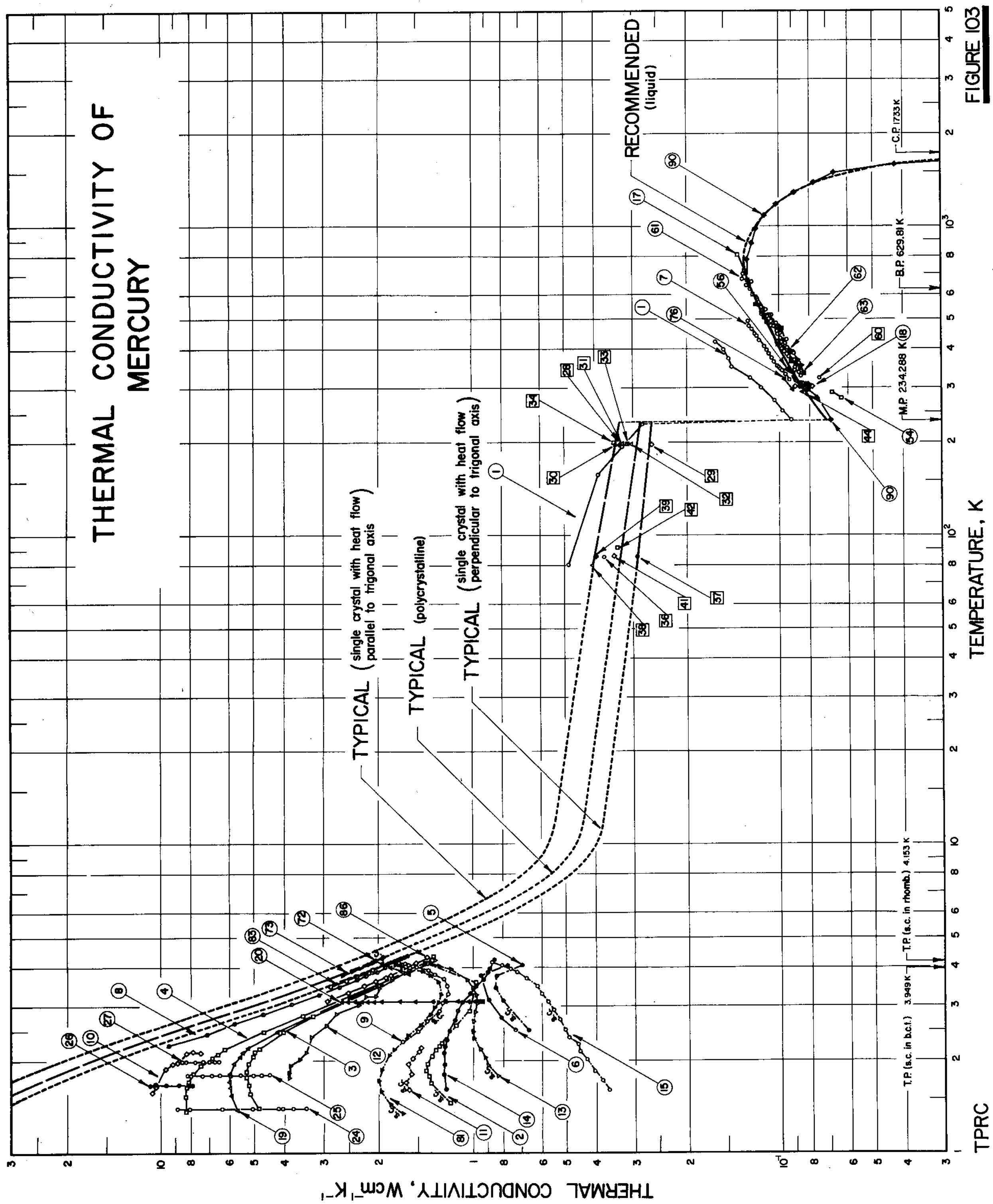

THERMAL CONDUCTIVITY OF MERCURY
TYPICAL (single crystal with heat flow parallel to trigonal axis)
TYPICAL (polycrystalline)
TYPICAL (single crystal with heat flow perpendicular to trigonal axis)
RECOMMENDED (liquid)
C.P. 1733 K
B.P. 629.81 K
M.P. 234.288 K
T.P. (s.c. in b.c.t.) 3.949 K
T.P. (s.c. in rhomb.) 4.153 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 103

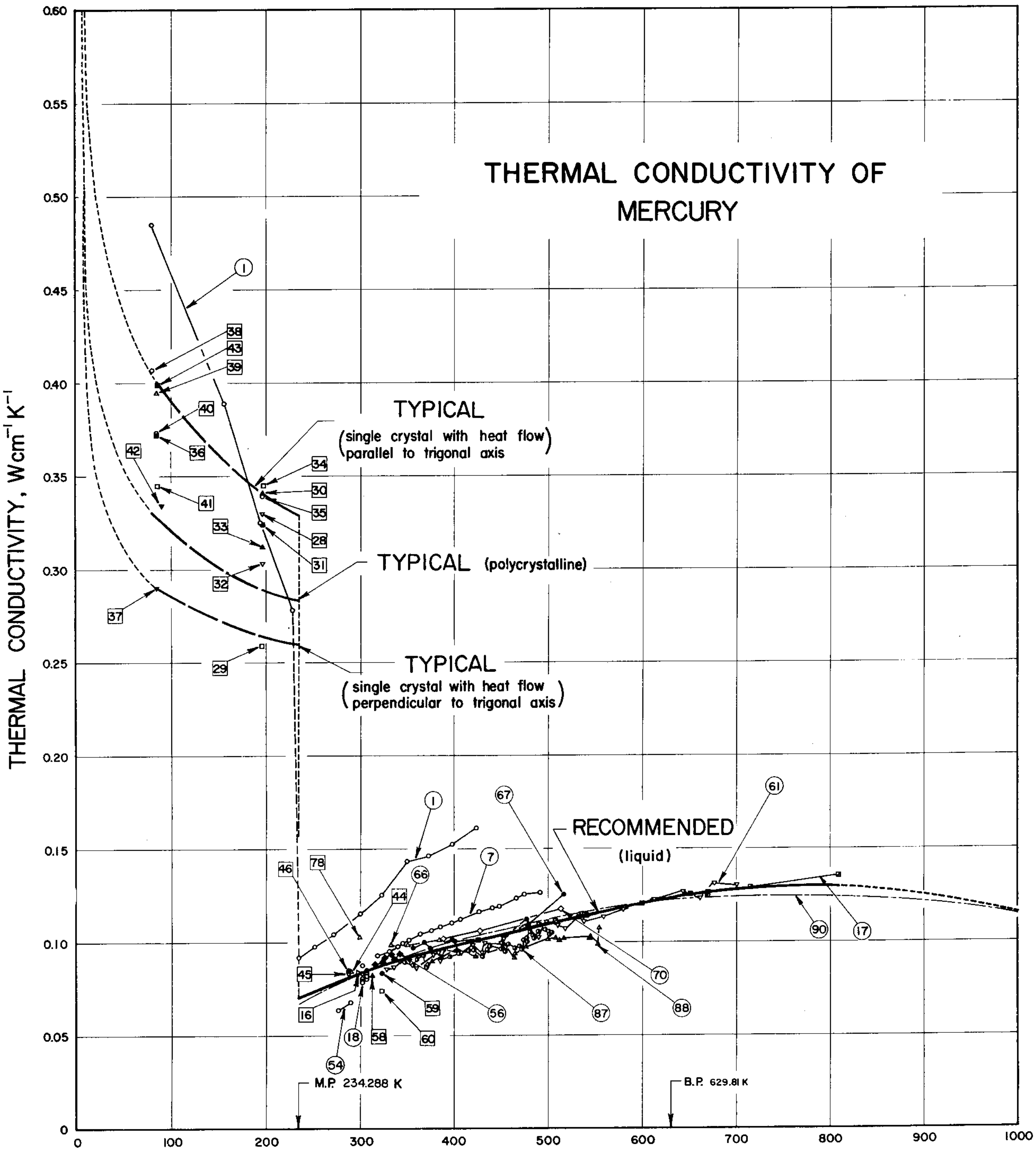

THERMAL CONDUCTIVITY OF MERCURY
TYPICAL (single crystal with heat flow parallel to trigonal axis)
TYPICAL (polycrystalline)
TYPICAL (single crystal with heat flow perpendicular to trigonal axis)
RECOMMENDED (liquid)
M.P. 234.288 K
B.P. 629.81 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 104

TABLE 97. THERMAL CONDUCTIVITY OF MERCURY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	483	Gehlhoff, G. and Neumeier, F.	1919	L	80–423		Pure; liquid specimen tested in an iron cylinder; electrical conductivity reported as 13.77, 7.292, 5.327, 4.287, 1.070, and 1.055 x 10^4 ohm^{-1} cm^{-1} at -193, -115, -75.1, -44.7, -37, and -20.5 C, respectively.
2	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.5–4.1	Hg 3	Impurities given by supplier as <0.005 noble metals and <0.0001 base metals; due to contamination, impurities shown by after-test spectrographic analysis as upper limits: 0.05 Cu, 0.05 Ag, and traces of other base elements; purity during test believed ~99.995; polycrystalline; commercially available cp reagent from Eimer and Amend, Cat. No. M-141; in superconducting state.
3	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.4–3.5	Hg 3	The above specimen measured in a transverse magnetic field of 859 gauss; in normal state.
4	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.4–4.4	Hg 3	The above specimen measured in a transverse magnetic field of 491 gauss; in normal state.
5	334	deHaas, W. J. and Bremmer, H.	1936	L	2.5–4.1		High purity; specimen contained in an U-shaped tube; in superconducting state.
6	334	deHaas, W. J. and Bremmer, H.	1936	L	2.5–4.1		The above specimen measured in a magnetic field of 436 gauss; in normal state.
7	580, 581	Hall, W. C.	1936	L	318–492		Pure; liquid specimen tested in a 4.9 cm dia asbestos cylinder.
8	642	Hulm, J. K.	1950	L	2.3–4.4	Hg 1	99.99^+ pure; in normal state.
9	642	Hulm, J. K.	1950	L	2.3–4.2	Hg 1	99.99^+ pure; in superconducting state.
10	642	Hulm, J. K.	1950	L	1.6–2.1	Hg 2	0.002 Cd; in normal state.
11	642	Hulm, J. K.	1950	L	1.6–2.2	Hg 2	0.002 Cd; in superconducting state.
12	642	Hulm, J. K.	1950	L	1.8–4.2	Hg 3	0.007 Cd; in normal state.
13	642	Hulm, J. K.	1950	L	1.8–4.0	Hg 3	0.007 Cd; in superconducting state.
14	642	Hulm, J. K.	1950	L	1.6–4.3	Hg 6	0.10 In; in normal state.
15	642	Hulm, J. K.	1950	L	1.6–4.1	Hg 6	0.10 In; in superconducting state.
16	662	Istrati, M. I.	1926	P	298		Liquid specimen tested in a cylindrical tube of 4 cm dia and 20 cm long; thermal conductivity value calculated from measured thermal diffusivity.
17	416	Ewing, C. T., Seebold, R. E., Grand, J. A., and Miller, R. R.	1955	L	426–810		99.999^+ Hg; 0.0001-0.001 Mg; impurities shown by chemical analysis after experiment as 0.0004 Fe, 0.0002 Cr, and 0.0001 Ni; Lorenz function reported as 2.64, 2.59, 2.61, 2.63, and 2.64 x 10^{-8} V^2 K^{-2} at 100, 184, 256, 288, and 297 K, respectively.
18	1514	Weber, R.	1903	L	303–308		Pure; specimen tested in a container of cross sectional area 315 cm^2 and thickness 0.955 cm.
19	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.4–4.2	Hg 3	The same specimen as for the curve No. 2; measured in a transverse magnetic field of 737 gauss; in normal state.
20	1512	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	Impurities given by supplier as <0.005 noble metals and <0.0001 base metals; due to contamination, composition shown by after-test spectrographic analysis as 99.99^+ Hg, <0.005 Ag, and trace of Cu; purity during test believed ~99.995; polycrystalline; commercially available cp reagent from Eimer and Amend, Cat. No. M-141; measured in transverse magnetic fields ranging from 8.4 to 190 gauss; in superconducting state.

TABLE 97. THERMAL CONDUCTIVITY OF MERCURY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
21*	1512	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in transverse magnetic fields with strength H ranging from 247 to 974 gauss; in normal state.
22*	1512	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in longitudinal magnetic fields with strength H ranging from 139 to 198 gauss; in superconducting state.
23*	1512	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in longitudinal magnetic fields with strength H ranging from 284 to 727 gauss; in normal state.
24	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.4	Hg 2	99.995^+ Hg and trace Ag; commercially available cp reagent from Eimer and Amend, Cat. No. M-141; measured in transverse magnetic fields with strength H ranging from 455 to 965 gauss; in normal state.
25	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.8	Hg 2	The above specimen measured in transverse magnetic fields with strength H ranging from 460 to 1000 gauss; in normal state.
26	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.67	Hg 2	The above specimen measured in longitudinal magnetic fields with strength H ranging from 455 to 965 gauss; in normal state.
27	1512	Webber, T. T. and Spohr, D. A.	1957	L	1.98	Hg 2	The above specimen measured in longitudinal magnetic fields with strength H ranging from 440 to 943 gauss; in normal state.
28	1186	Reddemann, H.	1932	L	196.2	7	Single crystal; the angle between principal crystallographic axis and rod axis $\theta = 21^\circ$; grown in a glass tube; electrical resistivity 15.15 μohm cm at 196.2 K.
29	1186	Reddemann, H.	1932	L	196.4	22	Similar to above but $\theta = 90^\circ$ and electrical resistivity 19.30 μohm cm at 196.4 K.
30	1186	Reddemann, H.	1932	L	196.8	23	Similar to above but $\theta = 0^\circ$ and electrical resistivity 14.58 μohm cm at 196.9 K.
31	1186	Reddemann, H.	1932	L	197.5	26	Similar to above but $\theta = 28^\circ$ and electrical resistivity 15.72 μohm cm at 197.5 K.
32	1186	Reddemann, H.	1932	L	197.6	27	Similar to above but $\theta = 46^\circ$ and electrical resistivity 17.15 μohm cm at 197.6 K.
33	1186	Reddemann, H.	1932	L	197.1	28	Similar to above but $\theta = 38^\circ$ and electrical resistivity 16.41 μohm cm at 197.2 K.
34	1186	Reddemann, H.	1932	L	198.4	29	Similar to above but $\theta = 0^\circ$ and electrical resistivity 14.74 μohm cm at 198.4 K.
35	1186	Reddemann, H.	1932	L	197.3	30	Similar to above but $\theta = 0^\circ$ and electrical resistivity 14.63 μohm cm at 197.3 K.
36	1186	Reddemann, H.	1932	L	85.2	3	Similar to above but $\theta = 25^\circ$ and electrical resistivity 5.96 μohm cm at 85.2 K.
37	1186	Reddemann, H.	1932	L	85.4	22	Similar to above but $\theta = 90^\circ$ and electrical resistivity 7.48 μohm cm at 85.4 K.
38	1186	Reddemann, H.	1932	L	80.2	23	Similar to above but $\theta = 0^\circ$ and electrical resistivity 5.31 μohm cm at 80.3 K.
39	1186	Reddemann, H.	1932	L	85.5	24	Similar to above but $\theta = 8^\circ$ and electrical resistivity 5.75 μohm cm at 85.5 K.
40	1186	Reddemann, H.	1932	L	85.5	26	Similar to above but $\theta = 28^\circ$ and electrical resistivity 6.05 μohm cm at 85.6 K.
41	1186	Reddemann, H.	1932	L	86.6	27	Similar to above but $\theta = 46^\circ$ and electrical resistivity 6.65 μohm cm at 86.6 K.
42	1186	Reddemann, H.	1932	L	90.6	28	Similar to above but $\theta = 46^\circ$ and electrical resistivity 7.02 μohm cm at 90.5 K.
43	1186	Reddemann, H.	1932	L	86.2	30	Similar to above but $\theta = 0^\circ$ and electrical resistivity 5.73 μohm cm at 86.2 K.

* Not shown in figure.

TABLE 97. THERMAL CONDUCTIVITY OF MERCURY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
44	1022	Nettleton, H. R.	1913	L	290.5		In liquid state; measurement made on a flowing specimen at a rate of 871 g per 15 min.
45	1022	Nettleton, H. R.	1913	L	288.2		In liquid state; measurement made on a flowing specimen at a rate of 1003 g per 15 min.
46	1022	Nettleton, H. R.	1913	L	289.0		In liquid state; measurement made on a flowing specimen at a rate of 1079 g per 15 min.
47*	1022	Nettleton, H. R.	1913	L	290.7		In liquid state; measurement made on a flowing specimen at a rate of 1099 g per 15 min.
48*	1022	Nettleton, H. R.	1913	L	288.2		In liquid state; measurement made on a flowing specimen at a rate of 1159 g per 15 min.
49*	1022	Nettleton, H. R.	1913	L	288.2		In liquid state; measurement made on a flowing specimen at a rate of 1199 g per 15 min.
50*	1022	Nettleton, H. R.	1913	L	287.2		In liquid state; measurement made on a flowing specimen at a rate of 1296 g per 15 min.
51*	1022	Nettleton, H. R.	1913	L	288.7		In liquid state; measurement made on a flowing specimen at a rate of 1301 g per 15 min.
52*	1022	Nettleton, H. R.	1913	L	288.7		In liquid state; measurement made on a flowing specimen at a rate of 1361 g per 15 min.
53*	1022	Nettleton, H. R.	1913	L	288.7		In liquid state; measurement made on a flowing specimen at a rate of 1422 g per 15 min.
54	1513	Weber, H. F.	1880	P	278, 290		In liquid state; specimen tested in a cylindrical container; thermal conductivity values calculated from measured data of thermal diffusivity, specific heat, and density.
55*	1597	Zaitseva, L. S.	1959	R	567–717		Chemically pure mercury vapor.
56	1133	Powell, R. W. and Tye, R. P.	1961	C	304–343		Triple-distilled liquid mercury; contained in a thin walled stainless steel reservoir of 0.939 in. dia and 3.5 in. deep; electrical resistivity reported as 96.7, 98.6, 101.1, 103.5, 109.1, and 115.0 μohm cm at 30, 50, 75, 100, 150, and 200 C, respectively; first experiment with thermocouples welded on the steel wall of mercury reservoir; stainless steel used as comparative material.
57*	1262	Schleiermacher, A.	1889	R	476.2		In vapor state; contained in a glass tube of dia 18.2 mm; measured at pressures ranging from 3.0 to 10.3 mm Hg; measured by hot-wire method.
58	1023	Nettleton, H. R.	1915	L	313		In liquid state; contained in a cylindrical vessel of ~4.9 cm dia x 40 cm long.
59	137	Berget, A.	1887	L	323		In liquid state; contained in a tube of 13.2 mm dia x 20 cm long.
60	75b	Angström, A. J.	1864	P	323.2		In liquid state; thermal conductivity calculated from measured thermal diffusivity.
61	1036, 1483	Vel'tischeva, V. A., Kolakutskaya, N. A., Pchelkin, I. M., Klassen, T. V., and Nikol'skii, N. A.	1958	L	328–700	1	In liquid state.

* Not shown in figure.

TABLE 97. THERMAL CONDUCTIVITY OF MERCURY - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
62	1036, 1483	Vel'tischeva, V.A., Kolakutskaya, N.A., Pchelkin, I.M., Klassen, T.V., and Nikol'skii, N.A.	1958	L	353-556	2	In liquid state.
63	1036, 1483	Vel'tischeva, V.A., et al.	1958	L	333-560	3	In liquid state.
64*	1133	Powell, R.W. and Tye, R.P.	1961	C	307-351		Triple-distilled liquid mercury; contained in a thin-walled stainless steel reservoir of 0.939 in. dia and 3.5 in. deep; electrical resistivity reported as 96.7, 98.6, 101.1, 103.5, 109.1, and 115.0 μohm cm at 30, 50, 75, 100, 150, and 200 C, respectively; first experiment with thermocouple immersed in the mercury; stainless steel used as comparative material.
65*	1133	Powell, R.W. and Tye, R.P.	1961	C	334.7		Second experiment of the above specimen with thermocouples welded on the steel wall of mercury reservoir; mercury and stainless steel in poor electrical contact.
66	1133	Powell, R.W. and Tye, R.P.	1961	C	319-383		Second experiment of the above specimen with thermocouples immersed in the mercury.
67	1133	Powell, R.W. and Tye, R.P.	1961	C	318-517		Third experiment of the above specimen with a honeycomb of mica inserted to subdivide the mercury column and with thermocouples welded on the steel wall of mercury reservoir.
68*	1133	Powell, R.W. and Tye, R.P.	1961	C	332-416		Third experiment of the above specimen with thermocouples immersed in the mercury.
69*	1133	Powell, R.W. and Tye, R.P.	1961	C	307-368		Fourth experiment of the above specimen with the mercury column still further sub-divided by the insertion of 36 cellophane drinking straws and with thermocouples welded on the steel wall of mercury reservoir.
70	1133	Powell, R.W. and Tye, R.P.	1961	C	326-514		Measurement made on new mercury specimen after having the test apparatus thoroughly cleaned with new thermocouples welded on the steel wall of the mercury reservoir, a honeycomb of mica also being inserted to subdivide mercury column.
71*	1133	Powell, R.W. and Tye, R.P.	1961	L	304, 333		Similar to the above specimen but measured by guarded hot-plate method.
72	1506	Watson, J.H.P. and Graham, G.M.	1963	L	3.8-4.2		Very pure; crystallized from triple-distilled Hg; cylindrical specimen; cast in liquid air; in superconducting state.
73	1506	Watson, J.H.P. and Graham, G.M.	1963	L	3.8-4.2		The above specimen measured in a magnetic field of 600 gauss; in normal state.
74*	1506	Watson, J.H.P. and Graham, G.M.	1963	L	3.8-4.2		The above specimen measured in a magnetic field of 800 gauss; in normal state.
75*	580	Hall, W.C.	1936	L	373-412	Amalgam; 1	0.104 Na; liquid specimen contained in a hollow asbestos cylinder; prepared by melting (under paraffin) appropriate amounts of certified pure Hg (from Mallinckrodt Chemical Co.) and Na (from Chemistry Dept. of Univ. of Kansas) in furnace, the liquid then kept at 150 C for 12 hrs.
76	876	Mallon, C.E. and Cutler, M.	1965	E	297-358		In liquid state.
77*	34	Albrecht, F.	1932	R	298		No details reported. (Measuring temp assumed 25 C.)

* Not shown in figure.

TABLE 97. THERMAL CONDUCTIVITY OF MERCURY – SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
78	976	Mizushina, T., Iuchi, S., Sasano, T., and Tamura, H.	1960	R	300		99.999 pure; specimen contained in the space between two concentric copper cylinders with chromium-plated surfaces.
79*	976	Mizushina, T., et al.	1960	R	300		Another run of the above specimen.
80*	976	Mizushina, T., et al.	1960	R	300		Same as above but with a copper plate inserted in the middle of Hg layer between the cylinders.
81	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	1.4–4.4		99.99999 pure; specimen contained in a stainless steel tube 22 cm long, 0.1875 in. O. E. by 0.005 in. thick; supplied by United Mineral and Chemical Corp; crystal grown inside the cryostat at the rate from 3 to 20 hrs for 22 to 24 cm long crystal; annealed for one to four days at -50 C to -196 C; in superconducting state.
82*	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	2.5–4.2		The above specimen, second run; the above annealing done twice without melting the crystal between runs.
83	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	3.5–4.3		The above specimen measured in a longitudinal magnetic field of ~400 Oe; in normal state.
84*	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	3.3–4.3		The above specimen second run; twice annealed at -196 to -50 C for one to four hrs between runs without melting the crystal.
85*	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	1.4–4.4		Similar to the above specimen except measured in zero magnetic field; in superconducting state.
86	1288, 1289	Serlemitsos, A. T. and Bhagat, S. M.	1968	L	3.1–4.3		The above specimen measured in a longitudinal magnetic field of ~550 Oe; in normal state.
87	373, 375	Duggin, M. J.	1969	L	345-503		Liquid specimen tested in a Pyrex 7740 glass cell average width 2.31 mm, breadth 14.85 mm and ~5.0 cm long (the average cross-sectional area of the walls 1.138 cm^2); electrical resistivity reported as 1.012, 1.064, 1.121, 1.184, and 1.256 μohm cm at 350, 400, 450, 500, and 550 K, respectively. (reported data obtained from author in tabulated form).
88	375	Duggin, M. J.	1969	L	376-553		Similar to above except pyrex glass cell average width 5.73 mm.
89*	1594	Yurchak, R. P. and Smirnov, B. P.	1968	E	293.2		In liquid state.
90	546	Grosse, A. V.	1966	→	234-1733		Thermal conductivity values calculated from electrical resistivity data using the Lorenz function $2.62 \times 10^{-8}\ V^2\ K^{-2}$.

*Not shown in figure.

Molybdenum

There are only three curves in the low temperature region and these are for relatively impure samples of molybdenum and have but small maxima. The highest is due to Rosenberg [1220] (curve 13) for a 99.95 percent molybdenum and this has been fitted by a curve derived with $m = 3.20$, $n = 2.60$, $\alpha'' = 0.000000967$, and $\beta = 6.58$.

The maximum occurs at about 35 K and the calculated curve has been extended to about 50 K where the agreement with Rosenberg's data is still good. This curve at low temperatures is only for a sample having $\rho_0 = 0.167$ $\mu\Omega$ cm. It approximately follows Rosenberg's to its upper limit (96 K) where it is some 4 percent above a curve due to Bäcklund [102] (curve 12). A smoothly falling curve can be drawn through Bäcklund's experimental values and this tends to disprove the shallow minimum at about 200 K which had been indicated by Kannuluik [707] (curves 8 and 9). The recommended curve for moderate temperatures has accordingly been drawn some 2 percent above Bäcklund's curve to merge into that due to Tye [1437] (curve 29) for the range 323 to 473 K. This curve is continued smoothly and in a fairly mean position to the melting point. It falls at a steadily decreasing rate and in the high-temperature range lies up to 8 percent below the values of Rasor and McClelland [1178] (curve 63), Timrot, Peletskii, and Voskresenskii [1413] (curve 61), and those derived from the thermal diffusivity data of Kraev and Stel'makh [783] (curve 44), 5 percent below the revised value of Vardi and Lemlich [1468] (curve 59) at 2225 K, and exceeds the derived values of Wheeler [1533] (curve 33) by about 10 percent and the thermal conductivity measurements of Lebedev [823] (curve 46) and of several other workers by still greater amounts. Of the more recent determinations those of Khusainova and Filippov [756] for a single crystal sample (curve 56) are considered high.

The recommended curve gives a value of 0.94 W cm^{-1} K^{-1} at 1723 K, which with Tye's electrical resistivity of 44.7 $\mu\Omega$ cm leads to a Lorenz function at 1723 K of 2.44×10^{-8} V^2 K^{-2}, the theoretical value.

Further measurements are required to confirm the exact form of the thermal conductivity curve, particularly at high temperatures. The curve below room temperature is for a sample with the high ρ_0 of 0.167 $\mu\Omega$ cm and data are certainly required for a purer sample. The present values should be within some ±4 percent of that of high-purity molybdenum near normal temperatures, ±10 percent at low temperatures, and within ±15 percent as the melting point is approached.

TABLE 98. Recommended thermal conductivity of molybdenum†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	k	T	k	T	k
0	0	123.2	1.60	1300	1.03
1	0.152*	150	1.49	1373.2	1.01
2	0.304*	173.2	1.45	1400	1.00
3	0.456	200	1.43	1473.2	0.985
4	0.608	223.2	1.42	1500	0.980
5	0.760	250	1.40	1573.2	0.966
6	0.911	273.2	1.39	1600	0.960
7	1.06	298.2	1.38	1673.2	0.948
8	1.21	300	1.38	1700	0.944
9	1.36	323.2	1.38	1773.2	0.933
10	1.51	350	1.36	1800	0.929
11	1.66	373.2	1.35	1873.2	0.918
12	1.81	400	1.34	1900	0.915
13	1.95	473.2	1.32	1973.2	0.906
14	2.09	500	1.30	2000	0.903
15	2.23	573.2	1.27	2073.2	0.894
16	2.37	600	1.26	2173.2	0.885
18	2.63	673.2	1.23	2200	0.882
20	2.87	700	1.22	2273.2	0.876
25	3.36	773.2	1.19	2400	0.866
30	3.64	800	1.18	2473.2	0.861
35	3.70	873.2	1.16	2600	0.852
40	3.55	900	1.15	2673.2	0.848
45	3.28	973.2	1.13	2800	0.840
50	3.02	1000	1.12		
60	2.62	1073.2	1.09		
70	2.32	1100	1.08		
80	2.09	1173.2	1.06		
90	1.93	1200	1.05		
100	1.79	1273.2	1.03		

†The recommended values are for well-annealed high-purity molybdenum, and those below room temperature are applicable only to a specimen having $\rho_0 = 0.167$ $\mu\Omega$ cm.

*Extrapolated.

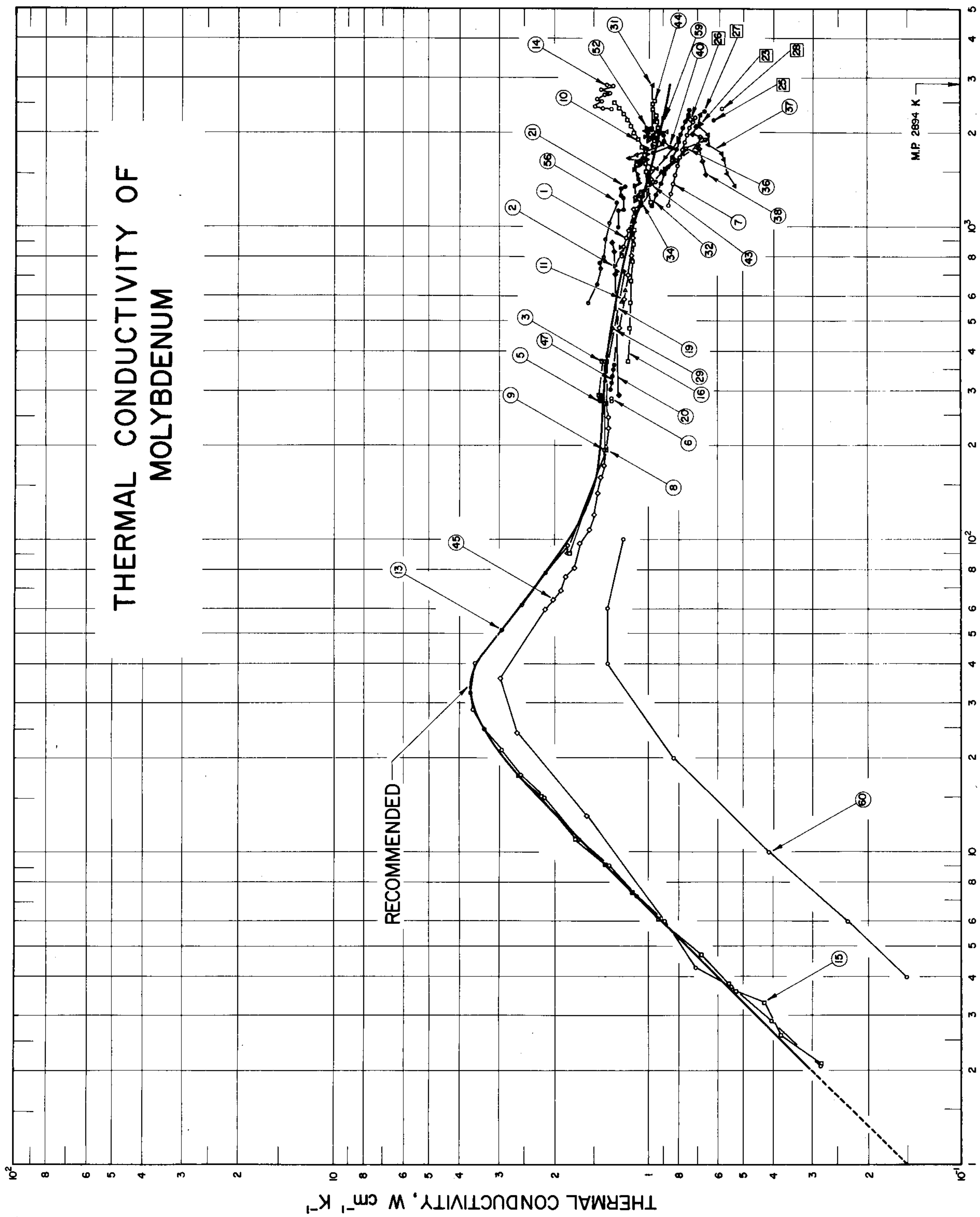
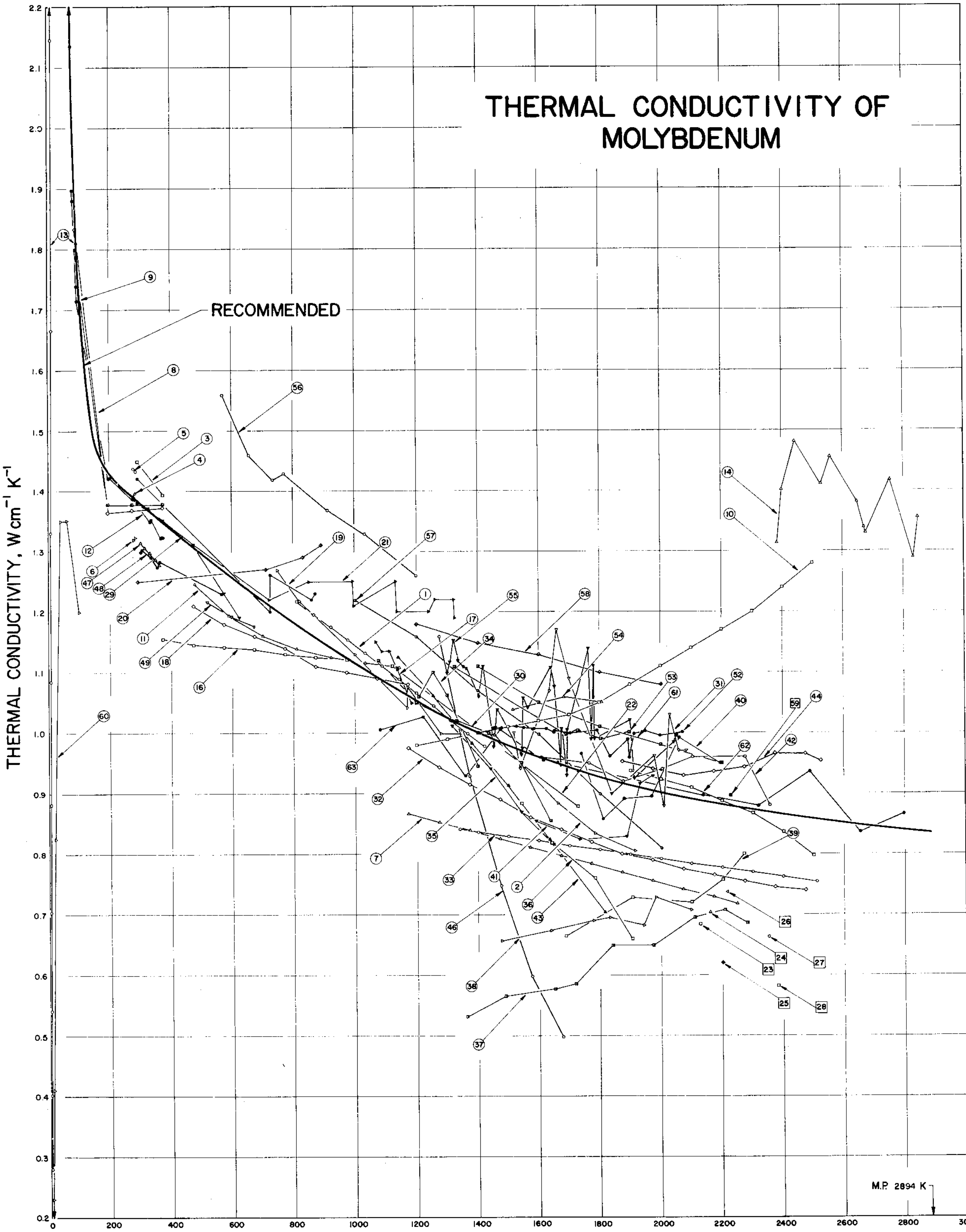

THERMAL CONDUCTIVITY OF
MOLYBDENUM
RECOMMENDED
M.P. 2894 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 105



TPRC

FIGURE 106

TABLE 99. THERMAL CONDUCTIVITY OF MOLYBDENUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	961	Mikol, E. P.	1952	R	811-1422		99.9 Mo, <0.005 Fe, and 0.003 C; test specimen consisted of 5 stacked disks each of ~5 in. O.D., 0.75 in. I.D., and 0.50 in. thick; obtained from Fansteel Metallurgical Corp; prepared by powder-metallurgy techniques; pressed, sintered, then rolled to finished size at just below the recrystallization temp.
2	427	Fieldhouse, I. B., Hedge, J. C., Lang, J. L., Takata, A. N., and Waterman, T. E.	1956	L	749-1915		Pure; 7 in. dia x 1.5 in. thick; arc-melted.
3	116	Barratt, T.	1914	F	290, 373		Pure; 0.0520 cm dia x 45.0 cm long; density 9.933 g cm^{-3}; electrical resistivity reported as 5.806 and 8.516 μohm cm at 0 and 100 C, respectively.
4	702	Kannuluik, W. G.	1931	E	277, 283	Mo 1	Pure; 0.09983 cm dia x 9.915 cm long; annealed at 220 C; electrical resistivity reported as 5.10 and 5.51 μohm cm at 0 and 18 C, respectively.
5	702	Kannuluik, W. G.	1931	E	278. 283	Mo 1	The above specimen annealed at 900 C; electrical resistivity 5.07 μohm cm at 0 C.
6	702	Kannuluik, W. G.	1931	E	277, 282	Mo II	Less pure than the above sample; 0.1069 cm dia x 10.14 cm long; annealed at 220 C; electrical resistivity reported as 5.81 and 6.22 μohm cm at 0 and 18 C, respectively.
7	422	Feith, A. D.	1965	R	1173-2248		0.0269 C, <0.01 Ca, <0.01 Cu, <0.01 Fe, <0.01 Mg, <0.01 Si, 0.0006 H, 0.0006 O, and 0.00019 N; as received; specimen 1.985±0.015 in. in dia; arc-cast; electrical resistivity reported as 5.6, 17.8, 32.2, 48.0, 63.2, and 73.3 μohm cm at 0, 500, 1000, 1500, 2000, and 2300 C, respectively; density 99% of theoretical value; measurements made on 7 heating and cooling cycles, mean values taken from data of 4th to 7th cycles reported.
8	707	Kannuluik, W. G.	1933	E	90-373	Mo 1	99.836^{+} Mo, 0.05 Bi, 0.05 Cd, 0.01 Al, 0.01 Ge, 0.01 Sn, 0.01 Ti, 0.01 V, 0.01 W, 0.001 Co, 0.001 Cu, 0.001 Pt, 0.001 Rh, and trace of C; 0.09979 cm dia x 12.627 cm long; electrical resistivity reported as 0.952, 3.39, 5.25, and 7.67 μohm cm at -183.00, -78.50, 0, and 100 C, respectively.
9	707	Kannuluik, W. G.	1933	E	90-373	Mo 2	Cut from the same wire as the above specimen; 0.09980 cm dia x 9.859 cm long; electrical resistivity reported as 0.882, 3.33, 5.17, 7.56, and 10.05 μohm cm at -183.00, -78.50, 0, 100, and 217.96 C, respectively.
10	1626	Zwikker, C.	1927	E	1200-2500		Pure; electrical resistivity reported as 29.2, 32.2, 35.2, 38.2, 41.2, 44.3, 47.3, 50.4, 53.5, 56.6, 59.7, 62.8, 66.0, and 69.2 μohm cm at 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, and 2500 K, respectively.
11	862	Lucks, C. F. and Deem, H. W.	1956	C	478-1144		Pure; supplied by Climax Molybdenum Co.; 2 cm dia x 15 cm long; arc melted; density 10.24 g cm^{-3}; Armco iron used as comparative material.
12	102	Bäcklund, N. G.	1967	L	86-377		Spectroscopically standardized molybdenum; 5 mm dia x 10 cm long; supplied by Johnson, Matthey and Co., Ltd; electrical resistivity reported as 0.18, 0.57, 0.80, 3.20, 5.55, and 7.31 μohm cm at 4, 76, 91, 194, 297, and 374 K, respectively.

TABLE 99. THERMAL CONDUCTIVITY OF MOLYBDENUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	1220	Rosenberg, H. M.	1955	L	2.1-95	JM 2331; Mo 1	99.95 pure; polycrystalline; 0.52 cm dia x 2.85 cm long; obtained from Johnson, Matthey and Co., Ltd; electrical resistivity reported as 0.167, 0.169, 0.173, 0.190, 0.252, 0.348, 0.580 and 0.868 μohm cm at 20.4, 25.2, 29.3, 37.2, 48.6 58.8, 75.3, and 90.1 K, respectively.
14	50	Allen, R. D., Glasier, L. F., Jr., and Jordan, P. L.	1960	E	2384-2849		0.18 Fe, 0.073 Si, 0.04 C, 0.036 Mn, 0.005 O, and 0.01 others; arc-melted and cast under inert gas, hot-worked and hot-rolled, polished; 0.125 in. dia x 10 in. long; obtained from Fansteel Corp.
15	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.1-21	JM 2331; Mo 1	99.95 pure; 1-2 mm dia x 5 cm long; supplied by Johnson, Matthey and Co., Ltd.
16	128	Bell, I. P. and Makin, S. M.	1954	L	373-973		Coarse grain structure on the outside and fine grain structure in the interior; with a large number of inclusions; 1 in. bar; forged and machined.
17	174	Bode, K. H.	1961	E	1068-1183		99.98 pure; 1 mm wire; obtained from Radium-Elektrizitätsgesellsch, Wipperfürth; polished; annealed in vacuo for 12 hrs at about 1000 C; electrical resistivity reported as 24.4, 25.5, 26.9, 28.3, and 29.7 μohm cm at 761, 800, 850, 900, and 950 C, respectively.
18	1284	Semchyshen, M. and Barr, R. Q.	1955	C	473-1173	Heat No. 990	Recrystallized at 1505 C; measured in a vacuum of 2 x 10^{-5} mm Hg; Armco iron used as comparative material; reported data taken from smoothed curve.
19	312	Cutler, M., Snodgrass, H. R., Cheney, G. T., Appel, J., Mallon, C. E., and Meyer, C. H., Jr.	1961	E	290-871		99.9 pure; received from Fansteel Metallurgical Corp; electrical resistivity 5.98 μohm cm at 23 C.
20	312	Cutler, M., et al.	1961	E	290-890		2nd run of the above specimen.
21	312	Cutler, M., et al.	1961	E	290-1325		3rd run of the above specimen.
22	892	Martinet, J.	1961	E	1122, 1727		Tubular specimen 8 mm O. D., 5 mm I. D., and 100 mm long.
23	611	Hoch, M. and Nitti, D. A.	1961		2129		Heated in high vacuum (10^{-5} mm Hg) by high frequency induction to 1000 to 3000 C; localized heating within 0.003 in. of the surface at current frequencies of 500,000 cps; specimen 0.4923 in. in dia and 0.863 in. in length; measured with the cylindrical axis parallel to the magnetic field; run G-2.
24	611	Hoch, M. and Nitti, D. A.	1961		2161		The above specimen; run G-3.
25	611	Hoch, M. and Nitti, D. A.	1961		2200		The above specimen; run G-5.
26	611	Hoch, M. and Nitti, D. A.	1961		2216.5		The above specimen; run G-4.
27	611	Hoch, M. and Nitti, D. A.	1961		2351.5		The above specimen; run M-1.
28	611	Hoch, M. and Nitti, D. A.	1961		2382		The above specimen; run M-3.
29	1437	Tye, R. P.	1961	L, C	323-623	JM 720	Spectrographically standardized molybdenum; obtained from Johnson, Matthey and Co., Ltd; rod of about 5 mm in dia and 15 cm in length; electrical resistivity reported as 5.65, 6.25, 7.45, 9.9, 12.45, 13.75, 15.1, 17.85, 20.6, 23.3, 26, 28.7, 31.5, 34.4, 37.2, 40.1, 43, and 44.7 μohm cm at 20, 50, 100, 200, 300, 350, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, and 1450 C, respectively; Armco iron used as comparative material.

TABLE 99. THERMAL CONDUCTIVITY OF MOLYBDENUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
30	310	Cutler, M. and Cheney, G. T.	1963	E	1075-1640		Single crystal; Lorenz function reported as 2.87, 2.76, 2.72, 2.71, 2.66, 2.57, and 2.33 x 10^{-8} V^2 K^{-2} at 1080, 1200, 1310, 1320, 1420, 1540, and 1650 K, respectively.
31	1229	Rudkin, R. L., Parker, W. J., and Jenkins, R. J.	1962	E	1520-2085		Spectrographically pure; wire specimen 0.010 in. in dia; electrical resistivity reported as 41.3, 50.6, 58.1, and 59.1 μohm cm at 1550, 1830, 2040, and 2110 K, respectively; measured in a vacuum of <10^{-5} mm Hg.
32	566, 822	Gumenyuk, V. S., Ivanov, V. E., and Lebedev, V. V.	1960	E	1173-2473		Wire; 1 mm dia x 30 mm long; electrical resistivity reported as 27.8, 35.6, 45.2, 56.4, and 74.8 μohm cm at 1173, 1473, 1773, 2073, and 2473 K, respectively; data taken from smoothed curve.
33	1533	Wheeler, M. J.	1965	P	1340-2510		~99.99 Mo (by difference), <0.01 Fe, and traces of other elements; 0.04 in. thick sheets; obtained from Murex Co.; sintered and hot-rolled; average grain size (after test) 110 μ; density 10.3 g cm^{-3}; thermal conductivity values calculated from measured thermal diffusivity data using the specific heat data compiled by Kubaschewski, O., and Evans, L. Ll. (Metallurgical Thermochemistry, Pergamon, 1956).
34	1055	Osborn, R. H.	1938	E	1207-1400		Very pure; 20 mil wire; polished; aged at about 2200 K for 15 mins; electrical resistivity reported as 26.4, 32.3, 37.8, 42.8, and 47.4 μohm cm at 1110, 1325, 1515, 1685, and 1840 K, respectively.
35	1055	Osborn, R. H.	1938	E	1315-1647		Same as the above specimen.
36	1055	Osborn, R. H.	1938	E	1545-1905		Same as the above specimen.
37	697	Jun, C. K. and Hoch, M.	1965	R	1362-2282	Sample 1	99.98⁺ Mo, 0.005 Fe, 0.004 Si, 0.003 Ni, 0.0023 O, 0.0021 C, 0.001 V, <0.0005 N, and 0.00023 H; specimen 2.118 cm in dia and 0.255 cm thick; prepared by powder metallurgy techniques; polished with No. 410 emery paper; average grain dia 34 μ; density 9.104 g cm^{-3}; experiment performed in high vacuum (10^{-6} mm Hg); specimen heated by high frequency induction current; specimen axis parallel to the axis of magnetic field; data calculated from total emittance measurements using specific heat data from an empirical formula in agreement with those of Kirilin, V. A., et al. within 2%; run No. 1.
38	697	Jun, C. K. and Hoch, M.	1965	R	1476-2100	Sample 2	99.964⁺ Mo, 0.028 C, 0.0021 O, 0.002 Si, 0.001 Cu, 0.001 Fe, 0.001 V, <0.0005 N, and 0.00015 H; specimen 1.905 cm in dia and 0.206 cm thick; prepared by arc melting technique; average grain dia 706 μ; density 10.119 g cm^{-3}; same measuring conditions and method as above; run No. 1.
39	697	Jun, C. K. and Hoch, M.	1965	R	1687-2272	Sample 2	The above specimen; run No. 2.
40	697	Jun, C. K. and Hoch, M.	1965	R	1740-2194	Sample 3	99.948⁺ Mo, 0.011 C, <0.01 Fe, <0.01 Si, <0.01 Ti, <0.01 Zr, 0.003 O, 0.0006 N, and 0.0002 H; specimen 1.910 cm in dia and 0.195 cm thick; prepared by arc melting and heated to 2500 K for a very long time in hydrogen such that it underwent grain growth; average grain dia 4850 μ; density 10.163 g cm^{-3}; same measuring condition and method as above; run No. 1.
41	697	Jun, C. K. and Hoch, M.	1965	R	1592-1974	Sample 3	The above specimen; run No. 2.
42	434	Filippov, L. P.	1966	P	1609-2355		No details reported.

TABLE 99. THERMAL CONDUCTIVITY OF MOLYBDENUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
43	1087	Pigalskaya, L.A., Yurchak, R.P., Makarenko, I.N., and Filippov, L.P.	1966	P	1140-1816	Specimen 1	99.9 Mo, 0.01 Mo_2O_3; 0.001 Ni, 0.001 SiO, traces MgO and CaO; cylindrical specimen 10 mm in dia and 70 mm long; density 10.2 g cm^{-3} at room temp; electrical resistivity 5.78 μohm cm at 23 C; thermal conductivity values calculated from measured data of thermal diffusivity, specific heat, and density; reported values taken from smoothed curve.
44	783	Kraev, O.A. and Stel'makh, A.A.	1966	P	1873-2523		Thermal conductivity values calculated from measured thermal diffusivity data with density data taken from Chirkin, V.C. (Teploprovodnost Promizhlennich Materialov. M., Mazhgiz, 1962) and specific heat data from Kraftmakher, Ya. A. (Fiz. Tverd. Tela, 6 (2), 503-5, 1964 or Soviet Physics Solid State, 6 (2), 396-8, 1964).
45	941	Merisov, B.A., Khotkevich, V.I., Zlobintsev, G.M., and Kozinei, V.V.	1967	→	6.0-264		Cylindrical specimen; measured by a thermal potentiometer method.
46	823	Lebedev, V.V.	1961	E	1273-1673		No details reported.
47	804	Küster, W., Bode, K.H., and Fritz, W.	1968	L	303-363		99.93 Mo, 0.01 Fe, 0.005 C, 0.005 O, 0.001 H, 0.001 N, and 0.02 others; 50 mm dia x 70 mm long; density 10.080 g cm^{-3}; measured in a standard apparatus.
48	804	Küster, W., et al.	1968	L	303-568		Similar to above.
49	804	Küster, W., et al.	1968	L	519-674		Similar to the above specimen but dimensions 50 mm dia x 90 mm long; measured in another apparatus.
50*	804	Küster, W., et al.	1968	L	565, 739		Similar to above.
51*	804	Küster, W., et al.	1968	L	424, 466		Similar to above.
52	1074	Peletskii, V.E. and Sobol, Y.G.	1969	L	1237-2070	1	99.9^+ Mo, 0.008 (O, N and H); prepared by powder metallurgy method followed by forging; specimen ~8 to 12 mm in dia and ~50 to 70 mm long; density 10.2 g cm^{-3}; (thermal conductivity data reported by the author in $Wm^{-1} C^{-1}$, probably a typographical error).
53	1074	Peletskii, V.E. and Sobol, Y.G.	1969	L	1324-1978	2	Similar to above.
54	1074	Peletskii, V.E. and Sobol, Y.G.	1969	L	1517-1804	3	Similar to above.
55	977	Moak, D.P. (compiler)	1966	C	999-2071		99.9 pure; 3.00 in. dia x 1.25 in. thick; density 10.2 g cm^{-3}; type 347 stainless steel used as comparative material.
56	756	Khusainova, B.N. and Filippov, L.P.	1968	P	571-1200		Single crystal; specimen 6.6 mm in dia and 54 mm long; supply by Rabotnov, S.N.; purified by band refining (three passages); electrical resistivity reported as 5.39, 6.57, 7.67, 8.59, 10.0, 10.6, 12.7, 14.8, 18.2, and 20.6 x 10^{-6} ohm cm at 310, 350, 414, 462, 526, 535, 628, 722, 847, and 936 K, respectively; Lorenz function reported as 3.15, 3.04, 2.98, 2.93, 3.00, and 3.00 x 10^{-8} V^2 deg^{-2} at 552, 603, 700, 801, 903, and 952 K, respectively; thermal conductivity values calculated from the measurements of thermal diffusivity and specific heat.
57	1073	Peletskii, V.E. and Sobol, Ya.G.	1968	L	1000-2000		Polycrystalline; commercial grade; specimen 8 mm in dia and 78 mm long; smooth data reported.

* Not shown in figure.

TABLE 99. THERMAL CONDUCTIVITY OF MOLYBDENUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
58	1073	Peletskii, V. E. and Sobol, Ya. G.	1968	L	1200-2000		Single crystal; specimen ~8 mm in dia and ~78 mm long; electrical resistivity reported as 28.95, 34.67, 40.49, 46.43, and 52.47 μohm cm at 1200, 1400, 1600, 1800, and 2000 K, respectively; Lorenz function at these temps reported as 2.85, 2.85, 2.85, 2.84, and 2.83 x 10^{-8} V^2 K^{-2}, respectively; L_0 = 2.45 x 10^{-8} V^2 K^{-2}; measured in [110] direction; smooth data reported.
59	1468	Vardi, J. and Lemlich, R.	1968		2225		Recalculation of the experimental data of Hoch, M. and Nitti, D. A. (see curves No. 23-28) based on a new theory for the high frequency electromagnetic heating method.
60	1101	Powell, R. L., Harden, J. L., and Gibson, E. F.	1960	L	4.0-100		1-2% (by volume) ThO_2 with the following impurities in mole percent, 0.01-0.1 Fe, Si; 0.001-0.01 Al, Nb, and Cu; <0.001 Ca, Cr, and Mg; cylindrical rod 3.67 mm in dia, 13 cm long; furnished by LASL; electrical resistivity at 4, 6, 10, 20, 40, 60, and 100 K being, respectively, 0.57, 0.57, 0.57, 0.57, 0.60, 0.80, and 1.50 μohm cm.
61	1413	Timrot, D. L., Peletskii, V. E., and Voskresenskii, V. Yu.	1966		1400-2200		99.95 pure; single crystal.
62	782	Kraev, O. A. and Stel'makh, A. A.	1964	P	1900-2500		8-9 mm in dia and 0.3 mm thick; thermal conductivity values not given in the paper but calculated by TPRC using the authors' thermal diffusivity data and using the TPRC selected density and specific heat values from Thermophysical Properties of High Temperature Solid Materials, Vol. 1, MacMillan, 1967, where the density values are calculated as a function of temp from the thermal expansion data.
63	1178	Rasor, N. S. and McClelland, J. D.	1957	R	1080-2795		0.25 Fe, 0.0730 Si, 0.0210 Ti, 0.0130 Cu, 0.0070 C, and 0.0003 Cr; after test: 0.0630 Si and 0.0080 C, others unchanged; 2 in. O.D. and 0.375 in. I.D.; supplied by Climax Molybdenum Co.; arc-melted; density 10.22 g cm^{-3}.

Neodymium

The only experimental determinations for the thermal conductivity of neodymium are limited to the normal temperature measurements of Legvold and Spedding [831] (curve 2), Zhuze, Golubkov, Goncharova, and Sergeeva [1609] (curve 4), and of Powell and Jolliffe [1127] (curve 1). These single temperature values are respectively 0.130, 0.163, and 0.165 W cm^{-1} C^{-1}. Williams and McElroy [1565] (curve 3) published estimated values for the thermal conductivity of neodymium from 300 to 1200 K at the time when they were engaged in making a similar estimation for promethium.

Williams and McElroy accepted values of 0.165 W cm^{-1} C^{-1} and 65 $\mu\Omega$ cm for the thermal conductivity and electrical resistivity of neodymium at 300 K. Assuming the theoretical Lorenz number L_0 to hold, led to values of 0.113 and 0.052 W cm^{-1} C^{-1} for k_e and k_g the electronic and lattice components of thermal conductivity at 300 K, with $k = k_e + k_g$. By assuming further that $k_g = 15.6\ T^{-1}$ and $k_e = L_0\ T\ \rho^{-1}$, throughout the temperature range, and using values of ρ compiled by Goldsmith, Waterman, and Hirschhorn [513], Williams and McElroy found k to increase with temperature at an increasing rate. At 1120 K (the phase transition temperature assumed by them), the estimated thermal conductivity shows a drop of between 4 and 5 percent. The temperature coefficient is again positive from 1120 to 1200 K, the upper limit of the available electrical resistivity data.

This curve has been provisionally accepted as representing the most probable curve for the temperature variation of the thermal conductivity of polycrystalline neodymium. An attempt has been made to extend the curve down to 200 K by the same procedure and by making use of the electrical resistivity values given for neodymium by Meaden [912]. Since the Debye temperature of neodymium is 159 K, departures from the theoretical Lorenz function can be anticipated as the temperature is further reduced.

The values are thought to be accurate to within ±15 percent of the true values near room temperature. The uncertainty increases to ±30 percent at the highest temperatures. There is an additional uncertainty about the values near 1120 K, the phase transition temperature given by Williams and McElroy [1565], which may be compared with 1135 K given in a reference book on the rare earths [1347a].

TABLE 100. Provisional thermal conductivity of neodymium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
200	0.166*	673.2	0.185*
223.2	0.165*	700	0.187*
250	0.164*	773.2	0.192*
273.2	0.165*	800	0.195*
298.2	0.165*	873.2	0.201*
300	0.165	900	0.203*
323.2	0.165*	973.2	0.212*
350	0.166*	1000	0.215*
373.2	0.167*	1073.2	0.222*
400	0.168*	1100	0.224*
473.2	0.171*	1120	0.225*
500	0.173*	1140	0.217*
573.2	0.178*	1173.2	0.220*
600	0.179*	1200	0.224*

†The provisional values are for high-purity polycrystalline neodymium.
*Estimated.

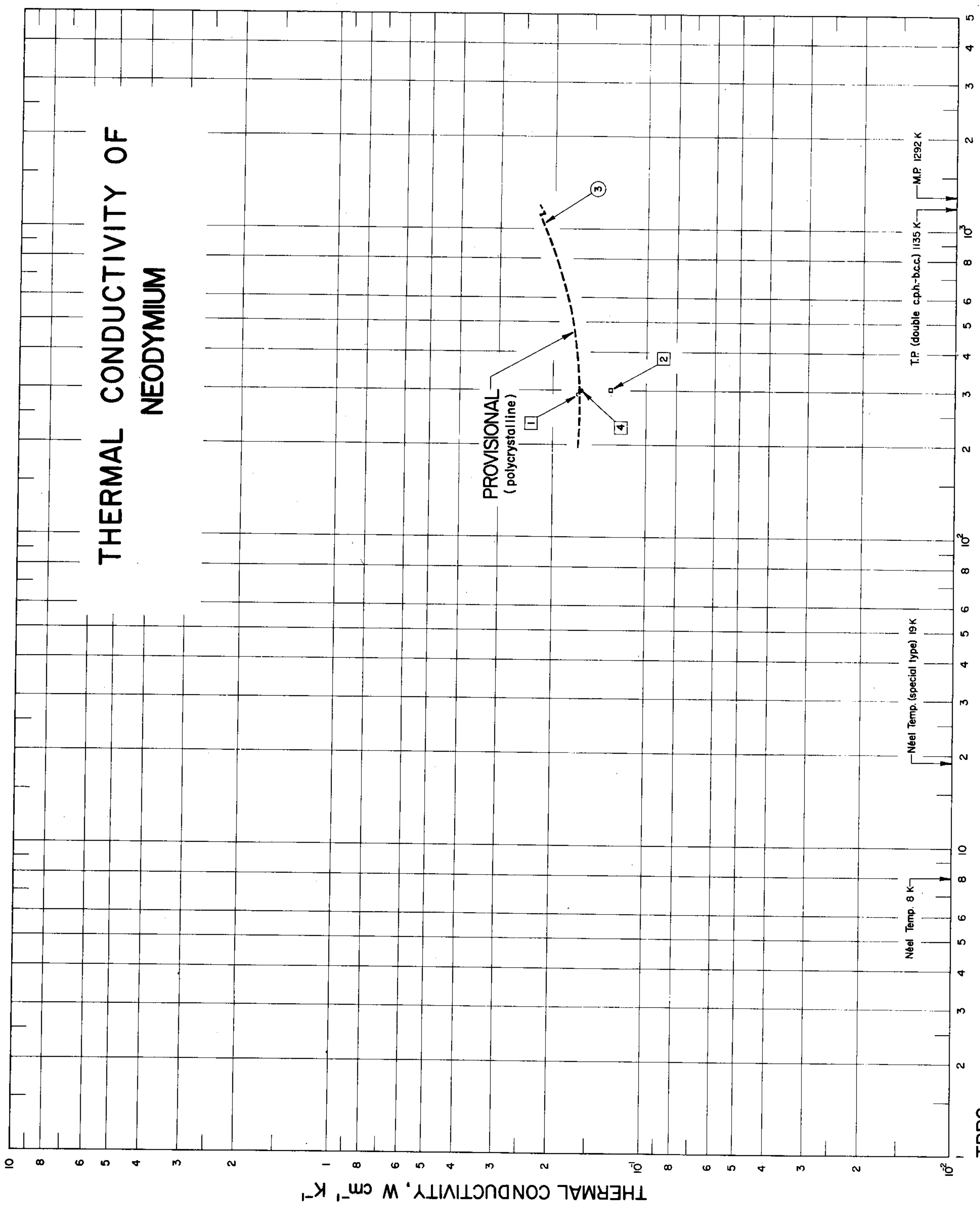

THERMAL CONDUCTIVITY OF NEODYMIUM
PROVISIONAL (polycrystalline)
T.P. (double c.p.h.-b.c.c.) 1135 K
M.P. 1292 K
Néel Temp. (special type) 19 K
Néel Temp. 8 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 107

TABLE 101. THERMAL CONDUCTIVITY OF NEODYMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1127	Powell, R.W. and Jolliffe, B.W.	1965	C	291.2		High purity; polycrystalline; specimen 0.25 in. in dia and 0.25 in. long; supplied by Johnson, Matthey and Co., Ltd.; electrical resistivity 65 μohm cm at 18 C; Monel metal used as comparative material; thermal conductivity data obtained from two measurements using different thermal comparators.
2	831	Legvold, S. and Spedding, F.H.	1954		301		No details reported.
3	1565	Williams, R.K. and McElroy, D.L.	1966	→	300-1200		Estimated values given as the sum of electronic thermal conductivity and the lattice thermal conductivity where electronic thermal conductivity values calculated from the theoretical Lorenz number $L_0 = 2.443 \times 10^{-8}\ V^2\ K^{-2}$ and the estimated electrical resistivity reported as 65, 76, 86, 95, 104, 112, 118, 123, 128, 130 (α), 136 (β), and 136 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1120, 1120, and 1200 K, respectively, and lattice thermal conductivity values are calculated from the empirical equation $k_L = 15.6\ T^{-1}$.
4	1609	Zhuze, V.P., Golubkov, A.V., Goncharova, E.V., and Sergeeva, V.M.	1963	L	300		2.5 x 0.5 x 0.5 cm; electrical conductivity $1.6 \times 10^4\ ohm^{-1}cm^{-1}$ at 300 K.

Neon

The thermal conductivity of neon in each of the physical states is discussed separately below.

Solid

White and Woods [1552] presented, in graphical form only, their experimental data, while calculations have been made by Benin [132, 133, 131] and Julian [696]. In addition, the [1552] values formed the basis for a book review graph [752]. Both sets of calculations are in fair agreement with the measurements above about 5 K. At lower temperatures, neither source predicts any thermal conductivity maximum. While the scatter of the White and Woods data from a smooth curve fit used here to generate the proposed values is above about ten percent or less for temperatures above 2 K, the Krupskii [791–2] values for other solid inert gases disagree by a much larger factor from the corresponding data of White and Woods. This was claimed by Krupskii as being due to impurity effects. Other effects may also be significant and a detailed experimental study is considered highly necessary to resolve the conflicts between the different data sets. Based upon the agreement for other inert solids, a twenty percent uncertainty above 5 K should be considered possible and values for lower temperatures are very uncertain.

Saturated Liquid

Only one set of experimental data was located for the thermal conductivity of saturated liquid neon, the measurements of Lochtermann [853]. These were compared with the correlation of Owens and Thodos [1058]. Severe disagreement is evident. The correlation predicted values are at least fifteen percent greater than the experimental data. In addition, the trend of the experimental data with temperature would predict a critical point of about 32 K, considerably below the accepted value. Surprisingly, no note of this fact was made in a recent review [362].

The procedure here adopted was to retain the correlation values for temperatures above 35 K and to fair these into the experimental values below about 27.5 K by drawing a smooth curve. While it is possible that the correlation values above 35 K are in error, no experimental evidence is available. New measurements are urgently required to resolve the anomalous trend in the only set of experimental data presently available and to confirm the correlation for higher temperatures. The uncertainty in the proposed values is probably about twenty percent below 35 K and can be as much as forty percent at the critical point.

Saturated Vapor

No experimental data were located for the thermal conductivity of saturated neon vapor. The correlation of Owens and Thodos [1058] was used and it was found that the value at the normal boiling point was eight percent lower than obtained from the atmospheric pressure thermal conductivity correlation. The values were therefore adjusted by amounts varying linearly with temperature, from eight percent at the boiling point to zero at the critical point.

In view of the complete lack of experimental data, no departure plot appears. An estimate of accuracy is difficult as quantum effects could become important at the lower temperatures and the correlation has neglected these. Tabular uncertainties of ten percent below 30 K, twenty percent at 40 K, and even forty percent at the critical point are probable. Experimentation to confirm the provisional values and error estimates is urgently required.

Gas

Major determinations of the thermal conductivity of gaseous neon have been reported by Kannuluik and Carman [705] from 90 to 579 K, by Keyes [747] from 91 to 273 K, by Zaitseva [1597] from 413 to 800 K, by Saxena and Saxena [1252] using the column method from 350 to 1500 K, and by Corriea and Schäfer [297] from 278 to 700 K, and indirectly by Collins and Menard [287] from about 500 to 5000 K. Other determinations, mainly at single temperatures, have been reported [113, 305, 319, 403, 705, 1356, 1405, 1517a, 1518], while some of these values and other values reproduced without source references are cited in [72, 257, 1355, 1499]. In addition, sets of calculated data from 60 to 200 K [54], 100 [433], 5000 K [1381], 89 to 598 K [839], and to 15 000 K [55] have appeared as well as numerous Russian correlations [1471, 1472, 1429, 273, 1473]. More recently, two analyses using potential functions have appeared [585, 743] as well as a standards publication [1474].

In this analysis the data of Kannuluik and Carman [705] were found to be represented, to within 2.5 percent, by the equation

$$k\ (\mathrm{mW\ cm^{-1}\ K^{-1}}) = 0.020568 + 2.28947 \cdot 10^{-3}\,T - 3.01160 \cdot 10^{-6}\,T^2 + 2.11782 \cdot 10^{-9}\,T^3,$$

which was used to generate the recommended values to 400 K. In the original tables [843, 1420, 608, 844], this formula was used to generate recommended values to 500 K and values at higher temperatures were selected to merge into the Collins and Menard values [287], which were then the only high temperature values available. More recent experimental and theoretical investigations indicate that the original tables were low by about one percent at 500 K, five percent at 1000 K, and possibly eight percent at 2000 K. Both the experimental [1252] and theoretical [743] work to 1500 K are in excellent agreement and were used as a basis for these tables above 400 K. Analysis indicated that between 400 and 1500 K, the thermal conductivity could be represented by a function varying as temperature to the power 0.659 and values computed from this function were adjusted to merge smoothly with those generated from the above equation and to pass through the mean of the [743, 1252] values at 1250 K. The function was then used to compute values to 2500 K.

In common with the previous formulation, the data of

Zaitseva [1597] appear high. Apparently this has influenced the formulations [273, 1473] and to a lesser extent, [1474], as well as [1417]. As for krypton, the trend of the Collins and Menard [287] values is lower than most experimental or theoretical estimates and this unsolved problem has limited the present formulation to 2500 K. Some evidence exists from the departure plot that the [287] values may be systematically low by about four percent. The recommended values are thought to be accurate to within two percent up to 400 K, the uncertainty increasing to about four percent at 1000 K, and ten percent at 2500 K.

TABLE 102. Recommended thermal conductivity of neon†

(Temperature, T, K; Thermal Conductivity, k, W $cm^{-1}K^{-1}$)

Solid		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		24	1.17		
1.0	7.3	26	1.15		
1.5	18.5	27	1.13	27	0.079*
2.0	29.5	28	1.12	28	0.082*
2.5	39.8	29	1.10	29	0.085*
3.0	45.7	30	1.08	30	0.089*
3.5	47.1	31	1.06	31	0.093*
4.0	44.0	32	1.04*	32	0.097*
4.5	39.3	33	1.02*	33	0.102*
5	33.6	34	0.99*	34	0.107*
6	24.5	35	0.96*	35	0.112*
7	17.0	36	0.92*	36	0.118*
8	13.0	37	0.88*	37	0.124*
9	10.2	38	0.84*	38	0.131*
10	8.4	39	0.79*	39	0.138*
12	6.0	40	0.73*	40	0.147*
14	4.5	41	0.67*	41	0.16*
16	3.7	42	0.61*	42	0.17*
18	3.1	43	0.54*	43	0.19*
20	2.7	44	0.33*‡	44	0.33*‡
22	2.3				
24	2.1				

†Values for the solid, saturated liquid above 35 K, and saturated vapor are provisional.
*Estimated or extrapolated.
‡Pseudo-critical value.

TABLE 102. Recommended thermal conductivity of neon—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas
(At 1 atm)

T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
27	0.079*	350	0.544	650	0.815	950	1.054
30	0.086*	360	0.553	660	0.824	960	1.061
35	0.097*	370	0.563	670	0.833	970	1.069
40	0.107*	380	0.572	680	0.842	980	1.076
45	0.117*	390	0.581	690	0.851	990	1.084
50	0.128*	400	0.590	700	0.861	1000	1.091
60	0.148*	410	0.600	710	0.870	1050	1.129
70	0.168*	420	0.609	720	0.879	1100	1.166
80	0.186	430	0.618	730	0.888	1150	1.202
90	0.204	440	0.628	740	0.897	1200	1.238
100	0.222	450	0.637	750	0.906	1250	1.273
110	0.239	460	0.647	760	0.914	1300	1.307
120	0.256	470	0.656	770	0.922	1350	1.340
130	0.272	480	0.666	780	0.929	1400	1.372
140	0.288	490	0.675	790	0.937	1450	1.404
150	0.303	500	0.685	800	0.945	1500	1.435
160	0.318	510	0.693	810	0.952	1550	1.467*
170	0.333	520	0.702	820	0.960	1600	1.499*
180	0.347	530	0.710	830	0.967	1650	1.530*
190	0.361	540	0.719	840	0.975	1700	1.561*
200	0.375	550	0.727	850	0.982	1750	1.590*
210	0.388	560	0.736	860	0.989	1800	1.618*
220	0.401	570	0.744	870	0.996	1850	1.648*
230	0.414	580	0.753	880	1.003	1900	1.673*
240	0.426	590	0.762	890	1.010	1950	1.700*
250	0.438	600	0.771	900	1.017	2000	1.727*
260	0.449	610	0.780	910	1.024	2100	1.79*
270	0.461	620	0.789	920	1.032	2200	1.84*
280	0.472	630	0.797	930	1.039	2300	1.90*
290	0.483	640	0.806	940	1.047	2400	1.95*
300	0.493					2500	2.00*
310	0.504						
320	0.514						
330	0.524						
340	0.534						

*Extrapolated or estimated.

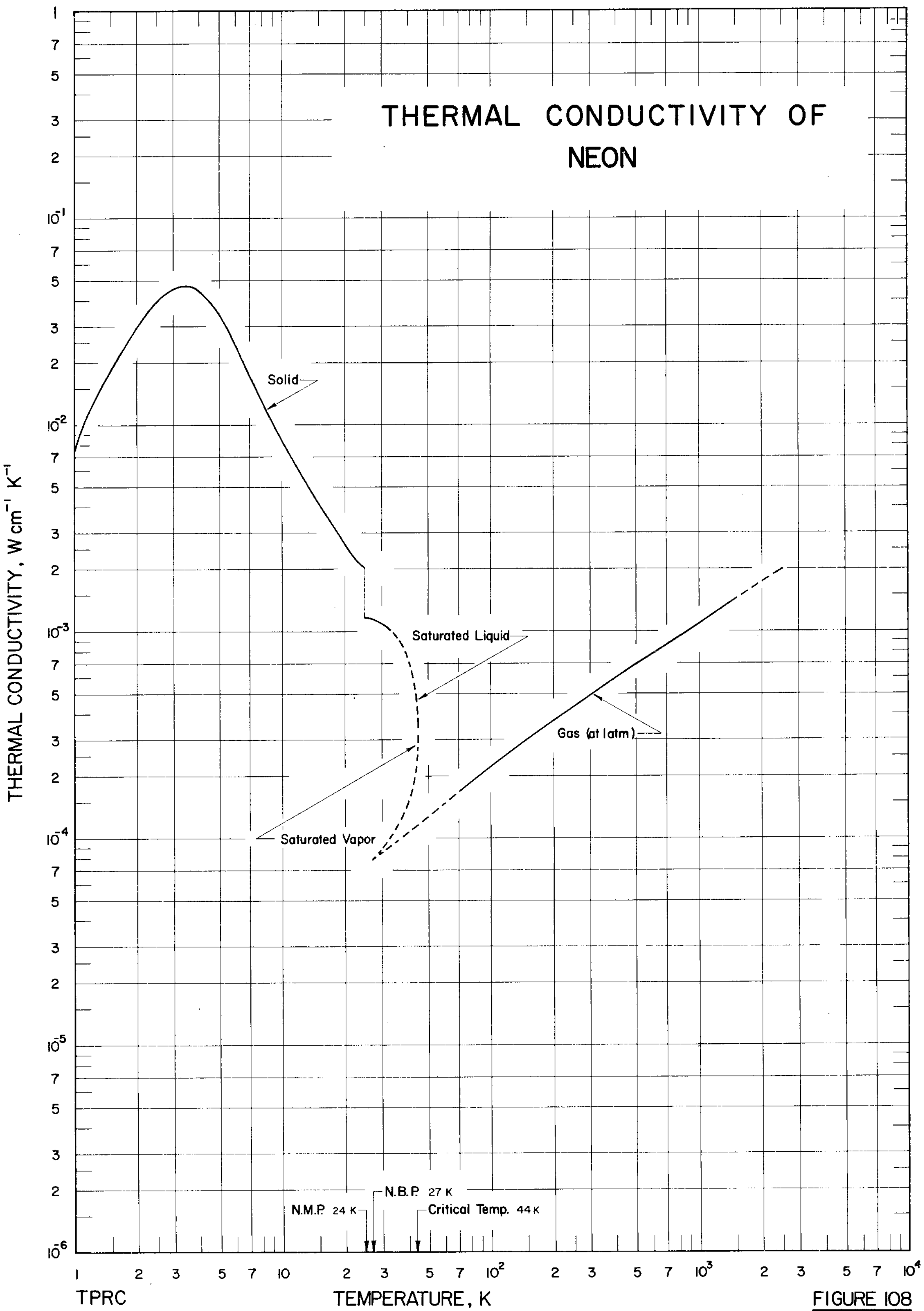

THERMAL CONDUCTIVITY OF NEON
Solid
Saturated Liquid
Saturated Vapor
Gas (at 1atm)
N.B.P. 27 K
N.M.P. 24 K
Critical Temp. 44 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 108

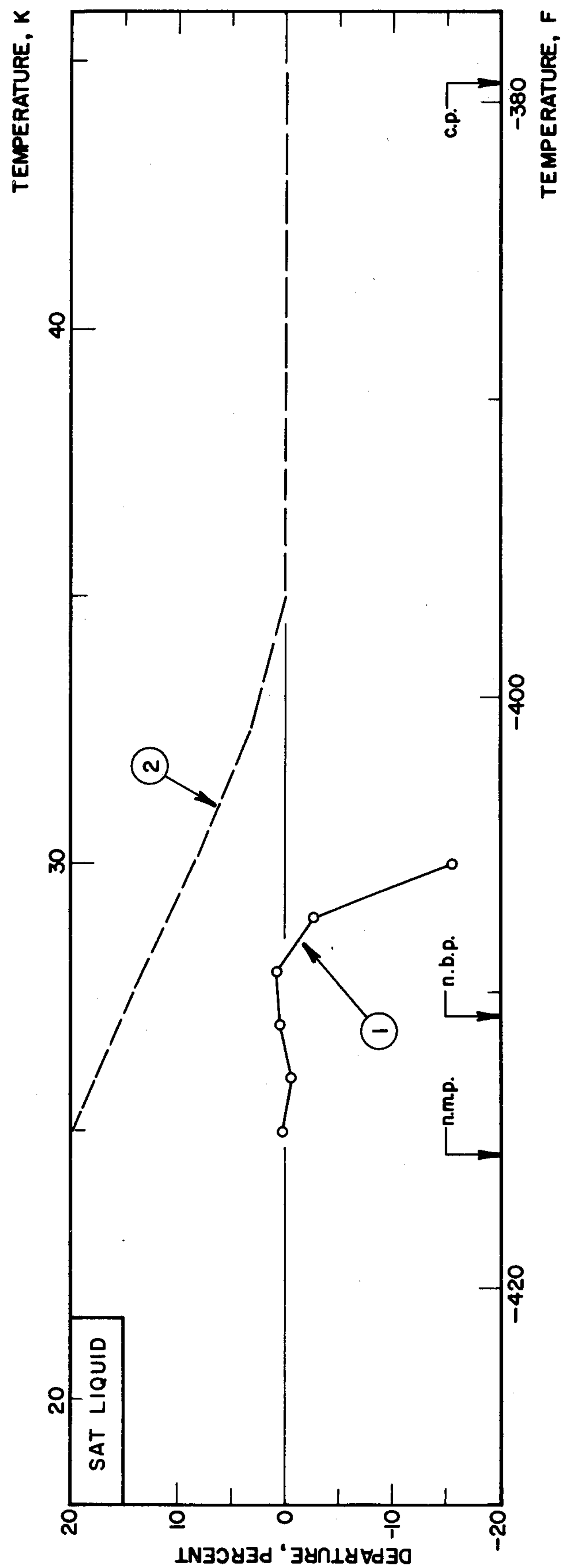
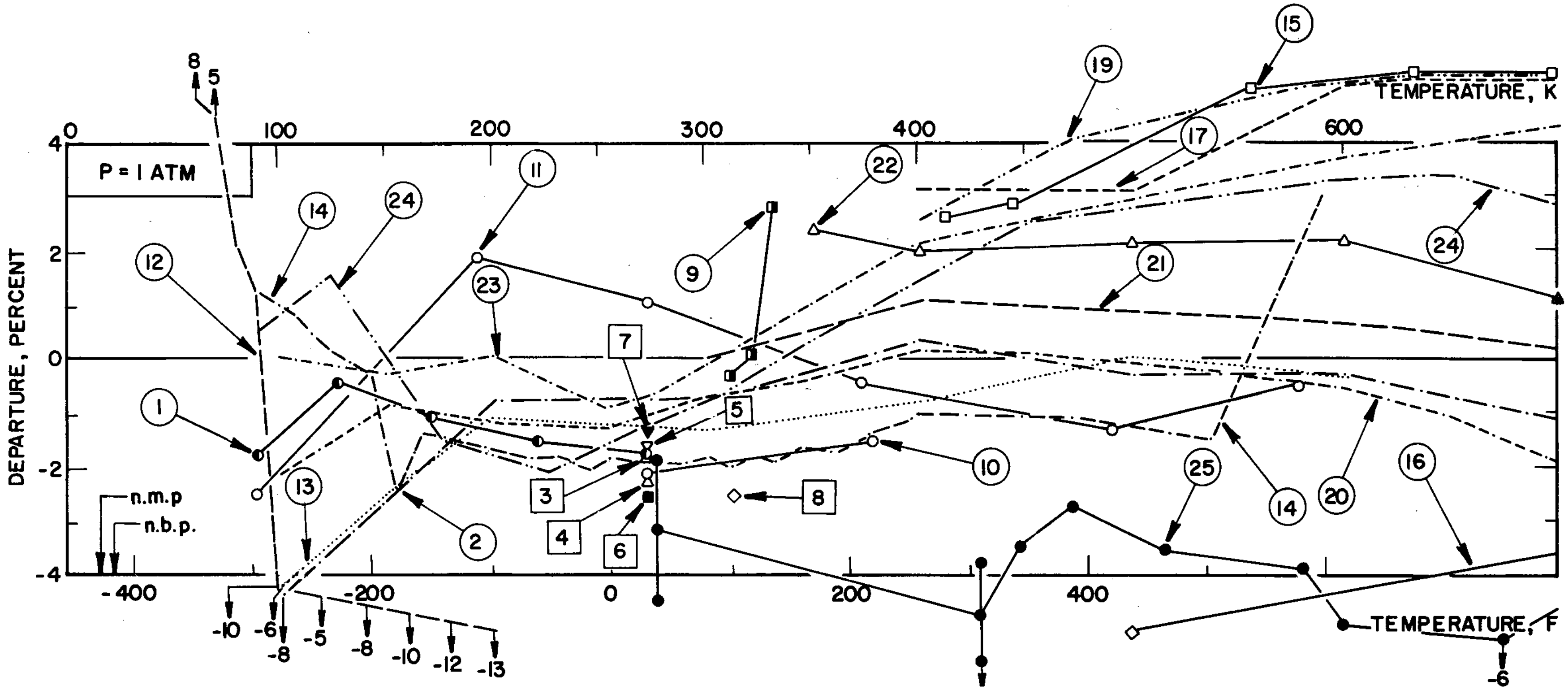


FIGURE 109. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID NEON

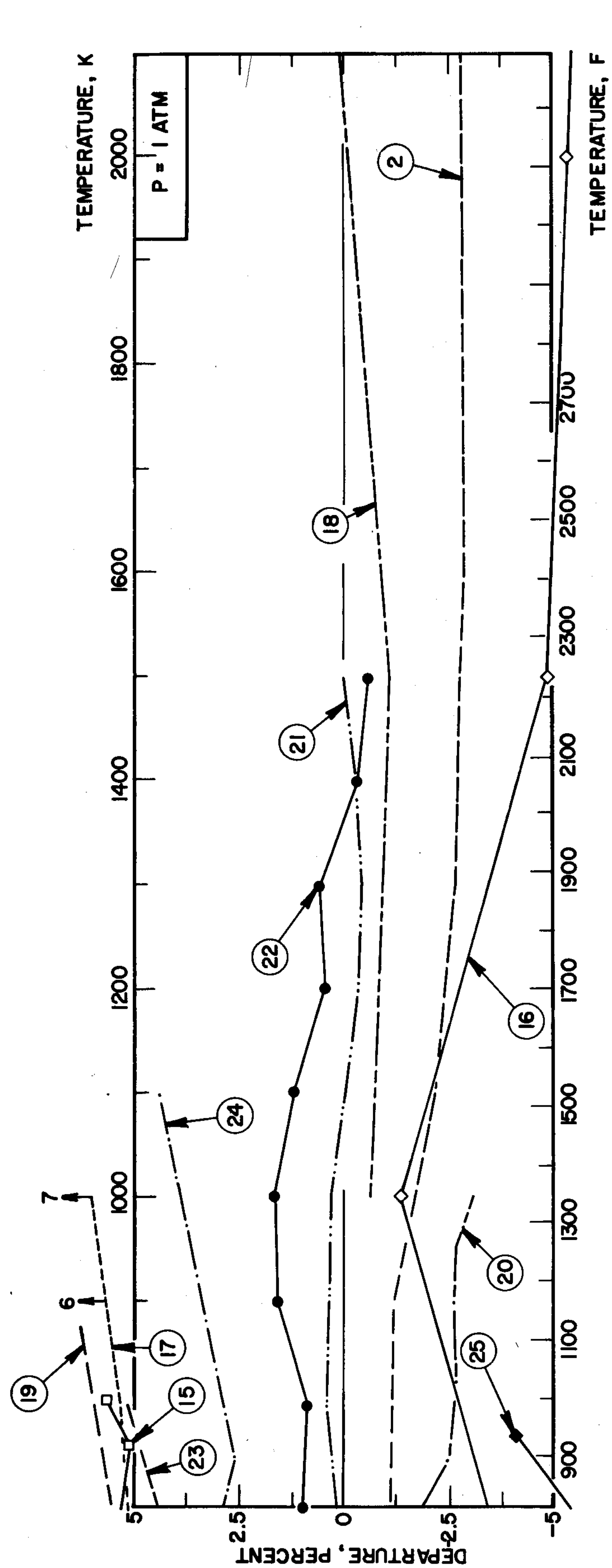
Curve	Reference
1	853
2	1058

FIGURE 110. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NEON



Curve	Reference	Curve	Reference	Curve	Reference
1	747	9	1405	17	1473
2	1381	10	1518	19	273
3	72	11	705	20	585
4	113	12	54	21	743
5	305	13	606,121a	22	1252
6	319	14	839	23	1417
7	403	15	1597	24	1474
8	1356	16	287	25	297

FIGURE 110. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NEON (continued)



Curve	Reference	Curve	Reference
2	1381	20	585
15	1597	21	743
16	287	22	1252
17	1473	23	1417
18	55	24	1474
19	273	25	297

Neptunium

Lee [826] in a report on the physical properties of neptunium includes a short paragraph which states: "The thermal conductivity of α-neptunium determined from resistivity measurements using Kannuluik's method was 0.01 ±0.001 cgs units at 300 K." No further details are given and this appears to be the only experimental information available for the thermal conductivity of neptunium. The same paper indicates the electrical resistivity to be 116.5 $\mu\Omega$ cm at 300 K, hence the derived value for the Lorenz function is 1.62×10^{-8} V^2 K^{-2}. A Lorenz function that is much lower than the theoretical value at a temperature nearly twice the Debye temperature of 163 K suggests that the foregoing thermal conductivity value could prove to be low, and an increase of at least 50 percent appears necessary. The calculated thermal conductivity is then 0.063 W cm^{-1} K^{-1} at 300 K and is probably good to within ±20 percent.

TABLE 103. Provisional thermal conductivity of neptunium†

(Temperature, T, K; Thermal Conductivity, k, W $cm^{-1}K^{-1}$)

Solid Polycrystalline	
T	k
300	0.063*

†The provisional value is for high-purity polycrystalline neptunium.
*Estimated.

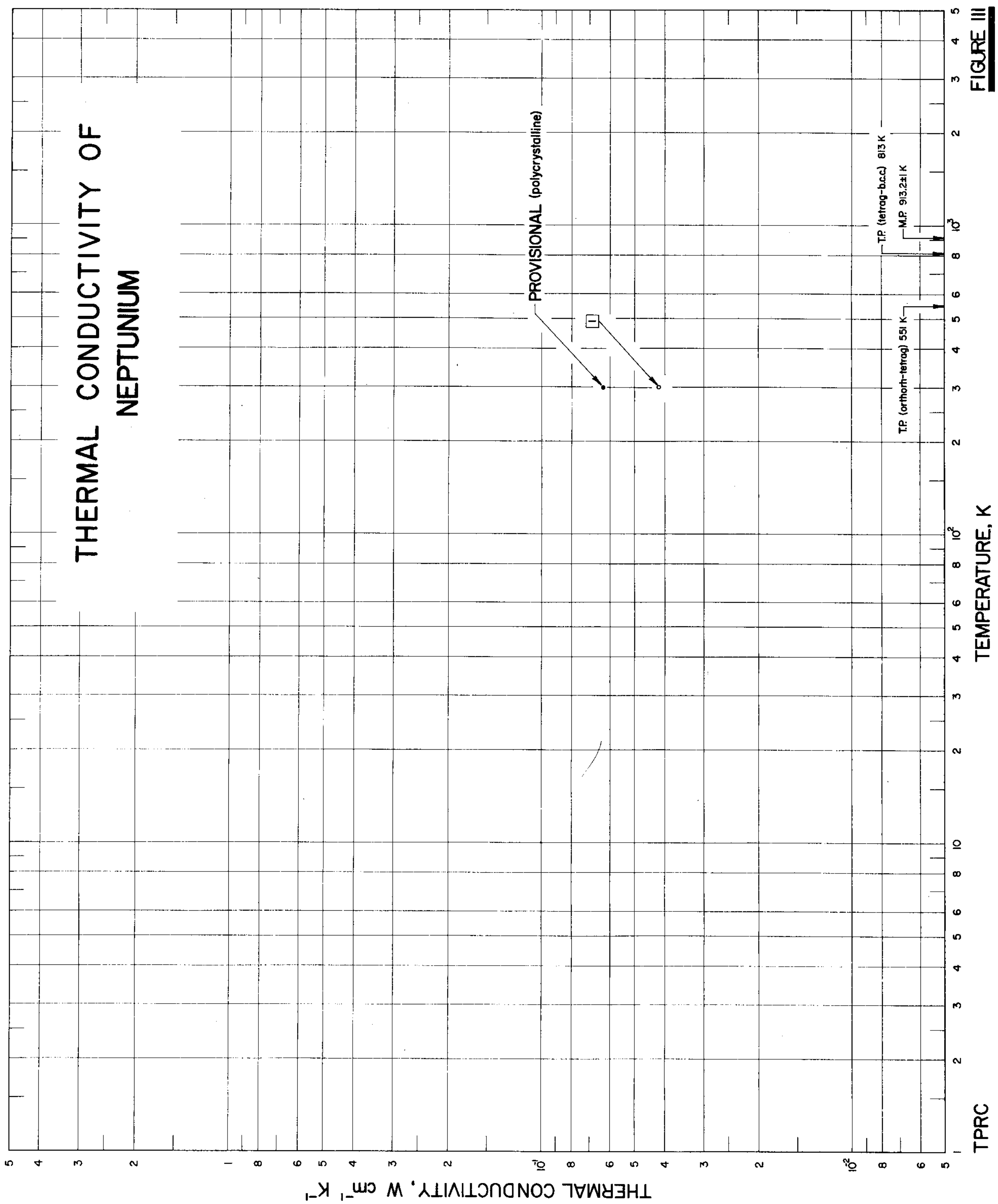

THERMAL CONDUCTIVITY OF NEPTUNIUM
PROVISIONAL (polycrystalline)
T.P. (tetrag-b.c.c.) 813 K
M.P. 913.2±1 K
T.P. (orthorh-tetrag) 551 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TPRC
FIGURE III

TABLE 104. THERMAL CONDUCTIVITY OF NEPTUNIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	826	Lee, J.A.	1961	E	300		Neptunium in α-phase; data determined from resistivity measurements using Kannuluik method; electrical resistivity reported as 116.4, 116.1, 117.7, 117.8, 119.1, 119.3, 120.5, 120.7, 120.9, 120.8, and 121.3 μ ohm cm at 310, 314, 334, 347, 370, 373, 425, 433, 472, 512, and 538 C, respectively.

Nickel

This examination of the available thermal conductivity data for nickel indicates both the need for further work and the interest likely to result from attempting to more fully understand the conduction processes involved. At cryogenic temperatures six curves are now available and that of White and Tainsh [1541], the highest, curve 53, has the maximum well displaced from the line which fits the other five. This departure from the simple correlation of Cezairliyan was believed by White and Tainsh [1541] and Herring [600] to be due to electron-electron interaction becoming important for the purest sample. Since the usual method for deriving a smooth curve fitting these results no longer holds, the curve for which recommended values are tabulated is based on the measurements of Farrell and Greig [421] (curve 65). The values below 1.5 T_m are calculated to fit the experimental data by using a β value of 0.460. This curve at low temperature is only applicable to a sample having $\rho_0 = 0.0112\ \mu\Omega$ cm.

Above 100 K the curve continues a few percent above the data of Bäcklund and Langemar [101] (curve 63) to reach room temperature just below the data of Spyra [1352] (curve 55), and follows closely the mean course of the curves of Shelton and Swanger [1302] (curve 3) and the highest (curve 25) of Powell, et al. [1138] to the Curie temperature. In this region a sharp minimum is shown, and the curve to about 1400 K is drawn as a straight line fitting the highest values (curve 28) of Powell, et al. [1138]. Their results indicated a Lorenz function of the order of 2.95×10^{-8} V^2 K^{-2} at this maximum temperature, which exceeds the value of Hopkins and Jones [633] by some 5 percent. These workers made a direct determination by using the necked-down-sample method.

The uncertainty of much of the recommended curve is thought to be about 10 percent. There also seems to be an increased dependence of the thermal conductivity on some factors other than impurity and imperfection throughout the range. The tendency observed in the case of iron, for instance, for data to converge at high temperatures towards a common value is absent for nickel for which the different curves tend to follow parallel courses.

No data are available for the thermal conductivity of liquid nickel, but Lebedev [821] does find the ratio ρ_L/ρ_S to be 1.3, and it is probable that the ratio for k_S/k_L also has a value of this order, or possibly rather greater as the thermal conductivity of the solid is augmented by a lattice component, and this may disappear on melting.

TABLE 105. Recommended thermal conductivity of nickel†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	0.975
1	2.17	273.2	0.941
2	4.34	298.2	0.909
3	6.49	300	0.907
4	8.59	323.2	0.880
5	10.6	350	0.850
6	12.5	373.2	0.827
7	14.2	400	0.802
8	15.8	473.2	0.741
9	17.1	500	0.722
10	18.1	573.2	0.673
11	18.9	600	0.656
12	19.4	630	0.639
13	19.7	673.2	0.648
14	19.7	700	0.654
15	19.5	773.2	0.670
16	19.1	800	0.676
18	18.1	873.2	0.693
20	16.5	900	0.697
25	12.6	973.2	0.712
30	9.56	1000	0.718
35	7.36	1073.2	0.734
40	5.82	1100	0.740
45	4.75	1173.2	0.756
50	4.00	1200	0.762
60	3.08	1273.2	0.777
70	2.50	1300	0.783
80	2.10	1373.2	0.798
90	1.83	1400	0.804
100	1.64	1473.2	0.820
123.2	1.37	1500	0.826
150	1.22		
173.2	1.13		
200	1.07		
223.2	1.02		

†The recommended values are for well-annealed high-purity nickel, and those below room temperature are applicable only to a specimen having residual electrical resistivity of 0.0112 $\mu\Omega$ cm.

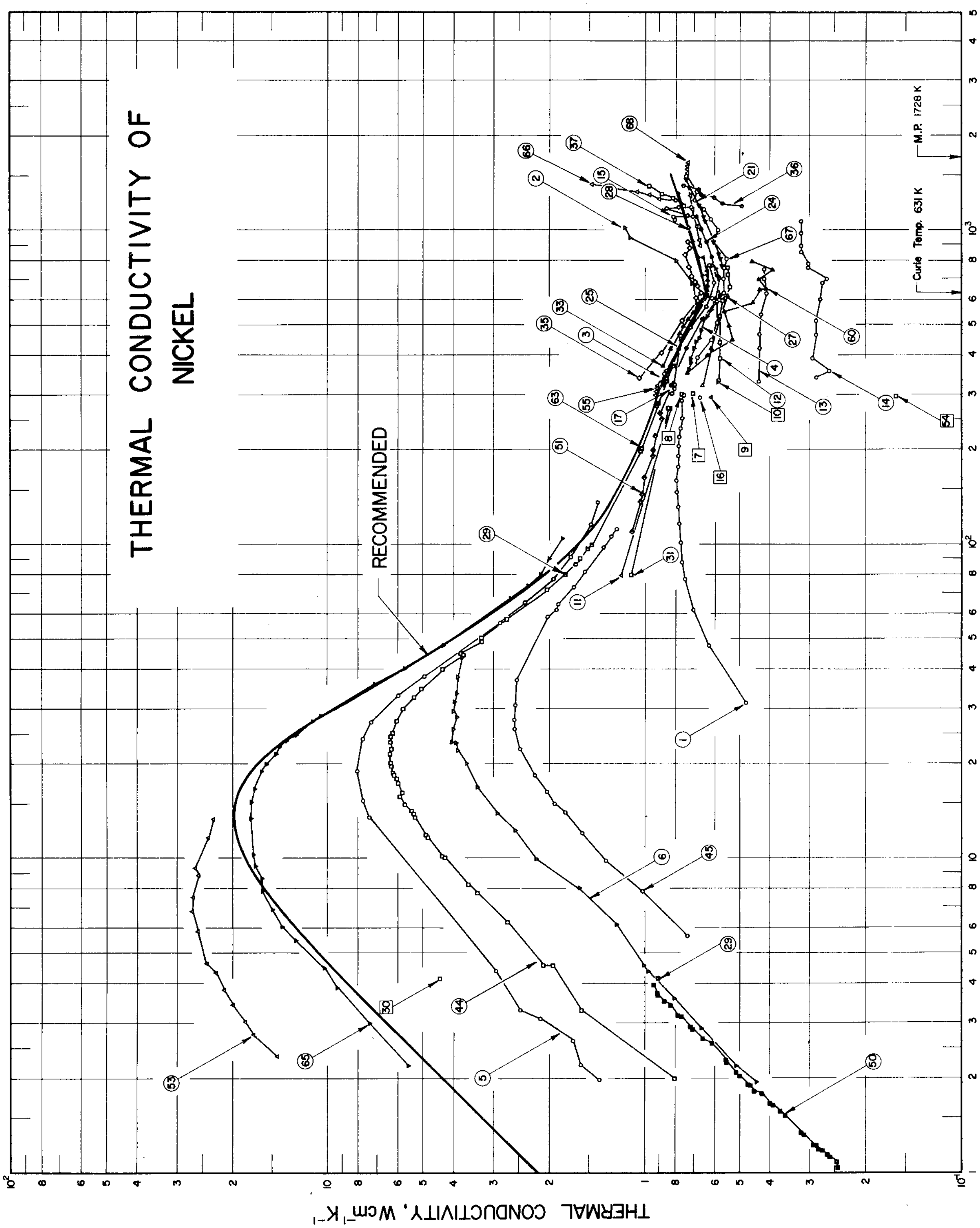

THERMAL CONDUCTIVITY OF NICKEL
RECOMMENDED
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TEMPERATURE, K
Curie Temp. 631 K
M.P. 1728 K
TPRC

FIGURE 112

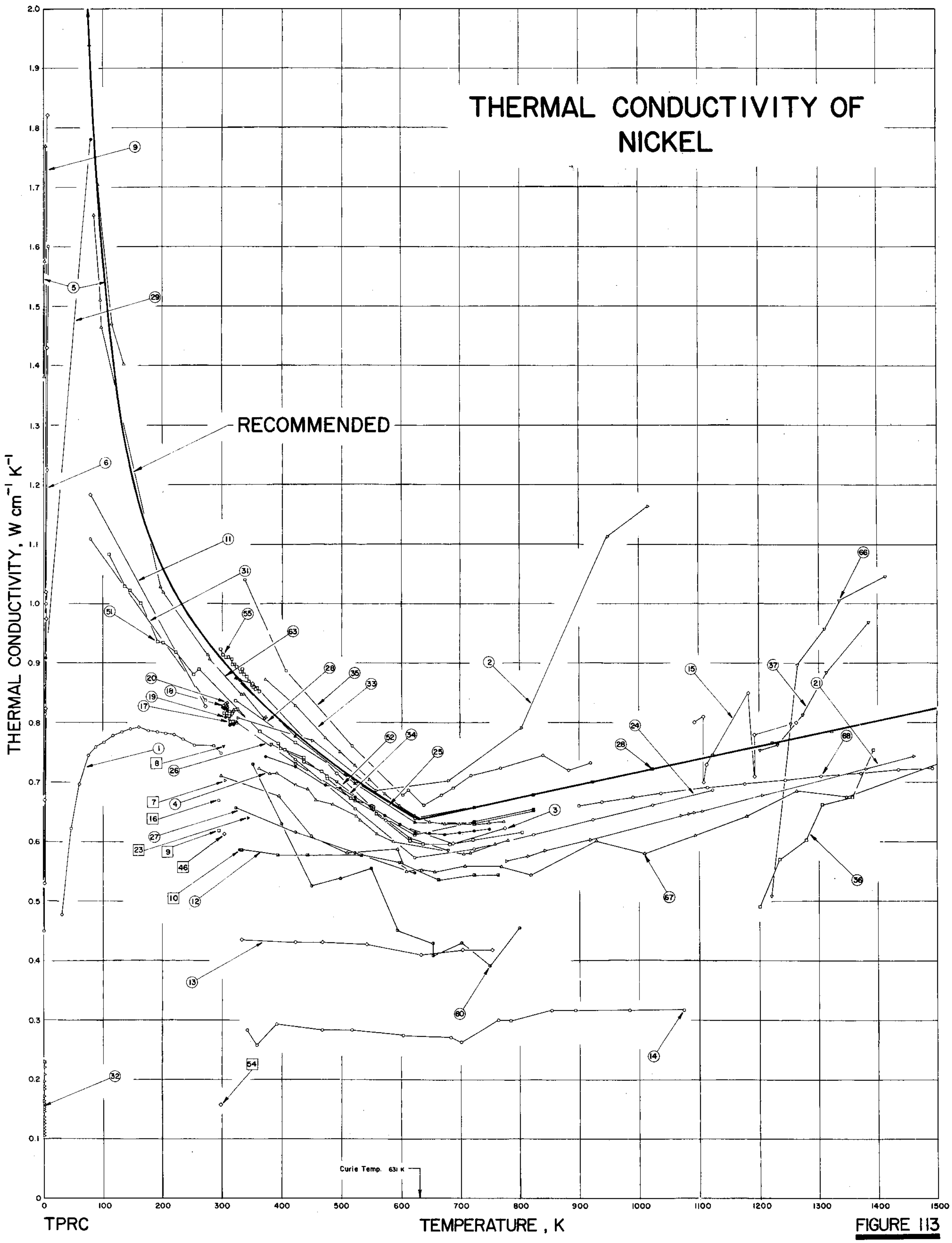

THERMAL CONDUCTIVITY OF
NICKEL
RECOMMENDED
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
Curie Temp. 631 K
TPRC

FIGURE 113

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1154	Powers, R.W., Schwartz, D., and Johnston, H.L.	1950	L	32-300	"L" nickel	Commercially pure; 0.5 in. dia x 20 in. long; supplied by International Nickel Co.
2	1234	Sager, G.F.	1930	P	327-1016		Pure nickel, electrolyzed from Mond anodes; wire, about 0.2 cm in dia; vacuum melted under a pressure of 0.3 mm Hg using an Arsen furnace and an alundum crucible; chill cast, forged, and cold drawn to the above dimensions, annealed twice at about 750 C for several hrs; electrical conductivity reported as 9.60, 5.95, 4.10, 3.03, 2.74, 2.47, and 2.32 x 10^4 ohm^{-1} cm^{-1} at 54, 179, 285, 407, 530, 676, and 743 C, respectively; density 8.74 g cm^{-3}; thermal conductivity values calculated from measured data of thermal diffusivity, specific heat, and density.
3	1302	Shelton, S.M. and Swanger, W.H.	1933	C	330-775	N_1	99.94 Ni, 0.03 Fe, 0.016 Co, 0.006 Cu, 0.006 Si, 0.005 C, and 0.004 S; specimen 2 cm in dia and 15 cm long; melted in Arsen furnace and furnace cooled; lead used as comparative material, reference value taken from International Critical Tables (Vol. V, p. 221).
4	1000	Moss, M.	1955	L	363-780		99.65 Ni (by difference), 0.094 Si, 0.082 Cu, 0.056 Fe, 0.027 C, 0.025 Co, 0.008 S, and 0.007 Al; specimen 7.938 in. long and 0.787 in. in dia; prepared in a zircon crucible from high purity electrolytic nickel shot, hot rolled at 1000 C to a bar 1 in. square, machined and ground to size; annealed for 45 min at 1000 C in hydrogen atmosphere.
5	738	Kemp, W.R.G., Klemens, P.G., and White, G.K.	1956	L	2.0-136	JM 4497	99.99^+ Ni, traces of Al, Ca, Cu, Si, Ag, and very faint traces of Li, Mg, and Na; material obtained from Johnson, Matthey, and Co.; specimen 2 mm in dia; annealed for 4 hrs in vacuo at 750 C; electrical resistivity 7.22 μohm cm at 293 K; residual electrical resistivity 0.0347 μohm cm.
6	1220	Rosenberg, H.M.	1955	L	2.0-44	JM 4884; Ni 1	99.997 pure; polycrystalline; specimen 2.92 cm long, 0.305 cm in dia; obtained from Johnson, Matthey and Co. (JM 4884); annealed at 1150 C for several hrs in vacuo; electrical resistivity ratio $\rho(293K)/\rho(20K) = 80.9$.
7	392	Ellis, W.C., Morgan, F.L., and Sager, G.F.	1928	P	305.2	R-12	Wire about 35 cm long, 0.32 cm in dia; electrical conductivity 9.66 x 10^4 ohm^{-1} cm^{-1} at approx. 32 C; thermal conductivity value calculated from measured data of thermal diffusivity and specific heat.
8	897	Masumoto, H.	1927	E	303.2		0.10 Fe, 0.037 C, 0.019 S, 0.013 Cu, 0.006 Si, traces of Al, Co, Mn, and P; specimen 20 cm long, 5 mm in dia; obtained from Mond and Co.; cast and machined, annealed for 40 min at 800 C; electrical resistivity 8.58 μohm cm at 30 C.
9	1359	Starr, C.	1937	P	298.2		99.98^+ pure; annealed in hydrogen at 870 C; density 8.79 g cm^{-3}; electrical resistivity 7.21 μohm cm at 22 C; thermal conductivity value calculated from measured data of thermal diffusivity, specific heat, and density.
10	1327	Smith, A.W.	1925	L	329.2	Electrolytic Nickel	99.75-99.85 pure; supplied by International Nickel Co. of America; electrical conductivity 8.24 x 10^4 ohm^{-1} cm^{-1}.
11	77	Aoyama, S. and Ito, T.	1940	C	80, 273		Specimen 60 mm long, 4 mm in dia; copper used as comparative material.
12	457	Francl, J. and Kingery, W.D.	1954	C	333-763	Nivac	Extremely pure; specimen 1 in. cube; supplied by the Vacuum Metal Corp; vacuum cast.

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	457	Francl, J. and Kingery, W. D.	1954	C	333–753		Similar to the above specimen but with cylindrical pores 0.146 cm in dia; porosity 9.8%.
14	457	Francl, J. and Kingery, W. D.	1954	C	343–1073		Similar to the above specimen but porosity 19.6%.
15	174	Bode, K. H.	1961	E	1093–1263	Nickel O	99.95 pure; wire 1 mm in dia; vacuum-melted and cast, polished, annealed for 12 hrs at ~1000 C.
16	1065	Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L.	1961	P	295.2		1.26 cm dia x 0.100 cm thick; thermal conductivity value calculated from measured data of thermal diffusivity and specific heat, and density value taken from Smithsonian Physical Tables (9th ed., 1954).
17	464	Fritz, W. and Bode, K. H.	1960	C	305–323		Specimen 20 mm in dia and 18 mm long; steel used as comparative material.
18	464	Fritz, W. and Bode, K. H.	1960	C	303–317		The above specimen using pure Ni as comparative material.
19	464	Fritz, W. and Bode, K. H.	1960	C	302–320		The above specimen using yellow brass as a comparative material.
20	464	Fritz, W. and Bode, K. H.	1960	C	305–321		The above specimen using Al as comparative material.
21	181	Booker, J., Paine, R. M., and Stonehouse, A. J.	1961	R	778–1462	"L" nickel	Specimen consisted of 5 vertically stacked hollow cylinders, each 2.625 in. O. D. and 1 in. high, and having a 0.25 in. bore concentric with the axis.
22*	223	Burger, R., Dittrich, H., and Koch, K. M.	1968	C	316.2		99.98 pure; measured in transverse magnetic fields ranging from 0.66 to 11.17 kOe.
23	223	Burger, R., et al.	1968	C	316.2		The above specimen measured in longitudinal magnetic fields ranging from 0.14 to 11.18 kOe.
24	1138	Powell, R. W., Tye, R. P., and Hickman, M. J.	1965	L, C	323–1123	Electrolytic nickel; sample 1	<0.03 Fe, <0.01 each of Al, Cr, Co, Cu, Mg, Mn, Mo, Si, Sn, Ti, Zn, and Zr, <0.005 Pb, and <0.002 B; supplied by the Castner Kellner Alkali Co.; tube of 1.272 cm I. D., 1.908 cm O. D. and 20 cm long; density 8.61 g cm^{-3}; electrical resistivity reported as 7.1, 8.3, 13.0, 19.4, 28.0, 32.8, 36.1, 39.3, 42.4, and 45.2 μohm cm at 293, 323, 423, 523, 623, 723, 823, 923, 1023, and 1123 K, respectively; Armco iron used as comparative material; data taken from smoothed curve.
25	1138	Powell, R. W., Tye, R. P., and Hickman, M. J.	1965	L, C	323–823	Electrolytic nickel; sample 2	Very high purity; supplied by the National Engineering Lab; tube with 0.634 cm I. D., 2.801 cm O. D., and 19 cm long; density 8.90 g cm^{-3}; electrical resistivity reported as 10.6, 18.5, 20.7, and 33.2 μohm cm at 100, 260, 290, and 500 C, respectively; Armco iron used as comparative material; data taken from smoothed curve.
26	1138	Powell, R. W., et al.	1965	L, C	323–823	Nickel; sample 3	99.5±0.1 Ni, 0.1–0.2 Co, 0.1–0.2 Si, 0.04 Fe, 0.03 Mg, and 0.01 Cr; supplied by the Atomic Energy Research Establishment in the form of 3 tubes of 1.589 cm O. D., 1.538 cm I. D., and about 43 cm long; 32 strips each 0.95 cm wide and 14 cm long cut from the tubes and pressed together to form a compact specimen; density 8.9 g cm^{-3}; electrical resistivity reported as 8.3, 9.6, 14.3, 20.6, 29.7, 34.1, and 37.3 μohm cm at 293, 323, 423, 523, 623, 723, and 823 K, respectively; Armco iron used as comparative material; data taken from smoothed curve.

*Not shown in figure.

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
27	1138	Powell, R. W., Tye, R. P., and Hickman, M. J.	1965	L, C	323-623	Nickel; sample 4	Commercial nickel; rod specimen 2.54 cm in dia, about 20 cm long; supplied by the Explosives Research and Development Establishment; electrical resistivity reported as 10.1, 11.3, 16.3, 22.8, and 31.5 μohm cm at 293, 323, 423, 523, and 623 K, respectively; Armco iron used as comparative material; data taken from smoothed curve.
28	1138	Powell, R. W., et al.	1965	L, C	323-1323	Nickel; sample 5	High spectrographic purity; very small impurities of Al, Ca, Cu, Li, Mg, Si, Ag, and Na; supplied by Messrs. Johnson, Matthey and Co., Ltd. (Lab. No. 4497); rod 0.5 cm in dia and 15 cm long; density 8.91 g cm^{-3}; electrical resistivity reported as 7.1, 8.3, 13.1, 19.4, 28.3, 33.2, 36.4, 39.2, 42.1, 44.7, 47.5, and 49.8 μohm cm at 293, 323, 423, 523, 623, 723, 823, 923, 1023, 1123, 1223, and 1323, respectively; Armco iron used as comparative material; data taken from smoothed curve.
29	136	Berger, L. and Rivier, D.	1962	L	4.2, 81	Ni 5011 (I)	Specimen 0.15 cm in dia turned from a cylindrical sample 5.2 cm long; supplied by Messrs. Johnson, Matthey and Co., Ltd.; annealed for 4 hrs at 1273 K in a vacuum of 10^{-5} mm Hg, then furnace cooled at a rate of 150 K per hr; electrical resistivity reported as 0.11, 0.676, and 7.16 μohm cm at 4.18, 80.5, and 292 K, respectively; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 60$.
30	136	Berger, L. and Rivier, D.	1962	L	4.18	Ni 5011 (II)	Specimen 0.19 cm in dia drawn from a cylindrical sample 5.0 cm long; supplied by Messrs. Johnson, Matthey and Co., Ltd.; annealed for 10 hrs at 1573 K in hydrogen and left at 1573 K in a vacuum of 10^{-2} mm Hg for 2 hrs; electrical resistivity reported as 0.0213, 0.60, and 6.35 μohm cm at 4.18, 80.5, and 273.15 K, respectively; $\rho(273K)/\rho(4.2K) = 298$.
31	404	Eucken, A. and Dittrich, K.	1927	L	80, 273	Electrolytic nickel	Electrical conductivity reported as 90.2 and 13.05 x 10^4 ohm^{-1} cm^{-1} at 80 and 273 K, respectively.
32	939	Mendelssohn, K., Sharma, J. K. N., and Yoshida, I.	1965	L	0.42-0.95		Pure.
33	1019	Neimark, B. E. and Bykova, T. I.	1965	E	373-773	No. 1	99.87 Ni + Co; tube 8.51 mm O.D. and 8.025 mm I.D.; electrical resistivity reported as 7.90, 9.30, 11.50, 17.24, 24.70, 31.84, and 35.36 μohm cm at 20, 50, 100, 200, 300, 400, and 500 C, respectively.
34	1019	Neimark, B. E. and Bykova, T. I.	1965	E	373-748	No. 2	Tube 12.96 mm O.D. and 11.025 mm I.D.; electrical resistivity reported as 11.60, 17.29, 24.74, 32.01, and 33.98 μohm cm at 100, 200, 300, 400, and 475 C, respectively.
35	763	Kirichenko, P. I. and Mikryukov, V. E.	1964	E	340-920		99.999 pure; specimen 30 cm long and 0.3 cm in dia; annealed in vacuum for 48 hrs at 1173 K; electrical resistivity reported as 8.0, 11.5, 17.0, 24.5, 29.0, 35.0, 38.5, 42.0, 44.0, and 46.0 μohm cm at 40, 105, 210, 305, 375, 485, 590, 720, 780, and 900 K, respectively.
36	669	Jain, S. C., Goel, T. C., and Chandra, I.	1967	E	1201-1393		99.95 pure; 14 cm x 1 cm x 0.05 cm; obtained from Johnson, Matthey and Co.; electrical resistivity 49.2, 49.8, 51.1, 52.2, 53.5, and 54.4 μohm cm at 1170, 1198, 1232, 1278, 1312, and 1360 K, respectively; data obtained without heating the ends of the specimen.

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
37	669	Jain, S.C., Goel, T.C., and Chandra, I.	1967	E	1202-1386		99.95 pure; 14 cm x 1 cm x 0.05 cm; obtained from Johnson, Matthey and Co.; measuring technique improved by heating the ends of the specimen.
38*	1382	Swift, D.L.	1966	P	298.2		Spherical granular specimen supplied by Linde Co. contained in a 0.75 in. dia x 2 in. long cylindrical cell; mesh size -230 +325; thermal conductivity measured by the transient line source method, measured in Freon-12 under a pressure of ~100 psig.
39*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in argon under a pressure of ~100 psig.
40*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in nitrogen under a pressure of ~100 psig.
41*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in methane under a pressure of ~100 psig.
42*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in helium under a pressure of ~100 psig.
43*	1382	Swift, D.L.	1966	P	298.2		Similar to above; measured in hydrogen under a pressure of ~100 psig.
44	533	Greig, D. and Harrison, J.P.	1965	E	2.0-90	A	0.0016 impurities (mostly Fe and Si); polycrystalline; 2 mm in dia; obtained from Johnson, Matthey and Co.; annealed for 12 hrs at 850 C; electrical resistivity 0.05230, 0.05290, 0.05544, 0.05695, 0.06132, 0.06845, 0.09794, and 0.1236 μohm cm at 3.5, 8.1, 13.4, 16.1, 20.1, 26.7, 34.4, and 40.0 K, respectively; residual electrical resistivity 0.0517 μohm cm.
45	533	Greig, D. and Harrison, J.P.	1965	E	5.7-114	B	0.13 Cu; specimen 4 mm in dia; supplied by Johnson, Matthey and Co.; chill cast from J.M. 890 Ni and J.M. 30 Cu; annealed for 12 hrs at 850 C.
46	392	Ellis, W.C., Morgan, F.L., and Sager, G.F.	1928	P	305.2	A nickel	0.25 cm dia x 35 cm long; density 8.90 g cm^{-3}; thermal conductivity value calculated from measured data of thermal diffusivity, specific heat, and density.
47*	1325	Smirnov, E.V., Muchnik, G.F., and Shklyarevskii, E.E.	1967	L	547-1243		Traces Mg, Mn, Si, and Cu; specimen 1.30-1.35 mm thick; thin metal layer depositing done by electro-air metallization; porosity 18%.
48*	1325	Smirnov, E.V., et al.	1967	L	647-1154		Traces Mg, Mn, Si, and Cu; specimen 1.60-1.70 mm thick; thin metal layer depositing done by plasma metallization; porosity 13%.
49*	1299	Sharma, J.K.N.	1967	L	0.42-0.93	Run 26	99.995 pure; polycrystalline wire specimen; supplied by Johnson, Matthey and Co. (Lb. No. 37043); form factor $(\ell/a) = 2.88 \times 10^3$ cm^{-1}; electrical resistivity 0.1044 μohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 100$; anomalous peak occurred at 0.72 K.
50	1299	Sharma, J.K.N.	1967	L	1.0-4.0		Obtained from the same batch as the above specimen.
51	1508	Watson, T.W. and Robinson, H.E.	1964	L	110-803		99.85 Ni, 0.11 Co, 0.026 Cu, 0.006 Fe, 0.001 Al, <0.004 Si, <0.002 Ti, <0.001 Mg, <0.001 Cr, and <0.0005 Mn; specimen 2.54 cm in dia and 37.0 cm long; electrical resistivity 2.0, 2.7, 3.5, 3.5, 4.6, 4.8, 5.5, 6.6, 6.9, 9.7, 10.8, 13.0, 12.7, 13.1, 14.5, 17.1, 17.4, 20.0, 22.2, 22.8, 29.7, 32.3, 33.4, and 36.8 μohm cm at -163, -135, -126, -109, -79, -70, -48, -17, -8, 54, 90, 122, 126, 132, 165, 196, 206, 244, 281, 286, 364, 410, 448, and 530 C, respectively.
52	1508	Watson, T.W. and Robinson, H.E.	1964	L	383-682		The above specimen measured with decreasing temp; electrical resistivity 11.9, 15.0, 18.0, 22.6, 27.7, and 32.7 μohm cm at 111, 165, 220, 278, 342, and 407 C, respectively.

* Not shown in figure.

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
53	1541	White, G.K. and Tainsh, R.J.	1967		2.3–13		Specimen 0.1 x 0.1 x 7 cm; prepared by Albano, V.J. and Soden, R. at Bell Telephone Laboratories; annealed at 500 C in vacuum of 10^{-7} torr; electrical resistivity ratio $\rho(273K)/\rho(4K) \approx 2500$; electrical resistivity 0.00329, 0.00339, 0.00346, 0.00366, 0.00377, 0.00417, 0.00476, 0.00553, 0.00780, and 0.00859 μohm cm at 2.32, 2.97, 3.24, 3.83, 4.36, 5.72, 7.31, 9.12, 13.1, and 14.1 K, respectively.
54	1532	Wheeler, H.L., Jr.	1948	R	298.2		Porous specimen; thermal conductivity value reported as the average of 4 measurements.
55	1352, 1353	Spyra, W.	1962	L	299–364		99.90 Ni, 0.04 Cu, 0.018 Al, 0.012 S, 0.01 C, <0.01 Fe, 0.007 N, and traces of Mo, P, and Si; cylindrical specimen; obtained from the vacuum melting plant at Hanau.
56*	135	Berger, L.	1960	L	4.2	Ni 5011	The same specimen as reported in curve No. 29; electrical resistivity 0.0011 and 0.00676 μohm cm at 4.2 and 80 K, respectively; measured in parallel magnetic fields ranging from 0.017 to 0.189 V sec m^{-2}.
57*	135	Berger, L.	1960	L	80	Ni 5011	The above specimen measured in parallel magnetic fields ranging from 0.009 to 0.171 V sec m^{-2}.
58*	135	Berger, L.	1960	L	4.2	Ni 5011	The above specimen measured in transverse magnetic fields ranging from 0.19 to 2.00 V sec m^{-2}.
59*	135	Berger, L.	1960	L	80	Ni 5011	The above specimen measured in transverse magnetic fields ranging from 0.15 to 2.12 V sec m^{-2}.
60	692	Jones, L.V. and Wittenberg, L.J.	1968	P	352–799		Cylindrical specimen; measured by a transient method.
61*	391	El-Darwish, A.S.	1958	P	295.8		Pure; 40 mm dia x 40 mm high; thermal conductivity value calculated from measured thermal diffusivity by using the values of density 8.870 g cm^{-3} and specific heat capacity 0.109 cal g^{-1} C^{-1}.
62*	320	Davis, M., Densem, P.C.E., and Rendall, J.H.	1955	→	423.2		0.07 C, 0.016 Si, 0.013 Fe, 0.01–0.2 O, 0.003 S, 0.0005 Mn, and 0.0003 Mg; prepared from grade A carbonyl nickel powder; supplied by the Mond Nickel Co., Ltd.; annealed, density 8.9 g cm^{-3}; electrical resistivity 6.8, 44, and 49 μohm cm at 20, 800, and 1000 C, respectively; Curie point 353 C; thermal conductivity value calculated from electrical resistivity data by the method of Fine, M.E. (Trans. Amer. Inst. Min. Met. Eng., 188, 951, 1950).
63	101	Bäcklund, N.G. and Langemar, K.T.	1967	L	87–374		Bar shaped specimen 0.5 cm in dia and 10 cm long; received from Johnson, Matthey and Co.; electrical resistivity 7.26 μohm cm at 295.3 K; density 8.92 g cm^{-3}.
64*	1245	Saunders, N.H.	1969		323–673		99.9989^{+} Ni, 0.0003 Fe, 0.0002 Mg, 0.0002 Si, 0.0001 Ag, and <0.0001 each of Al, Ca, and Cu; supplied by Johnson, Matthey and Co.; annealed in vacuum at ~900 C for 16 hrs; electrical resistivity 7.00, 8.22, 10.48, 13.00, 15.86, 19.16, 23.03, 27.86, and 31.18 μohm cm at 20, 50, 100, 150, 200, 250, 300, 350, and 400 C, respectively.

* Not shown in figure.

TABLE 106. THERMAL CONDUCTIVITY OF NICKEL - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
65	421	Farrell, T. and Greig, D.	1969	L	2.2-104		Polycrystalline; ~3 mm dia x 9 cm long; obtained from Metals Research Ltd.; zone-refined; annealed at 850 C for 15 hrs; electrical resistivity 6.31 μohm cm at 0 C; residual electrical resistivity 0.0095 μohm cm.
66	1436	Tyagi, R. C. and Mathur, R. S.	1970	E	1220-1413		High purity; cut from a sheet 0.5 mm thick and ~1.0 mm wide at the centre in a form of a butterfly of angle ~5°; supplied by Johnson and Matthey and Co.; measured in vacuo.
67	393	Emery, A. F. and Smith, J. R.	1968	P	300-1507	Nickel 200	Commercially pure; 0.5 in. in dia; thermal conductivity values calculated from measured thermal diffusivity and specific heat.
68	1616	Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V.	1968	P	900-1664		99.95 pure; 8 x 8 x 0.209 mm; machined from a rolled band; annealed in vacuum at 1200 K for 5 hrs; electrical resistivity ratio $\rho(298K/\rho(4.2K) = 80$; thermal conductivity values calculated from measured thermal diffusivity using the specific heat capacity data taken from Vollmer, O., et al. (Z. Naturforsch, 21a (1/2), 181, 1967) and the density values taken from Bozorth, R. M. ("Ferromagnetism," Van Nostrand, New York, p. 735, 1951).

Niobium

Niobium becomes superconducting at a higher temperature than that of any other element except technetium. This no doubt helps to account for the high proportion of thermal conductivity determinations on niobium that relate to the superconducting state. The highest values so far obtained in the superconducting region are due to Carlson [235] (curve 76) for a single crystal for which $\rho_{300}/\rho_{4.2} = 196$. By applying an appropriate magnetic field he has obtained thermal conductivity values for the normal state over the temperature range of 0.32 to 15 K. His values are much higher than those of Mendelssohn [233, 930] (curve 22) for a zone-refined 99.999+ percent pure single crystal. The purity of the last-mentioned sample seems questionable. The curve for which recommended values are tabulated is based on Carlson's data for the normal state. The values below about 1.5 T_m are calculated to fit the experimental data by using equation (7) and using the constants m, n, and α'' given in table 1 and a value of 2.78 for β. His sample is rather impure and the low-temperature values are only applicable to niobium in the normal state having $\rho_0 = 0.0679\ \mu\Omega$ cm. Niobium is a metal that readily takes up gaseous impurities at high temperature, even from a relatively good vacuum, and improved preparation techniques will probably yield samples of higher purity.

Only the measurements by Merisov, et al. [941] (curve 56) span the region 90 to 273 K for which almost constant values are obtained. Hence niobium is another example of a metal with a minimum in this region which is consistent with the steady increase in thermal conductivity shown by all determinations to higher temperatures.

The continuation of the low-temperature recommended curve shows such a minimum but is located a few percent above the values of Merisov, et al. The values in the range of approximately 323 to 873 K comprise six sets of measurements that differ by about 20 percent with the lowest of these measurements continuing to 1910 K. The recommended curve for moderate and high temperatures follows data by Raag and Kowger [1163] (curve 2) which lie in the higher section of this group of values. These workers determined the thermal diffusivity of a 99.95 percent niobium rod over the range 345 to 1195 K. They claimed an accuracy of ± 2 percent and, to derive thermal conductivity, made use of the specific heat data of Jaeger and Veenstra [666]. This is certainly regarded as the most acceptable of the available specific heat data. Raag and Kowger also measured the electrical resistivity and obtained values of the Lorenz function that increase from 2.73×10^{-8} V^2 K^{-2} at 300 K to 2.77×10^{-8} V^2 K^{-2} at 1200 K, and for the lower two thirds of this range are in reasonable agreement with the data of Bell and Tottle [126, 1419] (curve 27). The recommended curve has been drawn as a straight line through the thermal conductivity data so derived by Raag and Kowger.

At still higher temperatures, five sets of data are available. All are lower than the normal extension of the present curve, but this difference could be due in part to the low purity of the samples studied. The values of Neimark and Voronin [1020] (curve 68), who used Bode's method for a sample containing 0.3 percent Ta were from 7 to 10 percent lower over the range 1400 to 1940 K. They obtained a Lorenz function of 2.62×10^{-8} V^2 K^{-2} at the maximum temperature and their measurements are in fair accord with the recommended curve. The radial heat flow thermal conductivity determinations of Fieldhouse, Hedge, and Lang [426] (curve 3) lie on a linear curve which is about 14 and 11 percent below the recommended curve at 1200 and 1900 K, respectively. Those of Voskresenskii, Peletskii, and Timrot [1493] (curve 51) are within 2 percent of the curve of Fieldhouse, et al., whilst the thermal conductivity values deduced from the thermal diffusivity data of Kraev and Stel'makh [782 (curve 80) and 783 (curve 55)] are lower than those of Fieldhouse, et al. by 6 percent at 1800 K.

The two points at 1660 K were reported by Filippov and Makarenko [436] (curves 81 and 82) for the same sample. Both were obtained from variable-state methods. In one instance the periodic heating was by alternating electronic heating and in the other by induction heating. The recommended curve is close to the higher value. It is interesting that these two methods yielded values for the specific heat of 7.93 and 7.39 cal (g atom)$^{-1}$ K^{-1}, which were respectively about 2 and 9 percent greater than the value used when treating the thermal diffusivity data of Kraev and Stel'makh. This emphasizes the uncertainty of such derivations and the curve derived from Kraev and Stel'makh's data would be still lower had the Filippov and Makarenko's specific heat values been used. In the variable state method of Filippov and Makarenko the thermal conductivity was experimentally determined.

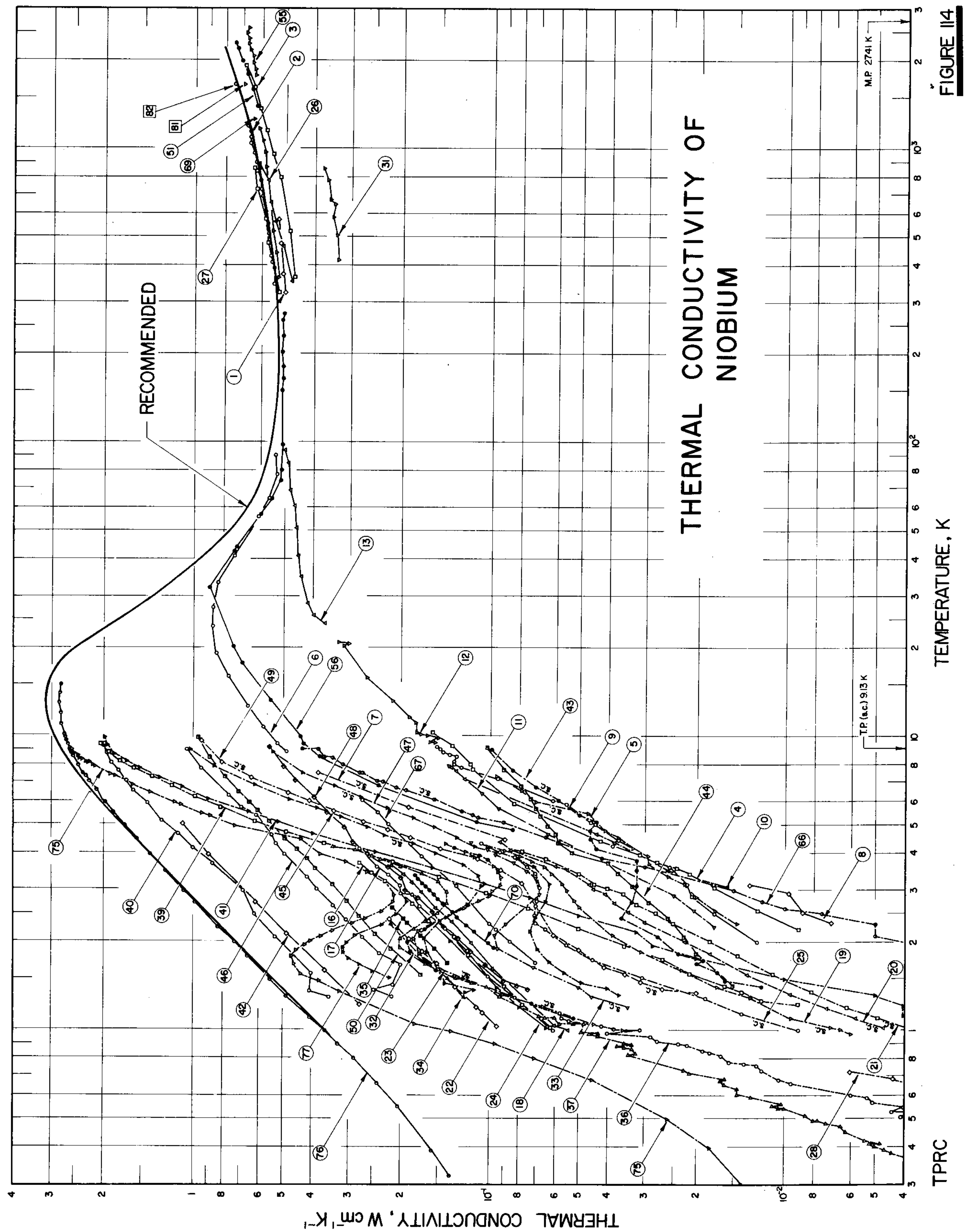
The recommended values are thought to be accurate to within ± 5 to ± 10 percent at moderate temperatures and ± 15 percent at low and high temperatures. The values below 150 K are of course only for niobium in the normal state having $\rho_0 = 0.0679\ \mu\Omega$ cm.

TABLE 107. Recommended thermal conductivity of niobium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	350	0.544
1	0.360	373.2	0.548
2	0.718	400	0.552
3	1.07	473.2	0.563
4	1.42	500	0.567
5	1.75	573.2	0.578
6	2.06	600	0.582
7	2.34	673.2	0.594
8	2.58	700	0.598
9	2.78	773.2	0.609
10	2.94	800	0.613
11	3.05	873.2	0.625
12	3.11	900	0.629
13	3.14	973.2	0.640
14	3.12	1000	0.644
15	3.08	1073.2	0.656
16	3.01	1100	0.659
18	2.81	1173.2	0.671
20	2.49	1200	0.675
25	1.82	1273.2	0.686
30	1.39	1300	0.690
35	1.12	1373.2	0.701
40	0.953	1400	0.705
45	0.838	1473.2	0.717
50	0.758	1500	0.721
60	0.661	1573.2	0.732
70	0.612	1600	0.736
80	0.584	1673.2	0.747
90	0.566	1700	0.751
100	0.552	1773.2	0.761
123.2	0.537	1800	0.765
150	0.530	1873.2	0.775
173.2	0.527	1900	0.778
200	0.526	1973.2	0.787
223.2	0.527	2000	0.791
250	0.530	2073.2	0.801
273.2	0.533	2173.2	0.812
298.2	0.537	2200	0.815
300	0.537		
323.2	0.540		

†The recommended values are for well-annealed high-purity niobium, and those below 150 K are applicable only to a specimen having $\rho_0 = 0.0679$ $\mu\Omega$ cm.


THERMAL CONDUCTIVITY OF
NIOBIUM
RECOMMENDED
M.P. 2741 K
T.P. (s.c.) 9.13 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 114

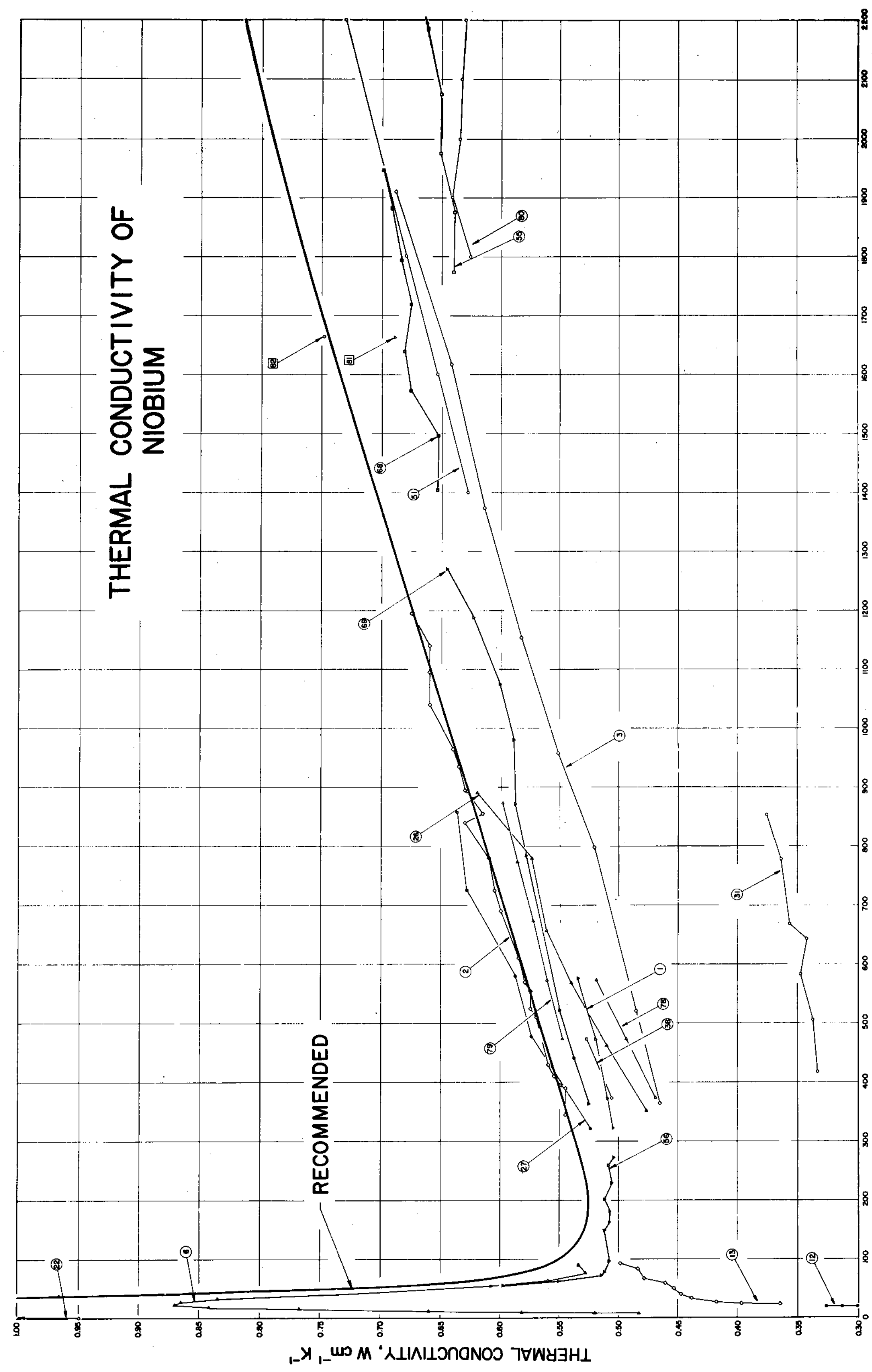

THERMAL CONDUCTIVITY OF NIOBIUM
RECOMMENDED
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TPRC

FIGURE 115

TABLE 108. THERMAL CONDUCTIVITY OF NIOBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1437	Tye, R. P.	1961	C	323-573		<0.1 Ta, 0.015 Ti, <0.01 C, <0.01 Fe, <0.01 N, <0.01 O, and <0.01 Si; ~6 mm dia x 10 cm long; manufactured by Murex Ltd.; sintered above 2000 C and cold swaged; electrical resistivity reported as 15.0, 16.5, 18.7, 23.2, and 27.7 μohm cm at 293, 323, 373, 473, and 573 K, respectively; Armco iron used as comparative material.
2	1163	Raag, V. and Kowger, H. V.	1965	P	345-1195		99.95^+ Nb, 0.011 O, 0.005 C, 0.0027 N, and 0.0006 H; specimen 0.25 in. in dia and 2 in. long; obtained from Kawecki Chemical Co.; refined by electron beam melting, annealed, and machined to size; density 8.61 g cm^{-3}; electrical resistivity reported as 15.2, 28.2, 39.1, and 49.3 μohm cm at 300, 600, 900, and 1200 K; thermal conductivity values calculated from measured data of thermal diffusivity and using specific heat data taken from Jaeger, F. M. and Veenstra, W. A. (Rec. Trav. Chim., 53, 677, 1934).
3	426	Fieldhouse, I. B., Hedge, J. C., and Lang, J. I.	1958	R	365-1911		High purity; specimen consisted of three stacked disks each of 0.625 in. I. D., 3.0 in. O. D., and 1 in. thick.
4	933	Mendelssohn, K. and Olson, J. L.	1950	L	2.2-10		High purity; in normal state; measured in a magnetic field.
5	933	Mendelssohn, K. and Olson, J. L.	1950	L	2.3-7.3		High purity; in superconducting state.
6	1548	White, G. K. and Woods, S. B.	1957	L	8.9-90	Nb 5	99.9^+ pure; 1.59 mm dia wire drawn from a rod of ductile niobium obtained from Fansteel Metallurgical Corp; ideal electrical resistivity reported as 0.038, 0.084, 0.25, 0.53, 0.97, 2.36, 3.90, 7.0, 9.8, 12.3, 13.5, and 14.5 μohm cm at 15, 20, 30, 40, 50, 75, 100, 150, 200, 250, 273, and 295 K, respectively; residual electrical resistivity = 0.475 μohm cm; transition temp 9.25 K; in normal state.
7	1548	White, G. K. and Woods, S. B.	1957	L	4.4-7.5	Nb 5	The above specimen measured in superconducting state.
8	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-3.1	JM 4526; Nb 1	99.99 pure; polycrstyalline; magnetic field "frozen in"; in superconducting state; measured after removing the applied magnetic field.
9	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.0-9.2	Nb 1	The above specimen in superconducting state; measured before applying any magnetic field.
10	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	3.1-7.8	Nb 1	The above specimen measured in a field of 2300 gauss; assumed in superconducting state below 6 K and in normal state above 6 K.
11	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-7.9	Nb 1	The above specimen measured in a field of 3300 gauss; assumed in superconducting state below 5 K and in normal state above 5 K.
12	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	9.5-21	Nb 1	The above specimen in normal state.
13	1220	Rosenberg, H. M.	1955	L	24-94	JM 4526; Nb 1	99.99 pure; polycrystalline; 0.470 cm dia x 3.03 cm long; electrical resistivity reported as 0.145, 0.149, 0.153, 0.166, 0.183, 0.220, 0.276, 0.319, 0.416, and 0.462 μohm cm at 20.6, 23.4, 26.2, 31.7, 38.9, 47.7, 59.2, 67.1, 82.9, and 90.0 K, respectively; $\rho(293K)/\rho(20K) = 10.4$.
14*	935	Mendelssohn, K. and Renton, C. A.	1953	L	0.54-0.75	Nb 1	99.99 pure; polycrystalline; magnetic field "frozen in"; in superconducting state; measured after removing the applied magnetic field.
15*	935	Mendelssohn, K. and Renton, C. A.	1953	L	0.55-0.97	Nb 1	99.99 pure; polycrystalline; in superconducting state; measured before applying the magnetic field.

* Not shown in figure.

TABLE 108. THERMAL CONDUCTIVITY OF NIOBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	930	Mendelssohn, K.	1958	L	1.0-3.7		Rod specimen; in normal state.
17	930	Mendelssohn, K.	1958	L	1.0-4.2		The above specimen bent until 5-13.4% strained; in normal state.
18	930	Mendelssohn, K.	1958	L	1.0-3.7		The above specimen bent until 19.5% strained; in normal state.
19	930, 1228	Mendelssohn, K.	1958	L	0.97-4.2		Single crystal; rod specimen; zone refined; not intentionally annealed; bent until 5.0-5.1% strained; in superconducting state.
20	930, 1228	Mendelssohn, K.	1958	L	1.0-4.4		The above specimen bent until 13.4% strained; in superconducting state.
21	930, 1228	Mendelssohn, K.	1958	L	0.87-4.1		The above specimen bent until 19.5% strained; in superconducting state.
22	233, 930	Mendelssohn, K.	1958	L	1.0-2.4	Nb II	0.0003 Cu and 0.0003 Mg; single crystal; specimen made by floating zone melting of polycrystalline rod; in normal state. (Data given in Ref. 930 10 times higher than those given in Ref. 233, the latter reported here.)
23	233, 930	Mendelssohn, K.	1958	L	1.0-4.3	Nb II	The above specimen in superconducting state. (Data given in Ref. 930 10 times higher than those given in Ref. 233, the latter reported here.)
24	233, 930	Mendelssohn, K.	1958	L	1.0-3.0	Nb I	Similar to the above specimen; not intentionally annealed; in normal state. (Data given in Ref. 930 10 times higher than those given in Ref. 233, the latter reported here.)
25	233, 930, 1228	Mendelssohn, K.	1958	L	1.0-4.3	Nb I	The above specimen in superconducting state. (Data given in Ref. 930 10 times higher than those given in Ref. 233, the latter reported here.)
26	126, 1419	Bell, I. P.; Tottle, C. R.	1955	L	353-888		99.95 Nb and <0.05 O; rectangular specimen; density 8.38 g cm^{-3}; electrical resistivity reported as 16.41, 20.85, 25.22, 29.74, 38.63, 43.07, and 45.30 μohm cm at 0, 100, 200, 300, 400, 500, 600, and 650 C, respectively.
27	126, 1419	Bell, I. P.; Tottle, C. R.	1955	L	323-856		99.95 Nb and <0.05 O; cylindrical specimen; density 8.65 g cm^{-3}; electrical resistivity reported as 15.22, 19.18, 23.13, 27.09, 31.04, 35.00, and 38.96 μohm cm at 0, 100, 200, 300, 400, 500, and 600 C, respectively.
28	936	Mendelssohn, K. and Renton, C. A.	1955	L	0.39-0.72	JM 4526	99.99 pure; polycrystalline; measured with magnetic shielding; in superconducting state.
29*	936	Mendelssohn, K. and Renton, C. A.	1955	L	0.54-0.76		The above specimen measured without magnetic shielding; in superconducting state.
30*	936	Mendelssohn, K. and Renton, C. A.	1955	L	0.54-0.99		Same as above; 2nd run.
31	127	Bell, I. P.	1954	L	417-853		Density 7.73 g cm^{-3}; electrical resistivity reported as 31.25, 35.78, 40.30, 44.83, 49.35, 53.88, and 58.40 μohm cm at 0, 100, 200, 300, 400, 500, and 600 C, respectively.
32	261	Chaudhuri, K. D., Mendelssohn, K., and Thompson, M. W.	1960	L	1.1-4.2		Single crystal; 4 mm in dia and 50 mm long; prepared by the "floating zone" technique in an electron bombardment furnace; in superconducting state.
33	261	Chaudhuri, D. K., et al.	1960	L	1.2-4.4		The above specimen irradiated by a dose of 10^{18} fast neutrons cm^{-2} at 30 ± 5 C, then allowed a few wks for radioactivity to decay; in superconducting state.
34	261	Chaudhuri, D. K., et al.	1960	L	1.3-2.3		The above specimen before irradiation; in normal state; measured in a magnetic field.
35	261	Chaudhuri, D. K., et al.	1960	L	1.7-2.6		The above irradiated specimen (curve 33); in normal state; measured in a magnetic field.

* Not shown in figure.

TABLE 108. THERMAL CONDUCTIVITY OF NIOBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
36	291	Connolly, A. and Mendelssohn, K.	1962	L	0.26-1.2	Nb II	0.0003 Cu and 0.0003 Mg; single crystal; dia 4.0 mm; ratio of length to cross-sectional area 25.7 cm^{-1}; obtained by the floating zone melting of polycrystalline rod of niobium in vacuum; electrical resistivity ratio $\rho(298K)/\rho_0$ = 60.5; in superconducting state.
37	291	Connolly, A. and Mendelssohn, K.	1962	L	0.25-4.2	Nb III	Dia 2.2 mm; ratio of length to cross-sectional area 89.6 cm^{-1}; electrical resistivity ratio $\rho(298K)/\rho_0$ = 120.0; in superconducting state.
38	1116	Powell, R.W.	1957	L, C	373, 473	Sample B	0.1 Ta; electrical resistivity reported as 16.2, 19.5, and 23.5 μohm cm at 20, 100, and 200 C, respectively; Armco iron used as comparative material.
39	796, 797	Kuhn, G.	1966	L	1.2-9.4	Nb I	0.03 Al, 0.03 Fe, 0.02 Si, 0.01 C, <0.01 Cl, <0.01 Cr, <0.01 Pb, and <0.01 Mn; single crystal; 2.34 mm in dia and 20 mm long; supplied by Johnson, Matthey and Co.; prepared by fusion in a floating zone by electronic bombardment; residual electrical resistivity 0.09 μohm cm; transition temp 9.5 K; in superconducting state.
40	796,797	Kuhn, G.	1966	L	1.3-9.4	Nb I	The above specimen in normal state.
41	796,797	Kuhn, G.	1966	L	1.1-9.9	Nb I	The above specimen irradiated by 5.6 x 10^{17} fast neutrons cm^{-2}; residual electrical resistivity 0.11 μohm cm; in superconducting state.
42	796,797	Kuhn, G.	1966	L	1.2-5.0	Nb I	The above specimen in normal state.
43	796,797	Kuhn, G.	1966	L	1.4-9.0	Nb I	The above specimen annealed at 1870 C in a vacuum of 5 x 10^{-5} torr for 63 hrs; residual electrical resistivity 2.48 μohm cm; in superconducting state.
44	796,797	Kuhn, G.	1966	L	1.4-9.2	Nb I	The above specimen in normal state.
45	796,797	Kuhn, G.	1966	L	1.3-9.0	Nb III DA	0.1 Ta, 0.01 Ti, 0.007 Fe, 0.005 Cu, 0.005 N, 0.005 O, 0.003 Na, 0.002 Al, 0.002 C, 0.002 Si, and 0.001 H; single crystal; 5.10 mm in dia and 21 mm long; made from polycrystalline sample of Pechiney; annealed at 1350 C in a vacuum of <10^{-5} torr for 3 min; residual electrical resistivity 0.21 μohm cm; transition temp 9.25 K; in superconducting state.
46	796,797	Kuhn, G.	1966	L	1.3-9.0	Nb III DA	The above specimen in normal state.
47	796,797	Kuhn, G.	1966	L	1.3-8.8	Nb IV AA	Single crystal; 2.96 mm in dia and 21 mm long; supplied by Kuhlmann; annealed at 1320 C by electron bombardment for 15 min in a vacuum of <10^{-5} torr; resistivity ρ_0 = 0.38 μohm cm; transition temp 9.25 K; in superconducting state.
48	796,797	Kuhn, G.	1966	L	1.4-9.2	Nb IV AA	The above specimen in normal state.
49	796,797	Kuhn, G.	1966	L	1.3-9.6	Nb IV B	Single crystal; 2.96 mm in dia and 21 mm long; supplied by Kuhlmann; obtained by fusion in a floating zone; residual electrical resistivity 0.22 μohm cm; transition temp 9.25 K; in superconducting state.
50	796,797	Kuhn, G.	1966	L	1.5-9.9	Nb IV B	The above specimen in normal state.
51	1493	Voskresenskii, V.Y., Peletskii, V.E., Timrot, D.L.	1966	E	1400-2300		99.7 Nb + Ta, 0.06 Si, 0.03 Fe, and 0.025 Ti; cylindrical specimen 65 mm long and 14 mm in dia finished to an "eighth-class" surface (max. height of asperities 2.2 μ); preheated at 2000 to 2200 K for 4 hrs; density 8.56 g cm^{-3}; measured in a vacuum of 5 x 10^{-5} mm Hg.

TABLE 108. THERMAL CONDUCTIVITY OF NIOBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
52*	1010	Muto, Y., Noto, K., and Mamiya, T.	1967	L	4.05	A	Pure; wire specimen prepared and heat-treated in an ultra-high vacuum; measured in magnetic fields ranging from 0 to 3.45 kOe.
53*	1010	Muto, Y., et al.	1967	L	3.40	B	Similar to the above specimen; measured in magnetic fields ranging from 0 to 3.54 kOe.
54*	1010	Muto, Y., et al.	1967	L	2.09	C	Similar to the above specimen; measured in magnetic fields ranging from 0 to 4.52 kOe.
55	783	Kraev, O. A. and Stel'makh, A. A.	1966	P	1773-2573		Thermal conductivity values calculated from measured thermal diffusivity data with density data taken from Chirkin, V. C. (Teploprovodnost Promihlennich Materialov. M., Mahgiz, 1962) and specific heat data taken from Kraftmakher, Ya. A., (Fiz. Tverd. Tela, 5 (3), 950-1, 1963 or Soviet Physics-Solid State, 5 (3), 696-7, 1963).
56	941	Morisov, B. A., Khotkevich, V. I., Zlobintsev, G. M., and Kozinei, V. V.	1967	→	4.8-274		Cylindrical specimen; measured by a thermal potentiometer method.
57*	795	Kuhn, G.	1962	L	1.4-9.0		Single crystal; 2.3 mm dia x 20 mm long; residual electrical resistivity 0.09 μohm cm; in superconducting state.
58*	795	Kuhn, G.	1962	L	1.3-9.5		The above specimen measured in a magnetic field of 8 kOe; in normal state.
59*	795	Kuhn, G.	1962	L	2.4-9.5		The above specimen irradiated by a dose of 5.7×10^{17} neutrons cm^{-2} with energy >1 MeV; measured with magnetic field removed; in superconducting state.
60*	795	Kuhn, G.	1962	L	0.1-5.1		The above specimen measured in a magnetic field of 8 kOe; in normal state.
61*	795	Kuhn, G.	1962	L	4.25		The above specimen measured in decreasing magnetic fields ranging from 4.03 to 0.65 kOe.
62*	795	Kuhn, G.	1962	L	4.25		The above specimen measured with the magnetic field direction reversed and increasing from 0.78 to 4.29 kOe.
63*	795	Kuhn, G.	1962	L	1.64		The above specimen measured in increasing magnetic fields ranging from 0.97 to 6.02 kOe.
64*	795	Kuhn, G.	1962	L	1.64		The above specimen measured in decreasing magnetic fields ranging from 5.14 to 1.01 kOe.
65*	795	Kuhn, G.	1962	L	1.64		The above specimen measured with the magnetic field direction reversed and increasing from 0.77 to 5.43 kOe.
66	1165	Radhakrishana, P. and Nielsen, M.	1963	L	1.8-8.0		99.8 Nb (by difference), 0.2 Zr; vacuum-annealed wire of 1 mm in dia; measured in superconducting state.
67	1165	Radhakrishana, P. and Nielsen, M.	1963	L	1.7-8.0		The above specimen in normal state.
68	1020	Neimark, B. E. and Voronin, L. K.	1968	E	1404-1944	Specimen No. 2	0.3 Ta, 0.01 C, 0.004 O, 0.001 N, and 0.001 H; specimen ~2 mm in dia and 140-160 mm long; obtained by electron-beam melting in vacuum; electrical resistivity reported as 56, 58, 60, 63, 64, 66, 69, 69, 71, 75, 77, and 80 μohm cm at 1137, 1227, 1297, 1368, 1446, 1519, 1536, 1603, 1670, 1745, 1813, and 1920 C, respectively; Lorenz function reported as 2.69, 2.67, 2.64, 2.62, 2.61, 2.58, 2.56, 2.55, 2.55, 2.56, 2.56, 2.56, 2.57, 2.58, 2.58, 2.60, and $2.62 \times 10^{-8}\ V^2\ deg^{-2}$ at 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, and 1700 C, respectively; measured by Bode's method.

* Not shown in figure.

TABLE 108. THERMAL CONDUCTIVITY OF NIOBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
69	1020	Neimark, B. E. and Voronin, L. K.	1968	E	364–1266	Specimen No. 2	The above specimen measured in another apparatus (Jaeger and Diesselhorst's method); electrical resistivity reported as 15, 18, 21, 22, 25, 25, 27, 27, 28, 30, 33, 35, 37, 38, 40, 42, 43, 44, 47, 48, 49, 50, and 51 μohm cm at 17, 84, 149, 169, 221, 247, 277, 300, 317, 383, 447, 511, 554, 596, 670, 703, 752, 790, 871, 915, 934, 954, and 992 C, respectively.
70	1344	Sousa, J. B.	1969	L	1.92–3.36	Nb (A)	Specimen 4 cm long; prepared from swaged rod (zone-refined) supplied by Murex Limited; electrical resistivity ratio $\rho(300K)/\rho(4.2K) \cong 380$; Curie point 9.1 ± 0.1 K; measured in a magnetic field of 4.5 kOe; in normal state.
71*	1042	Noto, K.	1969	L	3.4		Pure; specimen 0.67 mm in dia and 4.5 cm long; prepared and heat-treated in an ultra-high vacuum of 10^{-9} torr by Tsuda and Suzuki at the Institute for Solid State Physics, Tokyo University; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 1900$; residual electrical resistivity 6.9×10^{-3} μohm cm at 4.2 K obtained with extrapolation data above 5 kOe in transverse fields; transition temp 9.2 K; measured in longitudinal magnetic fields ranging from 0 to 3.53 kOe.
72*	1042	Noto, K.	1969	L	4.1		Similar to the above specimen; measured in transverse magnetic fields ranging from 0 to 3.44 kOe.
73*	1042	Noto, K.	1969	L	1.9		Similar to the above specimen; measured in decreasing magnetic fields ranging from 0 to 4.05 kOe.
74*	1042	Noto, K.	1969	L	1.9		The above specimen measured in decreasing magnetic fields ranging from 3.79 to 0.36 kOe.
75	235	Carlson, J.R.	1968	L	0.30–9.2		Single crystal; specimen 0.475 cm in dia and 10 cm long; prepared by electron-beam floating-zone technique with starting material obtained from Wah Chang Corp. of Albany, Oregon; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 196$; in superconducting state.
76	235	Carlson, J.R.	1968	L	0.32–15		The above specimen measured in magnetic field; in normal state.
77	235	Carlson, J.R.	1968	L	1.5–3.2		The above specimen in superconducting state after the surface of the specimen roughened.
78	1116	Powell, R. W.	1957	L, C	373–573	Sample A	Oxidized specimen; 0.3 Ta; electrical resistivity reported as 17.7, 21.2, 25.5, and 29.6 μohm cm at 20, 100, 200, and 300 C, respectively; energy flow measured calorimetrically and also by use of Armco iron as comparative material.
79	594	Heal, T. J.	1958		473–873		99.5^+ Nb and 0.3 Ta.
80	782	Kraev, O. A. and Stel'makh, A. A.	1964	P	1800–2600		8–9 mm in dia and 0.3 mm thick; thermal conductivity values not given in the paper but calculated by TPRC with the authors' thermal diffusivity data using the TPRC selected density and specific heat values from TPRC Report 16, 1966.
81	435	Filippov, L. P. and Makarenko, I. N.	1966	P	1660		99.2 Nb, 0.3 Ta, 0.08 Ti, 0.04 Fe, and 0.04 Si; 15 mm dia x 80 mm long; density 8.54 g cm^{-3}; electrical resistivity 16.4 μohm cm at room temp; measured by an alternating induction heating method.
82	435	Filippov, L. P. and Makarenko, I. N.	1966	P	1660		The above specimen measured by an alternating electron heating method.

* Not shown in figure.

Nitrogen

The thermal conductivity of nitrogen in each of the physical states is discussed separately below.

Solid

The only experimental data located for the thermal conductivity of solid nitrogen were values of Roder [1206] between 4 and 28 K. Five measurements around 4 K, one at 14 K and fifteen from 20 to 28 K were reported. In the analysis the two points above 25.2 K were neglected.

To compare these data with theory, some experimental evidence for the temperature at which the thermal conductivity reaches a maximum is required. This could not be obtained from the only source of data [1206]. Study of the papers of Julian [696] and Keyes [751] reveals no predicted maximum (in disagreement with experiment) while the White and Woods [1552] paper only considers the theory at sufficiently high temperatures where the thermal conductivity could be considered to vary inversely with absolute temperature. The experimental evidence was insufficient to determine if the maximum occurred below or above 4 K.

The recommended values were obtained from a double logarithmic plot of thermal conductivity versus temperature and must be regarded as tentative below 12 K. From 12 to 25 K an uncertainty of ten percent appears probable.

Saturated Liquid

There exist nine available experimental works on the thermal conductivity of liquid nitrogen. Extensive measurements on both Uhlir [1447] and Ziebland-Burton [229, 1612] were considered reliable from the standpoint of the experimental method and procedure. As they did not give the values at the saturated liquid, graphical extrapolation was used to obtain the values at the saturated vapor pressures. All of the values thus obtained are given equal weight. Another set of recommended values reported by Powers, et al. [1149, 1150] was also partly used in this analysis. On the other hand, two sets of data reported by Borovik [183, 182] deviate considerably, and the values of Hammann [583] and Prosad [1159] are too high. Therefore, no weight was given to these sets of data. Only a translation was available of the work of Golubev and Kal'sina [516]. This apparently omitted the graphical presentations but the original was not available as a check. Vasserman and Rabinovich [1481] did present a correlation from which thermal conductivity was tabulated for integral pressures and temperatures, so that approximate values for the liquid can be derived from their tables. Such values were not used as input in this analysis.

The correlation formula was determined from the reliable values described above, excluding those at the critical point considered to be less reliable. The correlation formula was given by

$$k\ (\mathrm{mW\ cm^{-1}\ K^{-1}}) = 2.91188 - 2.15682 \cdot 10^{-2}\,T + 2.111393 \cdot 10^{-5}\,T^2$$

and should be valid between 60 and 123 K. It was found that this equation fits the above-enumerated values with a mean deviation of 0.8 percent and a maximum of 2.2 percent. The approximate values from the [1481] tables are in excellent agreement with this equation, the mean deviation being —0.5 percent and a maximum of —0.9 percent. The recommended values up to 120 K were calculated from the above equation.

Above 120 K, the recommended values were obtained from a large-scale plot of all the available information. The principal uncertainty introduced is in the thermal conductivity at the critical point. At least a ten percent uncertainty exists in this value. On the departure plot only a part of the results of Hammann (curve 3), is plotted for the sake of clarity. The recommended values are considered accurate to a few percent below 120 K, the uncertainty reaching five percent at 125 K and at least ten percent at the critical temperature.

Saturated Vapor

No data were located for the thermal conductivity of saturated nitrogen vapor. Various correlations were plotted on a large scale. Between the normal boiling and critical points, that of Schaefer and Thodos [1257] appeared lower than those of Petrozzi [24] and Johnson [684]. In addition, the [24] values exhibited a somewhat anomalous variation with temperature below 110 K. The values predicted by the two correlations [684] and [1257] at the normal boiling point were respectively slightly above and below the atmospheric pressure value considered most probable for the gas. The average of these two correlations was selected as the most probable value for temperatures below 125 K. This procedure also resulted in good agreement with a value extrapolated from an isotherm of Keyes [748] at 92 K. Only a few estimates for the saturated vapor can be deduced from the published tables of Vasserman and Rabinovich [1481]. Such values are lower than those recommended here but fall within the error estimates.

The recommended values are thought to have an average error of a few percent for temperatures up to 90 K, the uncertainty then increasing to about ten percent at 100 K and as much as twenty-five percent near the critical point. These estimates may be pessimistic. Experimental measurements to confirm the recommended values are highly desirable.

Gas

In view of the extensive experimental, theoretical and correlated sets of values which are available for the thermal conductivity of gaseous nitrogen, the departure plots show the degree of disagreement between these different values to be larger than would be expected.

As will be observed from the departure plots, the recommended values, obtained by drawing a smooth curve through the experimental data, are somewhat lower than most previous correlations for temperatures between about

250 and 700 K and also lower than the correlation of Keyes [746] and Hilsenrath, et al. [604] for higher temperatures. It seems that the more recent measurements justify this change.

While measurements up to about 1200 K appear in reasonable agreement, for higher temperatures the trends of the experimental and theoretical values differ. The recommended values were selected to occur midway between the experimental values at 1200 K and to approach the theoretical estimates at about 2500 K. Theoretical estimates for temperatures above about 3500 K differ according to whether consideration is given to the influence of dissociation on the thermal conductivity. Even supposedly similar calculations differ increasingly at higher temperatures. Due to this reason, the tabulation of recommended values was only undertaken in [843, 1420, 608] for temperatures up to 3500 K, at which temperature the reaction contribution of some two percent was less than the uncertainty in the recommended values. In the present publication the tabulation has been arbitrarily limited to 2500 K pending a more detailed consideration of related studies of gaseous viscosities, etc.

Further experiments are required for the entire temperature range if accuracy better than two percent is desired. More accurate calculations are also required, possibly for temperatures from 1000 to 4000 K and certainly for higher temperatures. The accuracy of the recommended values can be assessed as two percent for temperatures below about 350 K, five percent for temperatures from 350 to 1200 K and ten percent above 1200 K. This assessment agrees with the percentage departures of the tables of Childs and Hanley [271] above 200 K and with the Russian Standards tables [1474].

TABLE 109. Recommended thermal conductivity of nitrogen

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
4	56				
5	45			60	0.056*
6	37			65	0.061*
7	30	63	1.64	70	0.066*
8	25	65	1.60	75	0.071*
9	20	70	1.51	80	0.077*
10	17	75	1.413	85	0.084*
11	14	80	1.322	90	0.091*
12	12	85	1.231	95	0.100*
13	10	90	1.142	100	0.111*
14	9.2	95	1.053	105	0.123*
15	7.6	100	0.966	110	0.138*
16	6.5	105	0.880	115	0.160*
17	5.6	110	0.795	120	0.195*
18	4.9	115	0.710	125	0.265*
19	4.5	120	0.628	126	0.37*‡
20	4.0	125	0.520*		
21	3.8	126	0.37*‡		
22	3.6				
23	3.5				
24	3.3				
25	3.2				

*Extrapolated or estimated.
‡Pseudo-critical value.

TABLE 109. Recommended thermal conductivity of nitrogen—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})
Gas

(At 1 atm)

T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		450	0.3564	850	0.564
		460	0.3626	860	0.569
78	0.0745	470	0.3688	870	0.574
80	0.0762	480	0.3749	880	0.578
90	0.0852	490	0.3808	890	0.583
100	0.0941	500	0.3864	900	0.587
110	0.1030	510	0.392	910	0.592
120	0.1119	520	0.398	920	0.596
130	0.1208	530	0.403	930	0.600
140	0.1296	540	0.408	940	0.605
150	0.1385	550	0.414	950	0.609
160	0.1474	560	0.420	960	0.613
170	0.1562	570	0.425	970	0.618
180	0.1651	580	0.431	980	0.622
190	0.1739	590	0.436	990	0.626
200	0.1826	600	0.441	1000	0.631
210	0.1908	610	0.446	1050	0.651
220	0.1989	620	0.452	1100	0.672
230	0.2067	630	0.457	1150	0.693
240	0.2145	640	0.462	1200	0.713
250	0.2222	650	0.467	1250	0.733
260	0.2298	660	0.472	1300	0.754
270	0.2374	670	0.478	1350	0.775
280	0.2449	680	0.483	1400	0.797
290	0.2524	690	0.488	1450	0.819
300	0.2598	700	0.493	1500	0.842
310	0.2671	710	0.498	1550	0.867*
320	0.2741	720	0.503	1600	0.893*
330	0.2808	730	0.508	1650	0.921*
340	0.2874	740	0.513	1700	0.950*
350	0.2939	750	0.517	1750	0.981*
360	0.3002	760	0.522	1800	1.013*
370	0.3065	770	0.526	1850	1.046*
380	0.3127	780	0.531	1900	1.080*
390	0.3189	790	0.536	1950	1.113*
400	0.3252	800	0.541	2000	1.146*
410	0.3314	810	0.546	2100	1.207*
420	0.3376	820	0.551	2200	1.263*
430	0.3438	830	0.555	2300	1.314*
440	0.3501	840	0.559	2400	1.361*
				2500	1.406*

*Extrapolated or estimated.

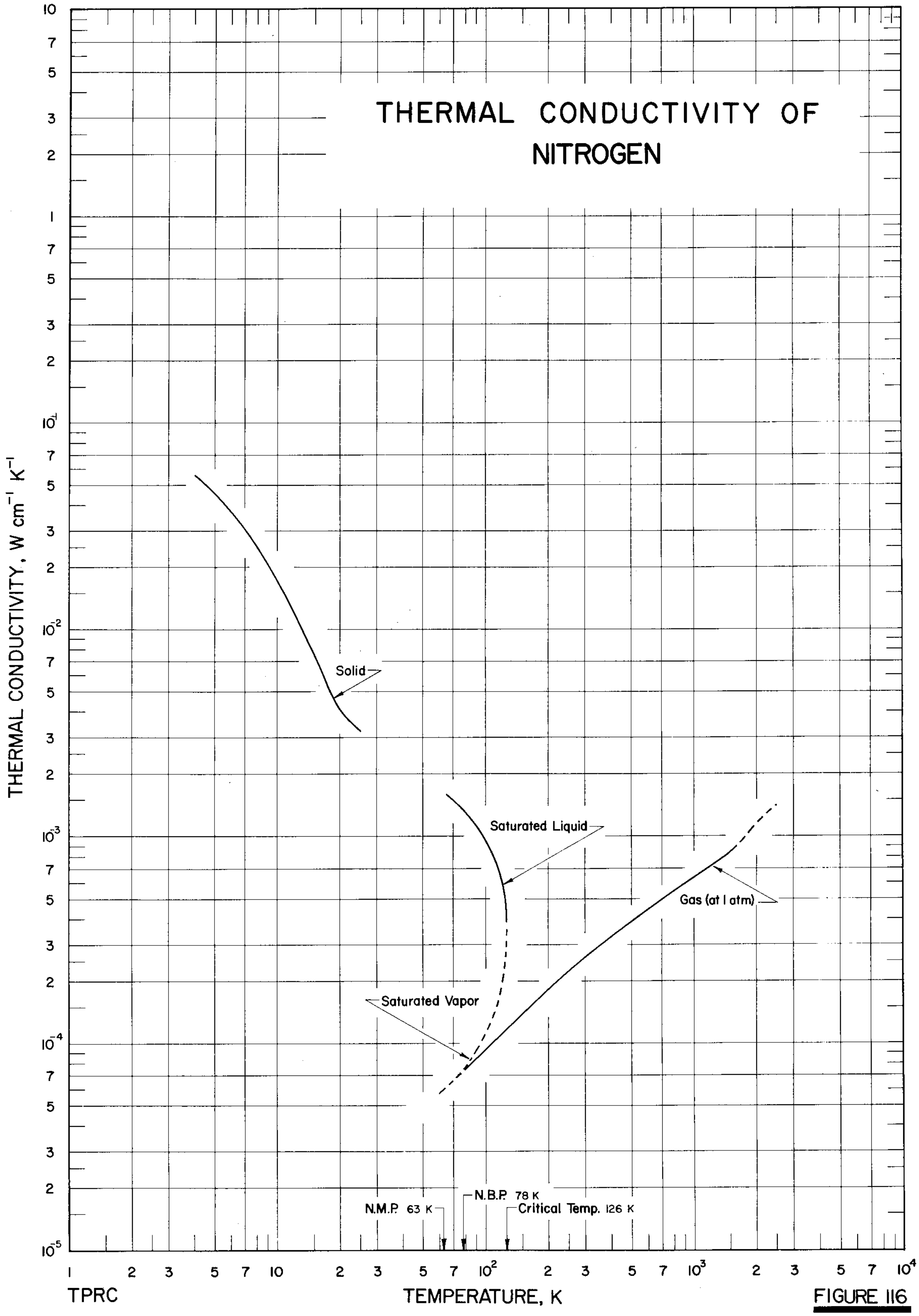

THERMAL CONDUCTIVITY OF
NITROGEN
THERMAL CONDUCTIVITY, W cm^{-1} K^{-1}
TEMPERATURE, K
Solid
Saturated Liquid
Gas (at 1 atm)
Saturated Vapor
N.M.P. 63 K
N.B.P. 78 K
Critical Temp. 126 K
TPRC

FIGURE 116

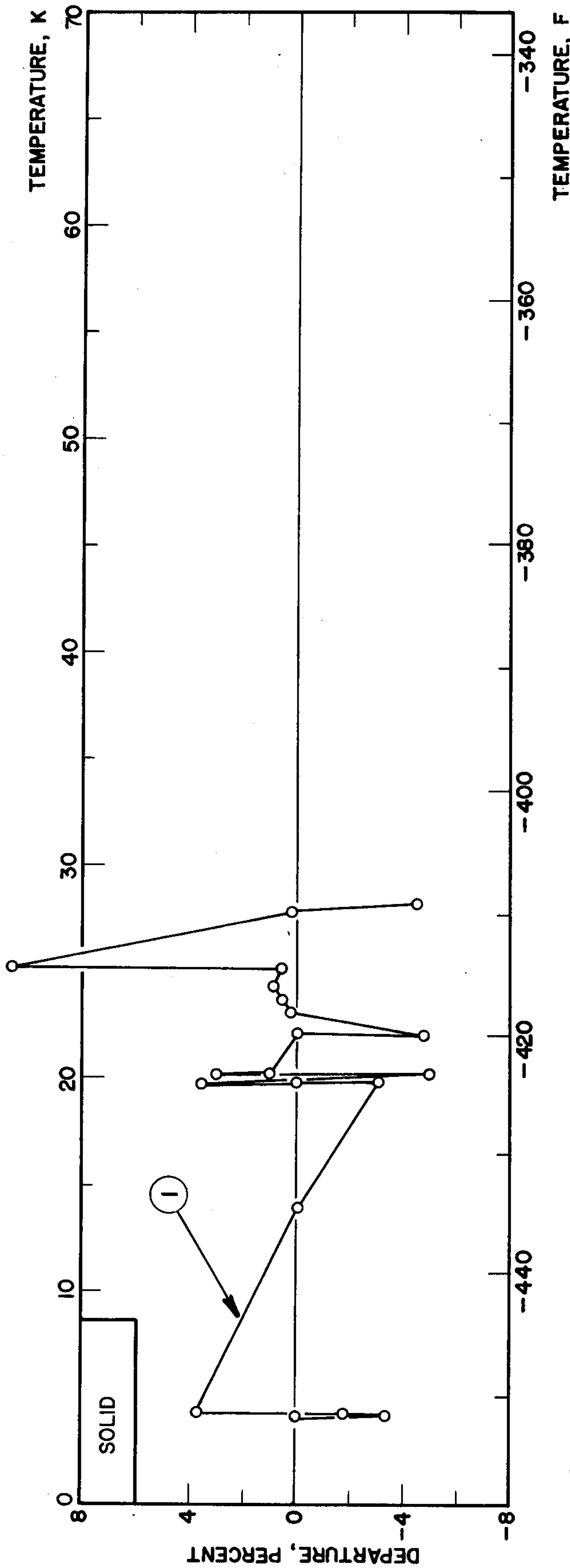
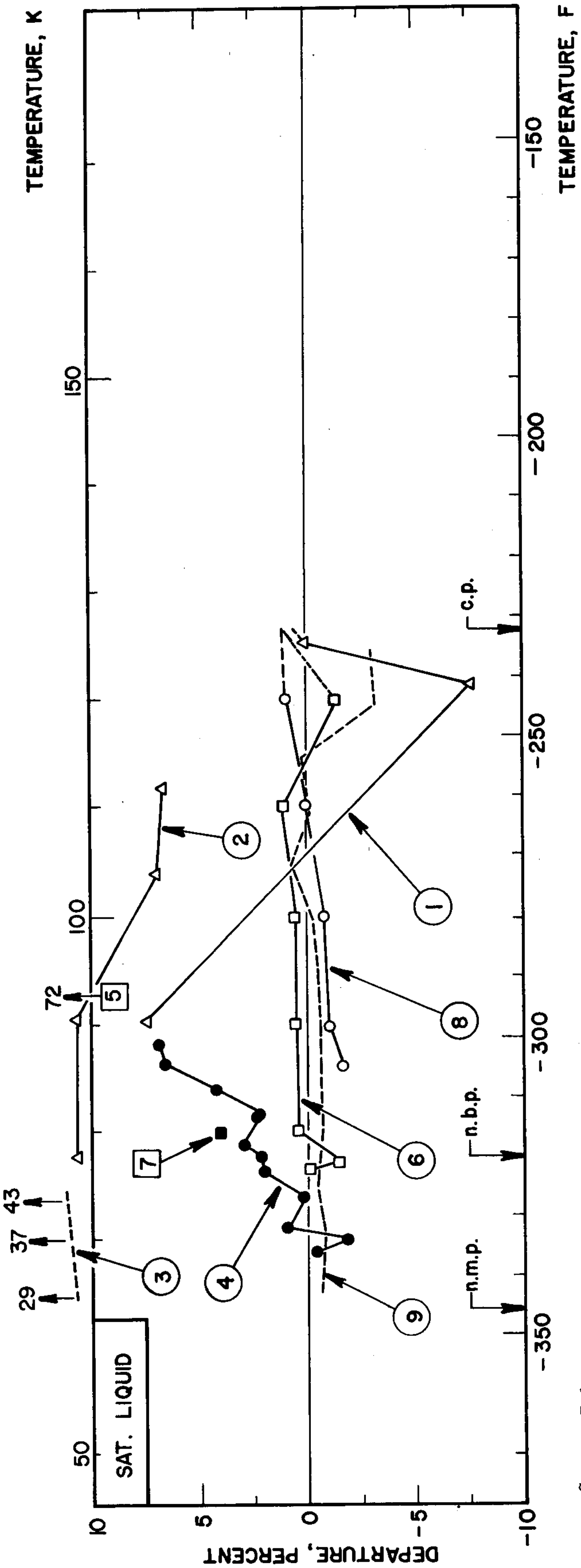


FIGURE 117. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SOLID NITROGEN

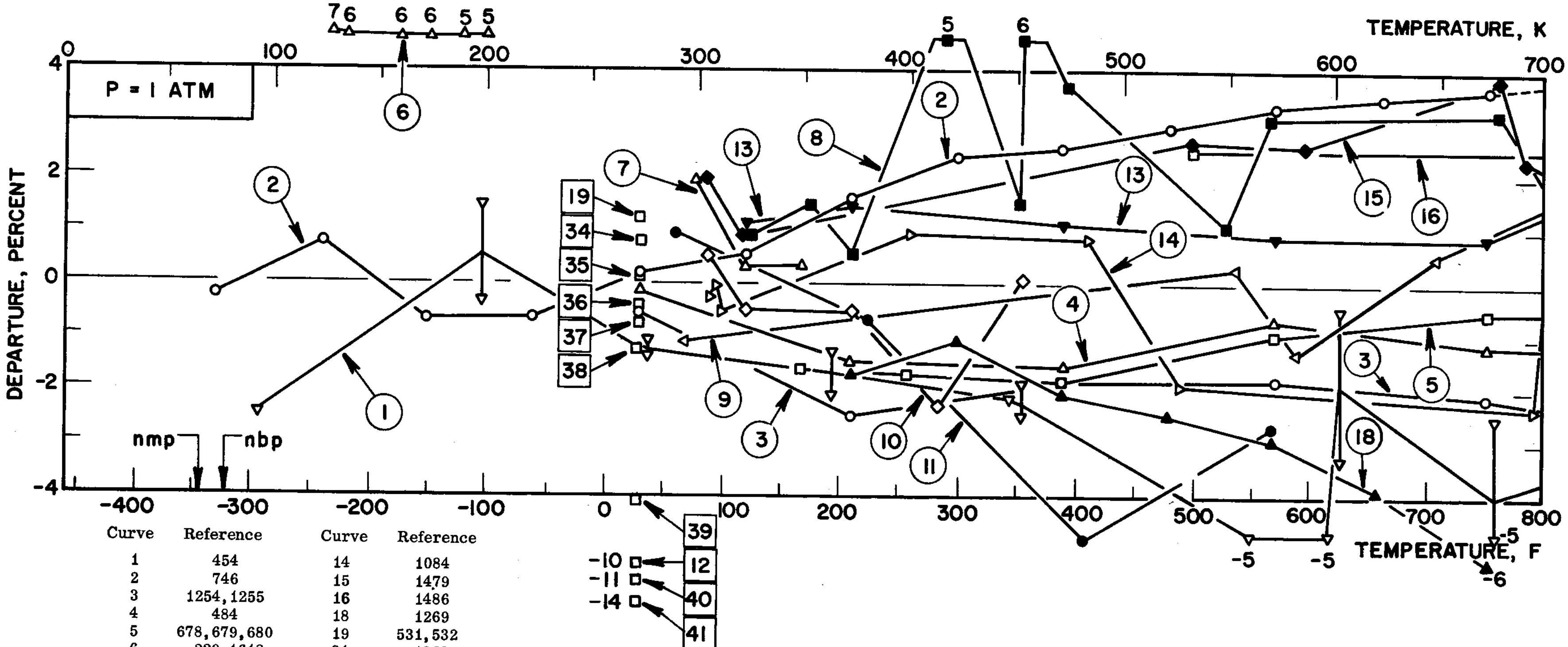
Curve	Reference
1	1206

FIGURE 118. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID NITROGEN



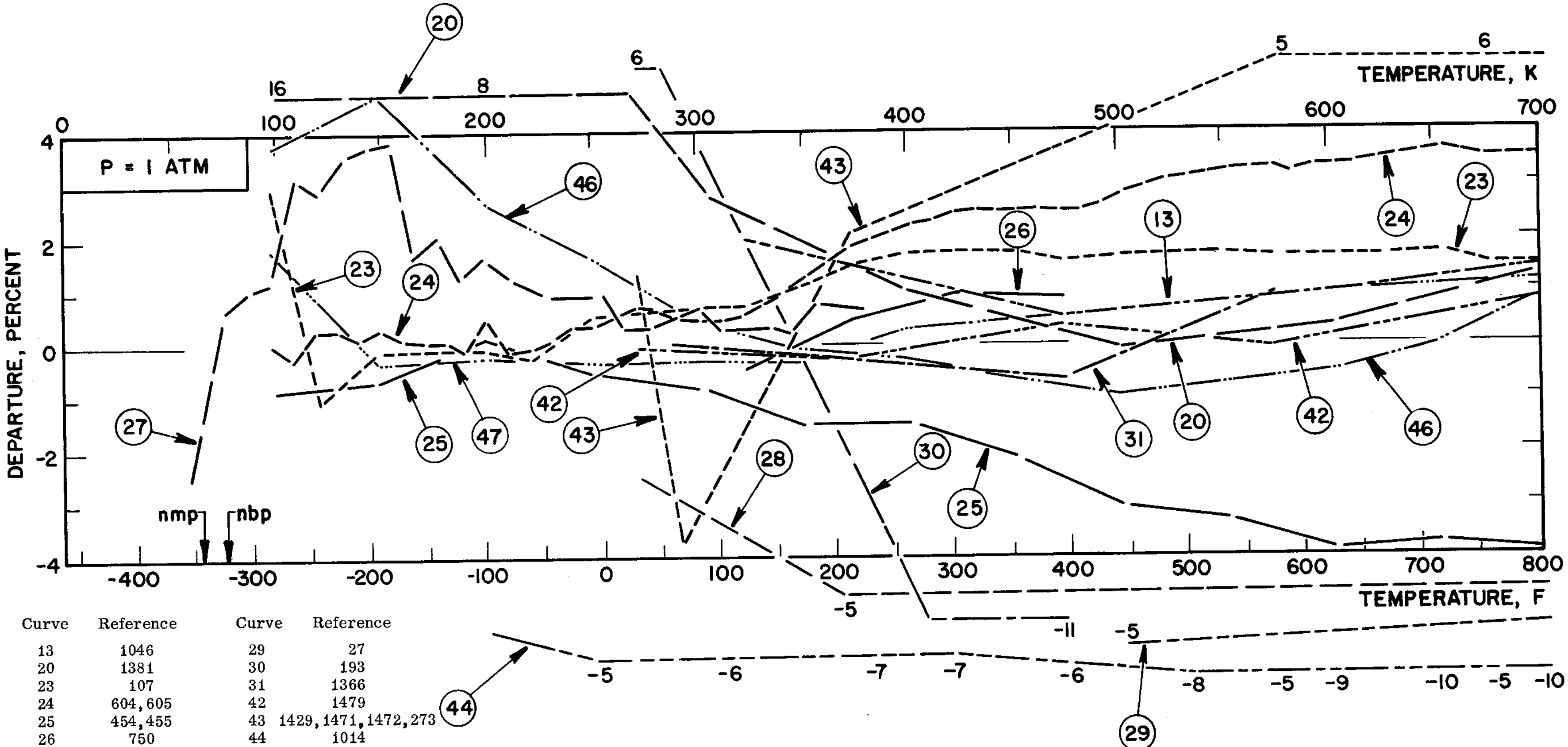
Curve	Reference
1	183
2	182
3	583
4	1149,115
5	1159
6	1447
7	1611
8	229,1612
9	1481

FIGURE 119. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN



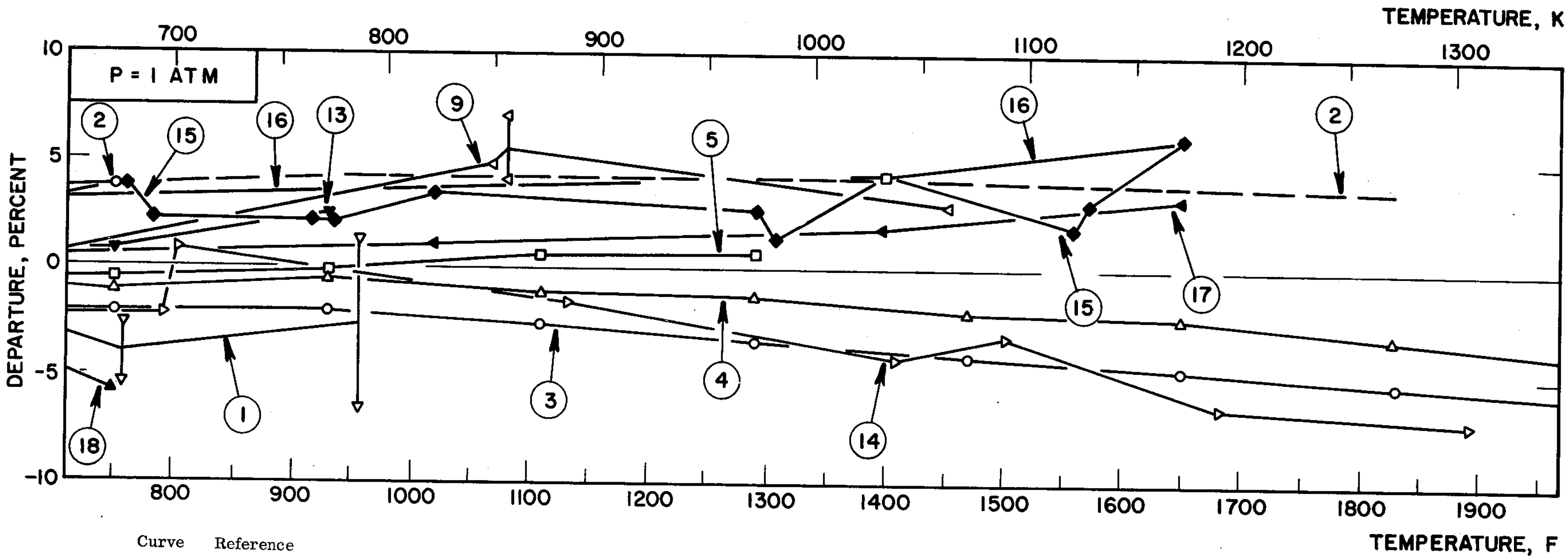
Curve	Reference	Curve	Reference
1	454	14	1084
2	746	15	1479
3	1254,1255	16	1486
4	484	18	1269
5	678,679,680	19	531,532
6	229,1612	34	1368
7	956	35	403
8	1475	36	1572
9	1529	37	568
10	1077	38	402,1519
11	1366	39	651
12	599	40	1570,1571
13	1046	41	1415

FIGURE 119. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



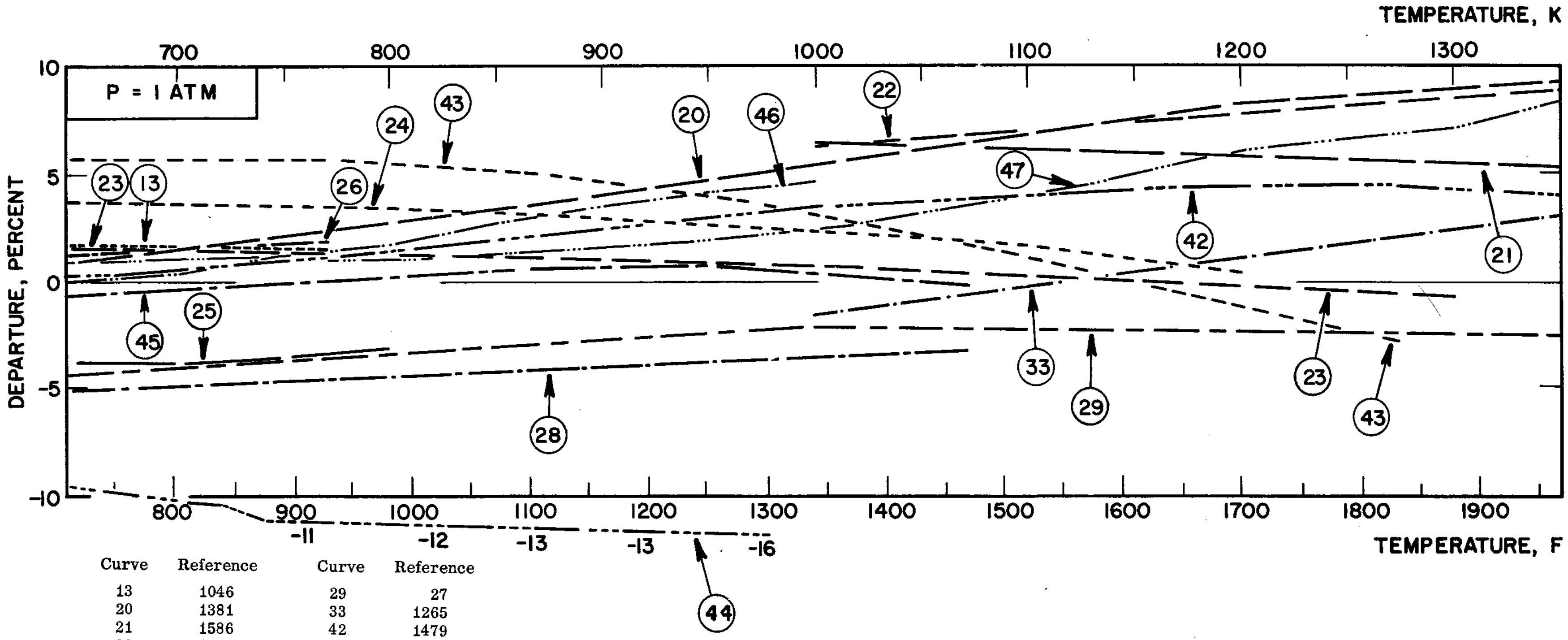
Curve	Reference	Curve	Reference
13	1046	29	27
20	1381	30	193
23	107	31	1366
24	604, 605	42	1479
25	454, 455	43	1429, 1471, 1472, 273
26	750	44	1014
27	839	46	271
28	1255	47	1474

FIGURE 119. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



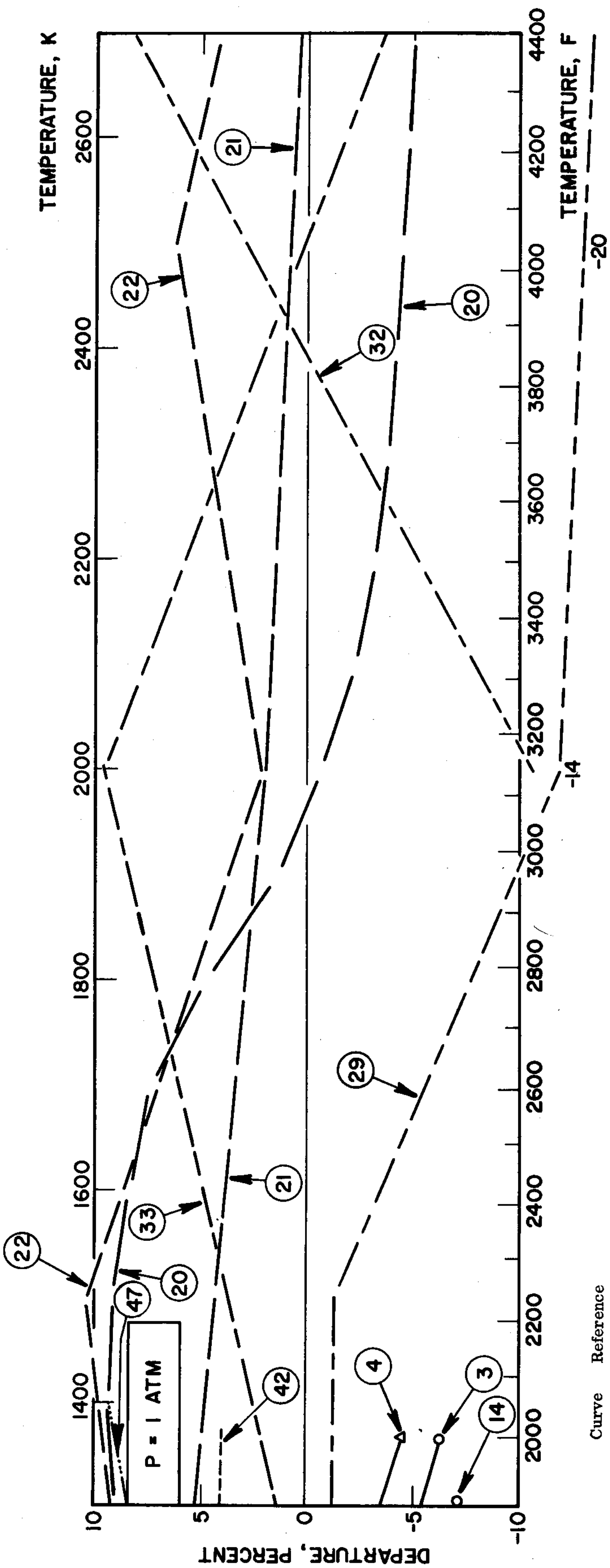
Curve	Reference
1	454
2	746
3	1254, 1255
4	484
5	678, 679, 680
9	1529
13	1046
14	1084
15	1479
16	1486
17	750, 1486
18	1269

FIGURE 119. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



Curve	Reference	Curve	Reference
13	1046	29	27
20	1381	33	1265
21	1586	42	1479
22	1590	43	273,1429,1471,1472
23	107	44	1014
24	604,605	45	1226
25	454,455	46	271
26	750	47	1474
28	1255		

FIGURE 119. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



Curve	Reference
3	1254, 1255
4	484
14	1084
20	1381
21	1586
22	1590
29	27
32	867
33	1265
42	1479
47	1474

Nobelium

No information is available for the thermal or electrical conductivity of nobelium. The actinide elements are chemically very similar to the lanthanide elements and their electronic structures are, as a whole, also closely similar. The elements thorium, protactinium, and uranium also partly resemble the IV B to VI B transition metals (which may partially explain their higher thermal conductivities than those of the lanthanides), but the transuranium elements do not. The transuranium elements are chemically and electronically similar to the lanthanides only. For instance, available evidence shows that americium and curium are, respectively, quite equivalent to europium and gadolinium in known chemical and physical properties. Since the first two transuranium elements, neptunium and plutonium, have their respective thermal conductivity values of 0.063 and 0.0674 W cm^{-1} K^{-1} at 300 K and since most of the lanthanides have their thermal conductivity values between 0.10 and 0.14 W cm^{-1} K^{-1} at 300 K, it seems reasonable to estimate that the thermal conductivity of nobelium at 300 K is of the order of 0.1 W cm^{-1} K^{-1}. This estimated value is probably good to ±50 percent.

Osmium

The thermal conductivity of osmium has only been measured to 523 K for a polycrystalline sample, and since osmium has a close-packed hexagonal crystal structure and a melting point of 3283 ±10 K, it is clear that much more information on the thermal conductivity of osmium still has to be obtained.

The two higher curves 6 and 7 at low temperatures were obtained by Schriempf [1277] for two single crystal samples with heat flow at 60 and 16 degrees, respectively, to the *c*-axis of the crystal. For the time being, these are taken as approximately representing the thermal conductivities along the two principal crystalline axes, and recommended curves for the two samples having $\rho_0 =$ 0.02778 and 0.01665 $\mu\Omega$ cm, respectively, have been mathematically fitted to the data using equation (7) and $m = 5.80$, $n = 3.00$, $a'' = 3.79 \times 10^{-10}$ as listed in table 1 and $\beta = 1.137$ and 0.682, respectively, for $k_\perp$ and $k_\parallel$. The recommended values for polycrystalline osmium below 30 K were derived from $k_\perp$ and $k_\parallel$ as the average of those calculated from equations (11) and (12). These values can also be obtained from equation (7) by using a value of 0.957 for β.

The curve for polycrystalline osmium has been extended smoothly to higher temperatures following the trend of curves 1–3 of White and Woods [1549, 1553]. It falls smoothly and flattens out to an almost constant value as it passes through the data of Powell, Tye, and Woodman [1141, 1145] (curves 4 and 5) for the range 323 to 523 K. Over this temperature range these workers found the Lorenz function to increase from 2.61×10^{-8} to 2.65×10^{-8} V^2 K^{-2}, so a further increase of from 2.65×10^{-8} to 2.70×10^{-8} has been assumed for the purpose of deriving thermal conductivity values from the electrical resistivity data reported to 1673 K by Powell, Tye, and Woodman [1141]. The thermal conductivity would appear to remain sensibly constant to this temperature, as is shown by the short-dashed line on the figure. No information is available for osmium at higher temperature for either the solid or liquid state.

The recommended values are for well-annealed high-purity osmium and those below 150 K for $k_\parallel$, $k_\perp$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 0.0167, 0.0278, and 0.0234 $\mu\Omega$ cm, respectively. The values are thought to be accurate to within ±15 percent of the true values at temperatures below 300 K, ±5 percent from 300 to 500 K, and ±10 percent above 500 K.

TABLE 110. Recommended thermal conductivity of osmium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

	‖ to c-axis	⊥ to c-axis	Poly-crystalline	Polycrystalline	
T	k	k	k	T	k
0	0	0	0	250	0.886*
1	1.47*	0.88*	1.05*	273.2	0.880*
2	2.93	1.76	2.09	298.2	0.876*
3	4.40	2.64	3.14	300	0.876*
4	5.86	3.52	4.18	323.2	0.874
5	7.32	4.39	5.22	350	0.870
6	8.77	5.27	6.26	373.2	0.870
7	10.2	6.13	7.28	400	0.869
8	11.6	6.99	8.29	473.2	0.869
9	13.0	7.83	9.29	500	0.869
10	14.3	8.65	10.2	573.2	0.869*
11	15.6	9.44	11.2	600	0.869*
12	16.8	10.2	12.1	673.2	0.869*
13	17.9	10.9	12.9	700	0.869*
14	18.9	11.6	13.7	773.2	0.869*
15	19.7	12.2	14.3	800	0.869*
16	20.4	12.7	14.9	873.2	0.869*
18	21.3	13.4	15.7	900	0.869*
20	21.5	13.8	16.0	973.2	0.869*
25	19.4	13.2	15.0	1000	0.869*
30	15.4	11.1	12.4	1073.2	0.869*
35			9.17	1100	0.869*
40			6.38	1173.2	0.869*
45			4.58	1200	0.869*
50			3.42	1273.2	0.869*
60			2.18	1300	0.869*
70			1.65	1373.2	0.869*
80			1.39	1400	0.869*
90			1.24	1473.2	0.869*
100			1.14	1500	0.869*
123.2			1.02	1573.2	0.869*
150			0.962*	1600	0.869*
173.2			0.932*	1673.2	0.869*
200			0.908*		
223.2			0.896*		

†The recommended values are for well-annealed high-purity osmium, and those below 150 K for $k_\|$, $k_\perp$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 0.0167, 0.0278, and 0.0234 μΩ cm, respectively.

*Extrapolated or interpolated.

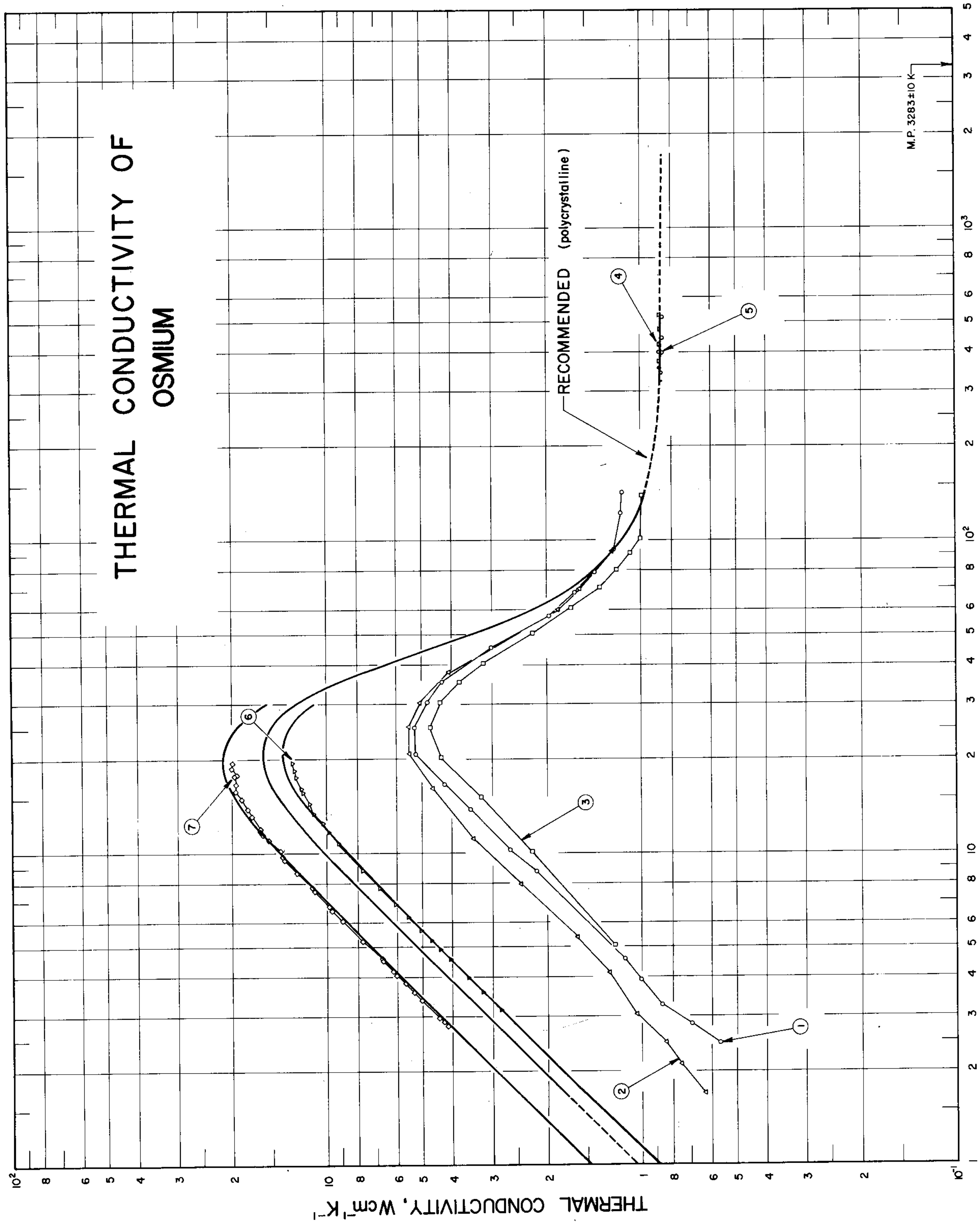

THERMAL CONDUCTIVITY OF
OSMIUM
RECOMMENDED (polycrystalline)
M.P. 3283±10 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 12O

TABLE 111. THERMAL CONDUCTIVITY OF OSMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1553	White, G. K. and Woods, S. B.	1958	L	2.0-140	Os 2	99.995 pure; specimen 0.6 cm in dia and 6 cm long; powder supplied by Johnson, Matthey and Mallory, Ltd; specimen prepared by arc-melting of processed powder; residual electrical resistivity 0.10 μohm cm, electrical resistivity ratio $\rho(295K)/\rho_0 = 92.6$.
2	1553	White, G. K. and Woods, S. B.	1958	L	2.0-91	Os 3	99.99 pure; specimen 0.188 in. dia and 5 cm long; powder supplied by Baker Platinum Co.; specimen prepared by arc-melting of pressed powder; residual electrical resistivity 0.0872 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0 = 105.7$.
3	1549	White, G. K. and Woods, S. B.	1957	L	10-100	Os 1	99.995^+ pure; powder supplied by Johnson, Matthey and Co., Ltd; specimen prepared by arc-melting of processed powder in helium atm; electrical resistivity ratio $\rho(295K)/\rho(4.2K) = 20.41$; reported values taken from smoothed curve.
4	1141	Powell, R. W., Tye, R. P., and Woodman, M. J.	1962	C	323-523		0.03 Ru, 0.002 Rh, 0.0005 Fe, 0.0002 Cu, and 0.0001 Ag; specimen 0.489 in dia and 2.7 cm long; supplied by Johnson, Matthey and Co., Ltd; prepared by argon-arc melting and ground to size; density 22.45 g cm^{-3}; electrical resistivity 8.532 and 0.272 μohm cm at 273 and 4.2 K, respectively; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 31.4$; data extracted from smooth curve.
5	1145	Powell, R. W., et al.	1967	C	337-518		0.03 Ru, 0.002 Rh, 0.0005 Fe, 0.0002 Cu, and 0.0001 Ag; polycrystalline; specimen 0.489 cm in dia and 2.7 cm long supplied by Johnson, Matthey and Co., Ltd; arc-melted and ground; annealed at 1820 K; density 22.45 g cm^{-3}; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 33.3$ (the paper reported density as 12.45 g cm^{-3}, and the latter ratio as 22.45, apparently a typographical error. This has been confirmed by the author).
6	1277	Schriempf, J. T.	1968	L	3.2-20	Os 1	Single crystal; obtained from Engelhard Industries; form factor 40.7 cm^{-1}; prepared by electron-beam zone-refining at $\sim 10^{-8}$ torr; residual electrical resistivity $\rho_0 = 0.02778$ μohm cm; electrical resistivity 8.69 μohm cm at 297 K; electrical resistivity ratio $\rho(297K)/\rho_0 = 314$; specimen axis 60° to c-axis; Lorenz number 2.49×10^{-8} V^2 K^{-2}.
7	1277	Schriempf, J. T.	1968	L	2.8-20	Os 2	Single crystal; form factor 30.4 cm^{-1}; same supplier and fabrication method as the above specimen; residual electrical resistivity $\rho_0 = 0.01665$ μohm cm; electrical resistivity 6.57 μohm cm at 297 K; electrical resistivity ratio $\rho(297K)/\rho_0 = 396$; specimen axis 16° to c-axis; Lorenz number 2.48×10^{-8} V^2 K^{-2}.

Oxygen

No information is available for the thermal conductivity of solid oxygen. The thermal conductivity of oxygen in each of the other physical states is discussed separately below.

Saturated Liquid

Six experimental investigations were located in the literature on the thermal conductivity of liquid oxygen. The extensive measurements of both Ziebland and Burton [228, 1611] and Tsederberg and Timrot [1469, 1431] were considered to be reliable from the standpoint of the experimental method and procedure. Values of the thermal conductivity of the saturated liquid, read from their diagrams, were used and given equal weight in this analysis. The data of Keyes [748], obtained near the saturated vapor pressures, were also used for the estimations of the most probable values. On the other hand, three investigations reported by Hammann [583], Prosad [1160] and Waterman [1503] give very high values. Therefore, no weight was given to these three sets of data.

The correlation formula obtained for the saturated liquid is given by

$$k\ (\mathrm{mW\ cm^{-1}\ K^{-1}}) = 2.37989 - 6.97803 \cdot 10^{-3}\,T - 3.09847 \cdot 10^{-5}\,T^2$$

In deriving this formula, values near the critical point were excluded, because the thermal conductivity of the liquid decreases at an extremely rapid rate near the critical point and the experimental accuracy also decreases. Therefore, the equation should be valid in the temperature range from 50 to 140 K and is found to fit the above-enumerated values with a mean deviation of 0.95 percent and a maximum of 2.7 percent. The recommended values up to 140 K were calculated from this equation. Above 140 K they were obtained from a large-scale plot of the available information. After this work had been completed, the tables of Vasserman and Rabinovich [1481] became available. They only tabulated the thermal conductivity for integral pressures and temperatures but it was found possible to obtain approximate values for saturation conditions from their tables. They chose the same works as the basis for their tables and the approximate values derived from their tables agree with those recommended here to an average deviation of 0.7 percent and a maximum deviation of 1.0 percent.

In the departure plot, only a part of the results of Prosad (curve 3) is plotted to aid clarity. The recommended values up to 150 K should be accurate to within about two percent. At the critical point itself an uncertainty of up to fifteen percent is possible.

Saturated Vapor

No experimental data were located. Various correlations were plotted on a large scale. Between the normal boiling and critical points, that of Schaefer and Thodos [1257] appeared lower than those of Petrozzi [24] and Brewer [205], the latter evidently being based on a monatomic gas correlation [1058]. Good agreement was obtained with the estimation of Johnson [684]. The [1257] correlation agreed well with the values deduced from the atmospheric pressure correlation at the normal boiling point. A few values for the saturated vapor state can be deduced from the tables of Vasserman and Rabinovich [1481] for integral pressures and temperatures, for temperatures from 120 to 150 K. Such values were lower than those recommended here by less than five percent departure. Experimental measurements are highly desirable to confirm the various correlations.

The recommended values were obtained from the [1257] correlation and are thought to have an uncertainty of a few percent below 100 K, the uncertainty then increasing to about ten percent at 125 K and as much as fifteen percent at the critical point.

Gas

Experimental data for the thermal conductivity of gaseous oxygen extend from about 80 K to 1380 K. Above 787 K only the measurements of Geier and Schafer [484] are available.

As shown by the departure plots, most previous experimental and correlated values agree to within one percent between about 80 and 330 K and the recommended values, derived from a smooth curve drawn through the experimental data plotted as a function of temperature, should be accurate to one-half percent in this temperature range. In the range 330 to 787 K only two sets of measurements [454, 484] are available for temperatures above 373 K. It was decided to base the recommended values for the higher temperatures upon the Geier and Schafer [484] data as the results of these workers have been found to be accurate for other gases and somewhat superior to those of Franck [454]. The departure plot for temperatures from 700 to 1400 K shows that the Geier and Schafer data also fall nicely between previous estimates of the high temperature values.

The accuracy of the recommended values can thus be assessed as within one-half percent from 80 to 300 K, two percent from 330 to 600 K, four percent from 600 to 900 K and probably within six percent above 900 K. Further experimental measurements are to be desired below the normal boiling point and above 373 K. The NBS [271] tables show a maximum deviation of —1.8 percent at 700 K, the average deviation from 100 to 1000 K being —0.6 percent. The Russian standards tables [1474] agree with the above estimates, except near 100 K and from 330 to 400 K.

TABLE 112. Recommended thermal conductivity of oxygen

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor	
T	$k \times 10^3$	T	$k \times 10^3$
55	1.90		
60	1.85		
65	1.80	90	0.081*
70	1.74	95	0.087*
75	1.682	100	0.093*
80	1.623	105	0.100*
85	1.563	110	0.108*
90	1.501	115	0.116*
95	1.437	120	0.124*
100	1.372	125	0.135*
105	1.306	130	0.15*
110	1.237	135	0.16*
115	1.168	140	0.18*
120	1.096	145	0.21*
125	1.023	150	0.25*
130	0.949	155	0.41*‡
135	0.873		
140	0.796		
145	0.712		
150	0.610		
155	0.41*‡		

*Estimated or extrapolated.
‡Pseudo-critical value.

TABLE 112. Recommended thermal conductivity of oxygen—Continued
(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Gas
(At 1 atm)

T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
90	0.0813				
100	0.0905	600	0.480	1100	0.771
110	0.0998	610	0.487	1110	0.776
120	0.1092	620	0.493	1120	0.781
130	0.1187	630	0.500	1130	0.786
140	0.1281	640	0.506	1140	0.791
150	0.1376	650	0.513	1150	0.796
160	0.1466	660	0.519	1160	0.801
170	0.1556	670	0.525	1170	0.806
180	0.1646	680	0.532	1180	0.811
190	0.1735	690	0.538	1190	0.816
200	0.1824	700	0.544	1200	0.821
210	0.1911	710	0.550	1210	0.826
220	0.1997	720	0.556	1220	0.831
230	0.2083	730	0.562	1230	0.836
240	0.2168	740	0.568	1240	0.841
250	0.2254	750	0.574	1250	0.846
260	0.2339	760	0.579	1260	0.851
270	0.2424	770	0.585	1270	0.856
280	0.2509	780	0.591	1280	0.861
290	0.2592	790	0.597	1290	0.866
300	0.2674	800	0.603	1300	0.871
310	0.2753	810	0.609	1310	0.876
320	0.2831	820	0.615	1320	0.881
330	0.2907	830	0.620	1330	0.886
340	0.2982	840	0.626	1340	0.891
350	0.3056	850	0.632	1350	0.896
360	0.3130	860	0.638	1360	0.901
370	0.3204	870	0.644	1370	0.906
380	0.3276	880	0.650	1380	0.911
390	0.3348	890	0.655	1390	0.916
400	0.342	900	0.661	1400	0.921
410	0.349	910	0.667	1410	0.926
420	0.356	920	0.672	1420	0.931
430	0.363	930	0.678	1430	0.936
440	0.370	940	0.684	1440	0.941
450	0.377	950	0.689	1450	0.946
460	0.384	960	0.695	1460	0.951
470	0.391	970	0.701	1470	0.956
480	0.398	980	0.706	1480	0.960
490	0.405	990	0.712	1490	0.965
500	0.412	1000	0.717	1500	0.970
510	0.419	1010	0.723		
520	0.426	1020	0.728		
530	0.433	1030	0.734		
540	0.440	1040	0.739		
550	0.447	1050	0.745		
560	0.453	1060	0.750		
570	0.460	1070	0.755		
580	0.467	1080	0.760		
590	0.474	1090	0.765		

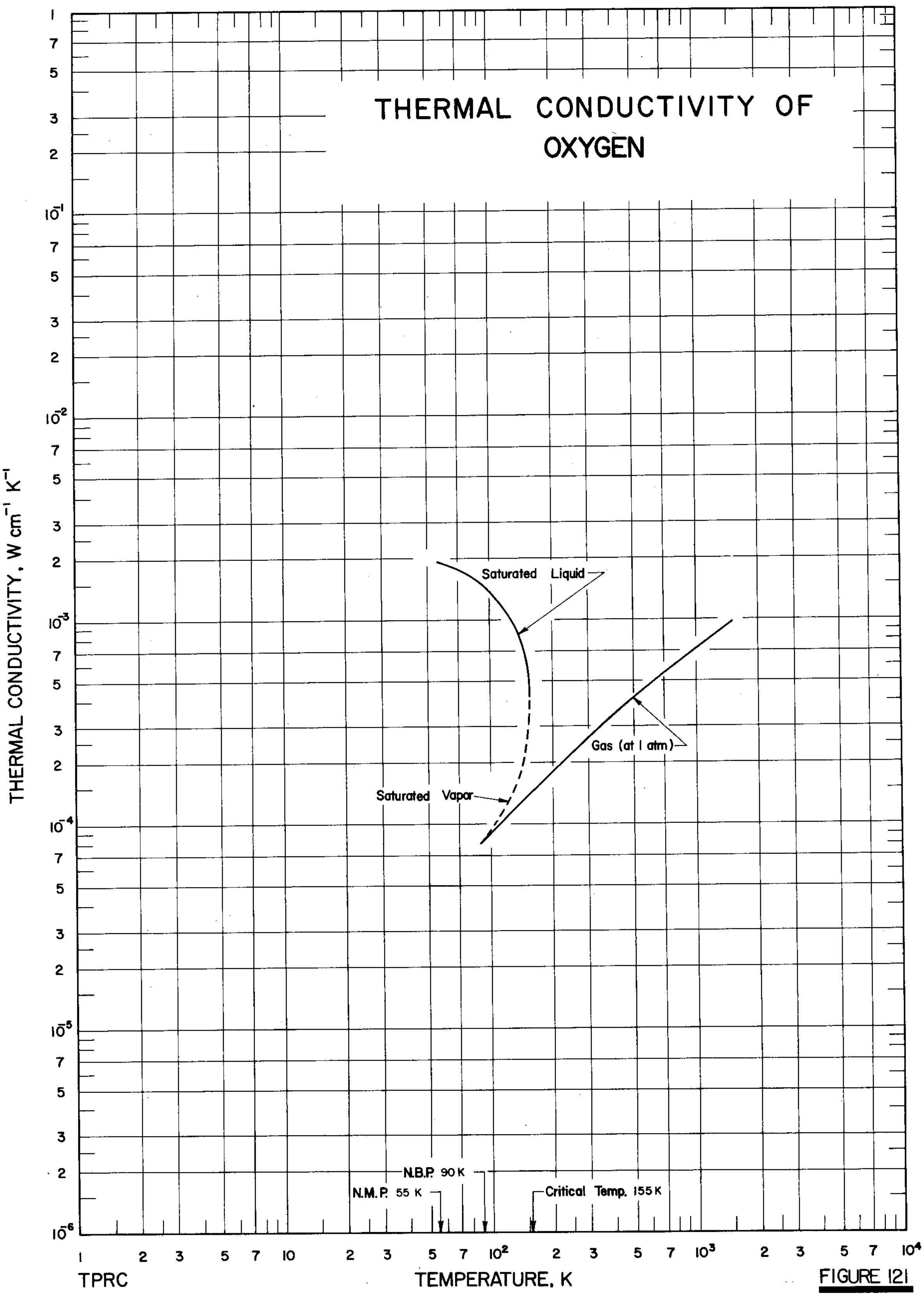
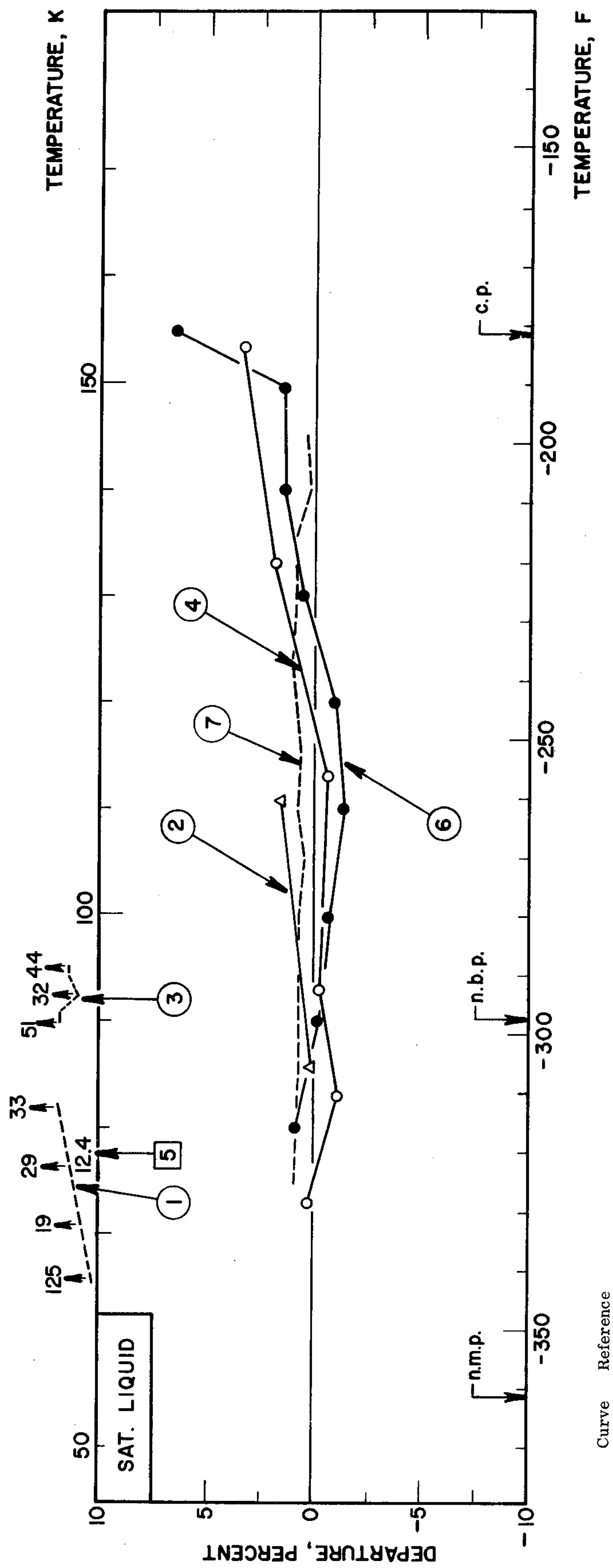

THERMAL CONDUCTIVITY OF
OXYGEN
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.B.P. 90 K
N.M.P. 55 K
Critical Temp. 155 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

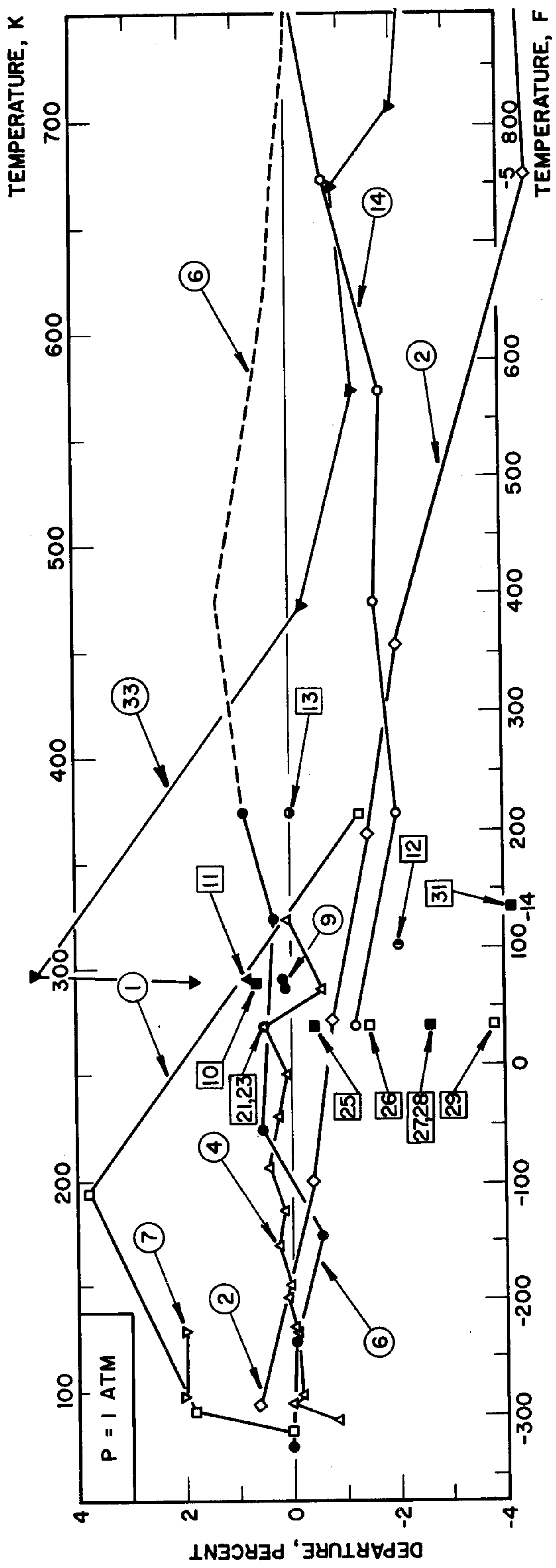
FIGURE 121

FIGURE 122. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID OXYGEN



Curve	Reference
1	583
2	748
3	1160
4	1431
5	1503, 1504
6	228, 1611
7	1481

FIGURE 123. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS OXYGEN



Curve	Reference	Curve	Reference
1	401	14	484
2	454	21	532
4	689	23	1041
6	746	25	710
7	748	26	1517
9	893	27	651
10	1285	28	402
11	1502	29	1570
12	1357	31	1415
13	267, 268	33	1530

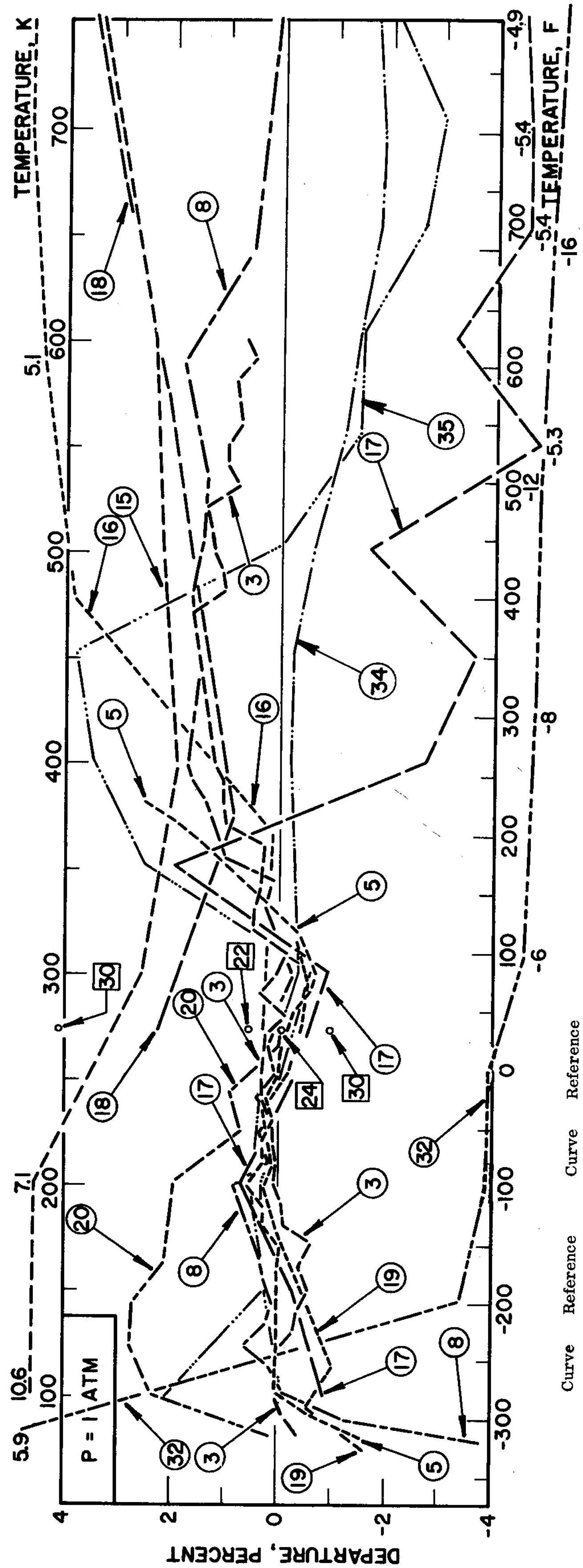
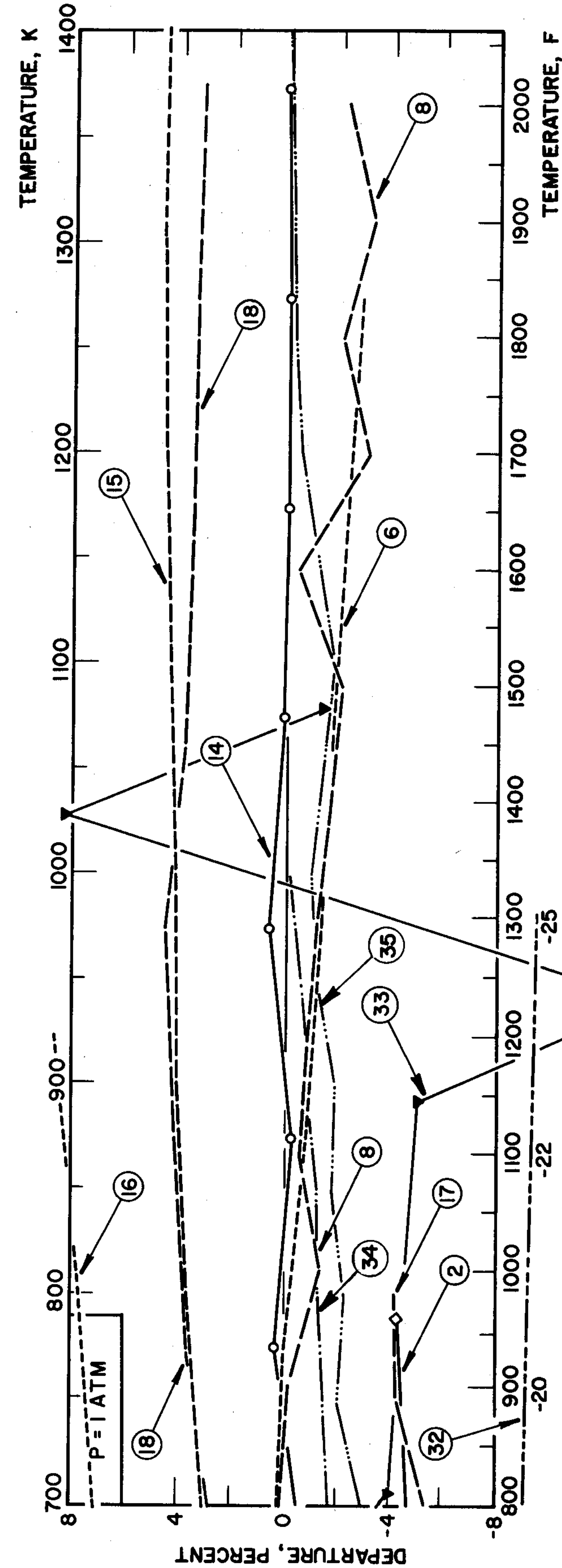


FIGURE 123. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS OXYGEN (continued)

Curve	Reference	Curve	Reference
3	604,605	20	579
5	689	22	1041
8	839	24	257
15	1381	30	193
16	856	32	1014
17	454	34	271
18	1203	35	1474
19	1428		

FIGURE 123. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS OXYGEN (continued)



Curve	Reference
2	454
6	746
8	839
14	484
15	1381
16	856
17	454
18	1203
32	1014
33	1530
34	271
35	1474

Palladium

At low temperatures the recommended values for a sample having $\rho_0 = 0.0123\ \mu\Omega$ cm are based on the highest (curve 7) of the six sets of data of Kemp, et al. [736]. Below 1.5 T_m the values were calculated using $m = 2.40$, $n = 2.00$, $\alpha'' = 1.54 \times 10^{-4}$, and $\beta = 0.502$. The measurements made on this sample extended to 157 K, and from 91 K to this upper limit their values are within 3 percent of a mean of 0.755 W cm^{-1} K^{-1}. As the values (curve 18) of Powell, et al. [1141] made over the range 314 to 502 K also agree with 0.755 W cm^{-1} K^{-1} to within these limits, the curve which fitted the data of Kemp, et al. has been extended to show a shallow minimum in between and then to follow the recent measurements of Laubitz and Chandrashekhar [819] (curve 24) to the highest temperature.

It is interesting to note that all the low-temperature curves except curve 19 of Schriempf [1273] can be well fitted by equation (7) using the constants, m, n, α'' given above and different values of β. Curve 19 has its T_m displaced on the low side by several degrees and was fitted by Schriempf with a three-term equation similar to equation (10) to account for the effect of electron-electron scattering. It is doubtful that the contribution of electron-electron scattering to thermal resistivity can be significant for a sample of such a purity.

No information is available for the thermal conductivity of molten palladium.

The recommended values are thought to be accurate to within ±10 percent below room temperature, ±5 percent from room temperature to about 1000 K, and ±10 percent above 1000 K. The values at temperatures below 150 K are, of course, applicable only to a sample having $\rho_0 = 0.0123\ \mu\Omega$ cm.

TABLE 113. Recommended thermal conductivity of palladium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	0.715*
1	1.99*	273.2	0.716*
2	3.96*	298.2	0.718
3	5.86	300	0.718
4	7.61	323.2	0.721
5	9.13	350	0.726
6	10.3	373.2	0.730
7	11.1	400	0.736
8	11.6	473.2	0.755
9	11.7	500	0.763
10	11.5	573.2	0.787
11	11.2	600	0.797
12	10.7	673.2	0.823
13	10.1	700	0.833
14	9.49	773.2	0.860
15	8.88	800	0.869
16	8.28	873.2	0.896
18	7.08	900	0.906
20	5.98	973.2	0.932
25	4.04	1000	0.942
30	2.85	1073.2	0.971
35	2.15	1100	0.981
40	1.73	1173.2	1.01
45	1.44	1200	1.02
50	1.24	1273.2	1.04
60	0.983	1300	1.05
70	0.868	1373.2	1.07
80	0.811	1400	1.07
90	0.783	1473.2	1.09
100	0.765	1500	1.10
123.2	0.742	1573.2	1.11
150	0.727	1600	1.12
173.2	0.720*	1673.2	1.13
200	0.716*	1700	1.14
223.2	0.715*	1773.2	1.15*
		1800	1.15*

†The recommended values are for well-annealed high-purity palladium, and those below 150 K are applicable only to a specimen having $\rho_0 = 0.0123$ $\mu\Omega$ cm.

*Extrapolated or interpolated.

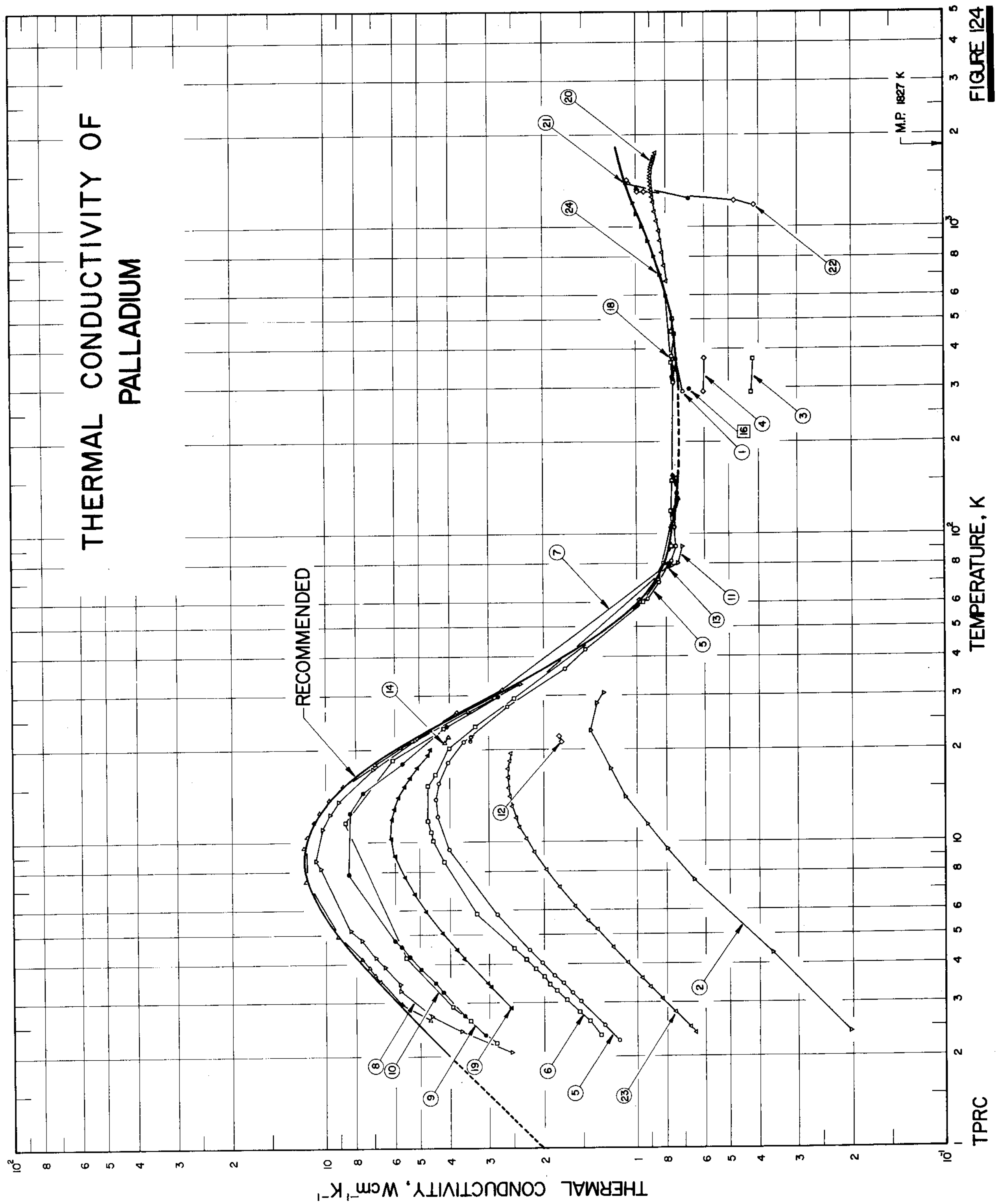

THERMAL CONDUCTIVITY OF PALLADIUM
FIGURE 124
RECOMMENDED
M.P. 1827 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, $W cm^{-1} K^{-1}$
TPRC

TABLE 114. THERMAL CONDUCTIVITY OF PALLADIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373		Pure; specimen 1.610 cm dia and 27.0 cm long; cast; density 11.96 g cm^{-3} at 18 C; electrical conductivity 9.33 and 7.27 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
2	937, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.4-31	Pd I	99.995 pure; annealed polycrystal; specimen 0.152 cm in dia and 2.82 cm long; supplied by Johnson, Matthey and Co., Ltd; electrical resistivity ratio $\rho(293K)/\rho(20K) = 34.1$.
3	116	Barratt, T.	1914	F	290, 373		Commercially pure; specimen 0.1010 cm in dia and 35.1 cm long; supplied by Messr. Isenthal and Co.; electrical resistivity 17.815 and 18.532 μohm cm at 4.96 and 93.57 C, respectively.
4	116	Barratt, T.	1914	L	290, 373		Pure; specimen 0.0905 cm in dia and 35.2 cm long; electrical resistivity 10.334 and 13.497 μohm cm at 13.26 and 99.14 C, respectively.
5	736	Kemp, W.R.G., Klemens, P.G., Sreedhar, A.K., and White, G.K.	1955	L	2.3-154	Pd I	99.995$^+$ pure; traces of Ca, Cu, Mg, Si, and Ag; specimen 3 mm in dia; supplied by Johnson, Matthey and Co., Ltd; strained.
6	736	Kemp, W.R.G., et al.	1955	L	2.3-150	Pd II	The above specimen annealed in vacuo for about 4 hrs at 250 C.
7	736	Kemp, W.R.G., et al.	1955	L	2.7-157	Pd III	The above specimen annealed at 450 C for ~4 hrs.
8	736	Kemp, W.R.G., et al.	1955	L	2.1-131	Pd IV	The above specimen annealed at 650 C for about 4 hrs.
9	736	Kemp, W.R.G., et al.	1955	L	2.4-91	Pd V	The above specimen annealed at 1000 C for about 4 hrs.
10	736	Kemp, W.R.G., et al.	1955	L	2.2-24	Pd VI	The above specimen drawn to 2 mm dia then annealed at 450 C for about 4 hrs; electrical resistivity given as $\rho = 1.82 \times 10^{-8} + 2.12 \times T^{3.2}$ ohm cm (the second term should have a factor 10^{-12}).
11	561	Grüneisen, G. and Reddemann, H.	1934	L	79-91	Pd I	Medium pure; ice-point electrical resistivity = 9.98 μohm cm.
12	561	Grüneisen, G. and Reddemann, H.	1934	L	21, 22	Pd I	The above specimen measured after 5.5 months; ice-point electrical resistivity = 9.93 μohm cm.
13	561	Grüneisen, G. and Reddemann, H.	1934	L	21-91	Pd II	Very pure; drawn; ice-point electrical resistivity = 9.81 μohm cm.
14	561	Grüneisen, G. and Reddemann, H.	1934	L	21-81	Pd II	The above specimen annealed for 2 hrs at 360 C; ice-point electrical resistivity = 9.77 μohm cm.
15*	1624	Zolotukhin, G.E.	1956	P	375.2		Pure.
16	1299	Sharma, J.K.N.	1967	L	0.42-0.92		Pure.
17*	939, 1299	Mendelssohn, K., Sharma, J.K.N., and Yoshida, I.	1965	L	0.42-0.92		99.999 pure; polycrystalline; wire specimen with form factor 2.13 x 10^3 cm^{-1}; supplied by Johnson, Matthey and Co., Ltd; electrical resistivity 0.0647 μohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 171$; anomalous peak of thermal conductivity at 0.67 K.

* Not shown in figure.

TABLE 114. THERMAL CONDUCTIVITY OF PALLADIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
18	1141, 1145	Powell, R. W., Tye, R. P., and Woodman, M. J.	1962	C	314-502		0.005 Rh, 0.0005 Au, 0.0005 Fe, 0.0002 Pt, 0.0001 Cu, and <0.0001 Ag; polycrystalline; specimen 0.636 cm in dia and 6.1 cm long; supplied by Johnson, Matthey and Co., Ltd; density 12.02 g cm^{-3}; electrical resistivity 2.72, 7.05, 10.9, 14.5, and 17.9 μohm cm at 100, 200, 300, 400, and 500 K, respectively; $\rho(273K)/\rho(4.2K) = 69$; Armco iron used as comparative material.
19	1273, 1275	Schriempf, J. T.	1968	L	2.9-20		Polycrystalline; rod specimen 2.4 mm in dia; electrical resistivity ratio $\rho(298K)/\rho(4.2K) = 400$; residual electrical resistivity $\rho_0 = 0.02687$ μohm cm; electrical resistivity 0.0271, 0.0272, 0.0273, 0.0275, 0.0275, 0.0279, 0.0283, 0.0288, 0.0296, 0.0308, and 0.0320 μohm cm at 2.71, 3.11, 3.68, 4.31, 4.48, 5.54, 6.46, 7.37, 8.53, 9.69, and 10.7 K, respectively; Lorenz function reported as 2.44, 2.35, 2.25, 2.07, 1.91, 1.82, 1.70, 1.64, 1.57, 1.51, 1.48, 1.44, 1.43, 1.41, 1.38, 1.37, 1.36, 1.36, and 1.35 x 10^8 V^2 K^{-2} at 2.8, 4.3, 5.7, 7.9, 10.0, 11.1, 12.6, 13.4, 14.3, 15.3, 15.9, 16.4, 16.8, 17.3, 17.7, 17.9, 18.3, 18.5, and 19.0 K, respectively.
20	1619	Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V.	1969	P	665-1742	1	Spectroscopically pure; specimen 8 x 8 mm^2 in cross-sectional area and 0.313 mm thick; supplied by Belyaev, I. F. and Kuranov, A. A.; annealed 5 hrs in a vacuum of ~1 x 10^{-5} mm Hg at 1200 K, then heated briefly to 1700 K; electrical resistivity ratio $\rho(293K)/\rho(4.2K) \cong 70$; thermal conductivity values calculated from the measurement of thermal diffusivity, using specific heat and density data taken from Savitskii, E. M., et al. ("Alloys of Palladium", in Russian, Izd. Nauka, Moscow, p. 19, 1967); reported values extracted from smooth curve.
21	673	Jain, S. C., Sinha, V., and Reddy, B. K.	1969	E	1240-1390	1	Spectroscopically pure; 0.1 cm dia x 20 cm long; obtained from Johnson, Matthey and Co.
22	673	Jain, S. C., et al.	1969	E	1175-1415	2	99.9 pure; 0.3 cm dia x 20 cm long; obtained from H. A. N. Mehra, Calcutta; electrical resistivity 34.8, 37.1, 38.5, 39.3, 40.4, 41.5, and 42.3 μohm cm at 1106, 1188, 1246, 1278, 1335, 1398, and 1462 K, respectively.
23	1278	Schriempf, J. T., Schindler, A. I., and Mills, D. L.	1969	L	2.4-20		~99.884 Pd, 0.116 Ni, and 0.0002 Fe (calculated compositions, 0.21 at.% Ni); specimen 0.125 in. in dia and 6 in. long; prepared from Johnson-Matthey Pd sponge and Johnson-Matthey nickel rod of 99.999 purity; melted in quartz crucible under argon atm and purified by use of dry-ice and acetone trap, swaged, annealed at 900 C for 4.5 hrs in a vacuum of 10^{-5} torr; residual electrical resistivity $\rho_0 = 0.08866$ μohm cm; electrical resistivity 10.84 μohm cm at 297 K.
24	819	Laubitz, M. J. and Chandrashekhar, G. V.	1969		300-1200		99.987 pure; obtained from Engelhard Ind.; density 12.016 g cm^{-3}; electrical resistivity ratio $\rho(298K)/\rho_0 = 250$; preliminary results.

Phosphorus

Phosphorus is an element for which relatively little thermal conductivity information is available. Black phosphorus, with an orthorhombic crystal structure, appears to have first been formed at high pressure by Bridgman [207, 208], who considered its room-temperature thermal conductivity to be much greater than that of glass. Only in recent years have thermal conductivity measurements been reported for both the white (or yellow) and black forms of phosphorus. It is significant that the thermal conductivity of black phosphorus exceeds that of white (or yellow) phosphorus by a factor of over 20 and that glass has an intermediate value. Information on the red phosphorus, which is used in large quantity in the manufacture of safety matches, is still not available.

The data of Slack [1321] (curve 1) appear to be satisfactory over the range 2.7 to 300 K and can be regarded as typical for thermal conductivity of black phosphorus.

The two available sets of data for white (or yellow) phosphorus only cover temperatures a little above and below the melting point and are in serious disagreement from several points of view. Kramer and Schmeiser [785] (curve 2) obtained a strong positive coefficient for both solid and liquid phases with no marked discontinuity at the melting point, whereas Turnbull [1434] (curves 3 and 4) obtained small negative coefficients for both phases with $k_S/k_L \approx 1.22$; also his value for k_S was about 1/3 that of Kramer and Schmeiser.

The drop reported by Turnbull is shown to have some theoretical support; furthermore, Turnbull used the same hot-wire method to determine the thermal conductivity of sulfur, for which his values are in good agreement with those of Kaye and Higgins [721], Yoshizawa, Sugawara, and Yamada [1587], and of Sugawara [1375].

On the basis of these considerations preference has been given to the data of Turnbull as representing the thermal conductivity of white (or yellow) phosphorus near its melting point; it should however be noted that his sample was stated to have 0.36 percent of dissolved water.

There is clearly need for further study on phosphorus, the black form to higher temperatures, the white (or yellow) form for a purer sample and a wider range of temperature, and the red form for the full temperature range.

The recommended values for white phosphorus at temperatures from 273 to 400 K are thought to be accurate to within ±10 percent, and those below 273 K and above 400 K are provisional. The values for black phosphorus are merely typical values.

TABLE 115. Recommended thermal conductivity of phosphorus†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid	
Black, polycrystalline		White		White	
T	k	T	k	T	k
0	0	200	0.00308*	317.3	0.00187
1	0.0000796*	223.2	0.00287*	323.2	0.00187
2	0.000645*	250	0.00265*	350	0.00183*
3	0.00220	273.2	0.00250*	373.2	0.00181*
4	0.00511	298.2	0.00236*	400	0.00178*
5	0.00998	300	0.00235	473.2	0.00170*
6	0.0167	317.3	0.00226*	500	0.00167*
7	0.0255				
8	0.0367				
9	0.0497				
10	0.0653				
11	0.0822				
12	0.101				
13	0.122				
14	0.144				
15	0.165				
16	0.187				
18	0.230				
20	0.272				
25	0.357				
30	0.401				
35	0.425				
40	0.435				
45	0.434				
50	0.427				
60	0.402				
70	0.377				
80	0.352				
90	0.328				
100	0.307				
123.2	0.266				
150	0.227				
173.2	0.201				
200	0.177				
223.2	0.160				
250	0.144				
273.2	0.132				
298.2	0.121				
300	0.121				

†The values are for high-purity phosphorus. Those for white phosphorus below 273 K and above 400 K are provisional and those for polycrystalline black phosphorus are merely typical values.
*Extrapolated.

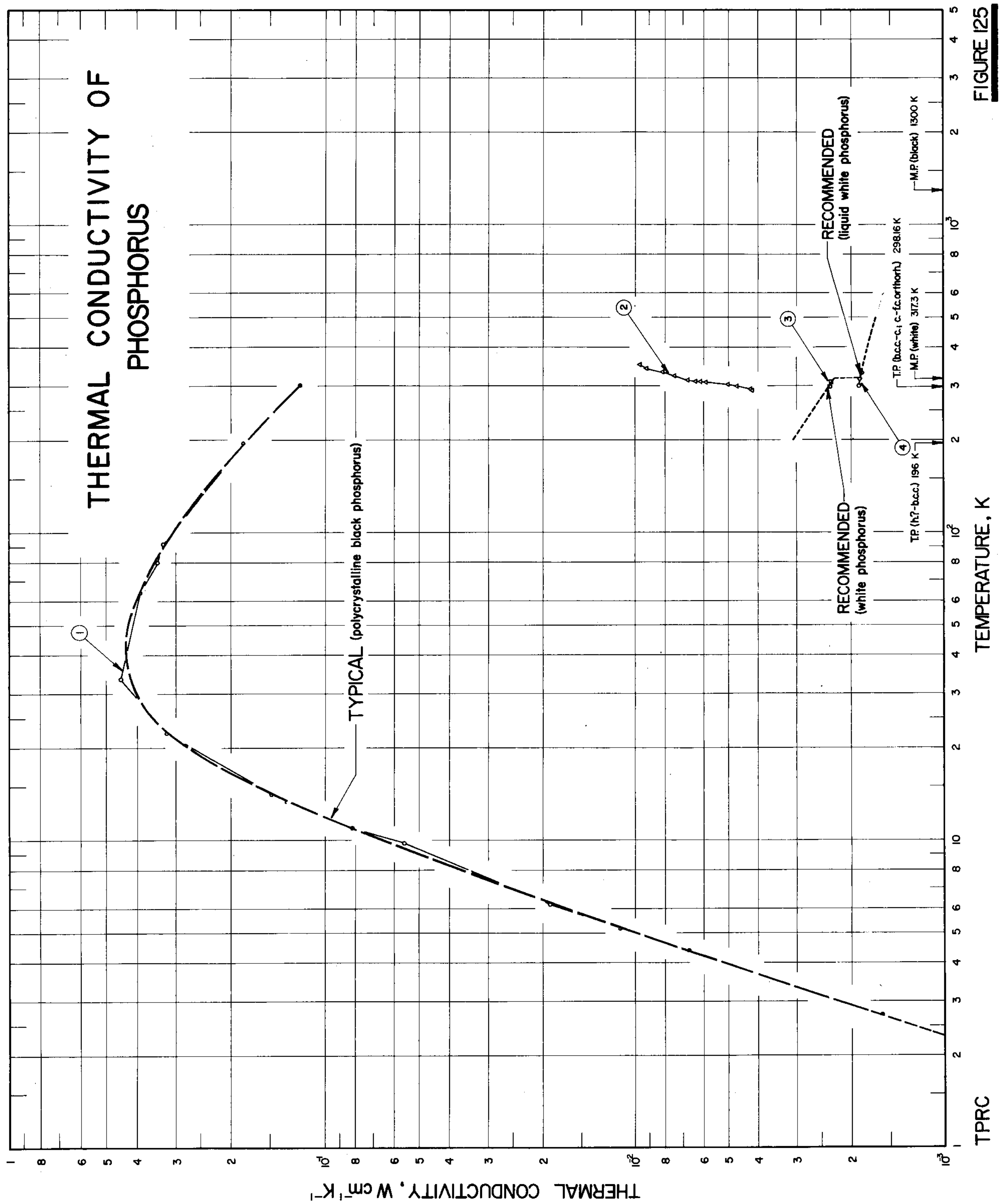

THERMAL CONDUCTIVITY OF PHOSPHORUS
TYPICAL (polycrystalline black phosphorus)
RECOMMENDED (white phosphorus)
RECOMMENDED (liquid white phosphorus)
M.P. (white) 317.3 K
M.P. (black) 1300 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 125

TABLE 116. THERMAL CONDUCTIVITY OF PHOSPHORUS - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1321	Slack, G.A.	1965	L	2.7-300		Prepared from 99.8 pure P; p-type; polycrystalline with crystal size ~ 200 μ; orthorhombic (black) phosphorus rod of dimensions 1.2 x 0.35 x 0.35 cm; cut from a larger ingot prepared by R.H. Wentorf of the General Electric Research Lab.; raw material for the ingot from the Fisher Scientific Co.; electrical resistivity 3.1 ohm cm at 300 K; carrier concentration 10^{15} cm^{-3}; heat flow approximately in the a-b plane of the crystallites.
2	785	Kramer, H. and Schmeiser, K.	1962	P	289-353		Yellow phosphorus; melting point 44.1 C; includes liquid phase.
3	1434	Turnbull, A.G.	1964	P	299,311		0.36 dissolved water, < 0.01 other total impurities; solid white α-phase (b.c.c.) phosphorus prepared from chemically pure yellow phosphorus which was treated with warm chromic acid and distilled water until water-white; melting point 44.0 ± 0.1 C.
4	1434	Turnbull, A.G.	1964	P	301-331		Similar to the above specimen except in liquid state(the first data point for supercooled liquid).

Platinum

Two sets of measurements exist for platinum in the 1 K and lower temperature range. Mendelssohn, Sharma, and Yoshida [939] had found small departures from linearity with temperature for several pure metals including platinum (curve 32). The second paper by Anderson, Peterson, and Robichaux [64] did not confirm any such anomalous behavior for the two metals studied, namely platinum (curve 53) and silver, but they did consider the electron-electron scattering in platinum to be about one order of magnitude greater than in silver.

Only two curves, those of Mendelssohn and Rosenberg [937] (curve 4) and White and Woods [1545] (curve 6) cover temperature ranges which include the low-temperature maximum. These curves are too close together to allow a well-defined value of m to be derived. The higher data of Mendelssohn and Rosenberg [937] have been fitted with a curve for which $n = 2.10$, $\alpha'' = 0.000301$, and $\beta = 0.433$. This curve is only applicable to platinum having $\rho_0 = 0.0106$ $\mu\Omega$ cm. It has been continued smoothly to pass 2 to 3 percent values at 83 and 91 K by Grüneisen and Goens [559] (curve 7) and Meissner [920] (curve 2). At about 300 K the curve has a minimum and lies some 2 percent above values by several workers including Schulze [1280] (curve 22), Meissner [920] (curve 2), Holm and Störmer [626] (curve 1), Jaeger and Diesselhorst [664] (curve 3), Zolotukhin [1624] (curve 18), Kannuluik and Carman [705] (curve 33), and Martin and Sidles [889] (curves 40 and 41), rather less above Bode [175] (curve 34), Moore, McElroy, and Barisani [987] (curve 49), and Laubitz and Van der Meer [820] (curve 46), and about 2 percent below Powell, et al. [1144] (curve 50), and 0.7 percent below Moore, et al. [987] (curve 48) for another sample.

For the range 300 to 1373 K the recommended curve for moderate and high temperatures continues to rise smoothly and is located between the values obtained by Flynn and O'Hagan [448] for a sample of 99.987 percent Pt by two different methods: one involving longitudinal heat flow (curves 54–57) and the other the direct electrical heating of a necked-down sample (curves 58–61). At 1200 K three determinations (curves 43–45) by Martin, Sidles, and Danielson [890], derived from thermal diffusivity measurements, gave values which ranged from 0.6 to 1.9 percent below this curve. 1200 K was the upper limit of their experiments, but Ciszek [279] (curve 47) has since extended the method to give values to 1611 K and the recommended curve continues to pass through this highest point and then gradually decreases in slope to tend towards that of another set of high-temperature data (curve 67) as derived from the measurements of Hopkins and Griffith [632] by Powell and Tye [1136]. This curve is very tentative for the region approaching the melting point and attention is directed to the lower and decreasing values derived by Zinov'ev, Krentsis, and Gel'd [1618] (curve 63) from thermal diffusivity determinations which extended to 1994 K. As however similar measurements made on other metals by these workers, notably in titanium, gave values that were considered low at the upper temperatures, little weight has so far been given to these values.

No determinations have been made on the thermal conductivity of molten platinum. Hopkins and Griffith [632] did extend their Lorenz function determinations by the electrically heated necked-down-sample method to the state where the constriction became a globule of molten platinum held in position by surface tension, but as values for the electrical resistivity were neither included, nor appear to be known, their data can not be treated to yield thermal conductivity. The Lorenz functions they obtained were about 25 percent above the theoretical value and were still increasing with temperature increase. It may be noted that Lebedev [821] gives the ratio of electrical resistance at liquid to solid state, ρ_L/ρ_S as 1.4. If this ratio holds true also for thermal conductivity, the thermal conductivity of molten platinum near melting point will be about 0.717 W cm^{-1} K^{-1}.

The estimated accuracy is within ±3 percent near room temperature, ±6 percent at about 100 K and 1200 K and ±10 percent below 100 K and at 2000 K. The tabulated values below 200 K are of course only for platinum having $\rho_0 = 0.0106$ $\mu\Omega$ cm.

TABLE 117. Recommended thermal conductivity of platinum†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	k	T	k
0	0	350	0.717
1	2.31	373.2	0.717
2	4.60	400	0.718
3	6.79	473.2	0.722
4	8.8	500	0.723
5	10.5	573.2	0.729
6	11.8	600	0.732
7	12.6	673.2	0.740
8	12.9	700	0.743
9	12.8	773.2	0.752
10	12.3	800	0.756
11	11.7	873.2	0.767
12	10.9	900	0.771
13	10.1	973.2	0.783
14	9.30	1000	0.787
15	8.41	1073.2	0.800
16	7.59	1100	0.806
18	6.12	1173.2	0.820
20	4.95	1200	0.826
25	3.13	1273.2	0.842
30	2.15	1300	0.848
35	1.68	1373.2	0.863
40	1.39	1400	0.871
45	1.22	1473.2	0.889
50	1.09	1500	0.895
60	0.947	1573.2	0.913
70	0.862	1600	0.919
80	0.815	1673.2	0.936
90	0.789	1700	0.942
100	0.775	1773.2	0.957
123.2	0.755	1800	0.961
150	0.740	1873.2	0.974
173.2	0.732	1900	0.978
200	0.726	1973.2	0.990
223.2	0.721	2000	0.994*
250	0.718	2045	1.004*
273.2	0.717		
298.2	0.716		
300	0.716		
323.2	0.716		

†The recommended values are for well-annealed high-purity platinum, and those below 200 K are applicable only to a specimen having $\rho_o = 0.0106$ $\mu\Omega$ cm.

*Extrapolated.

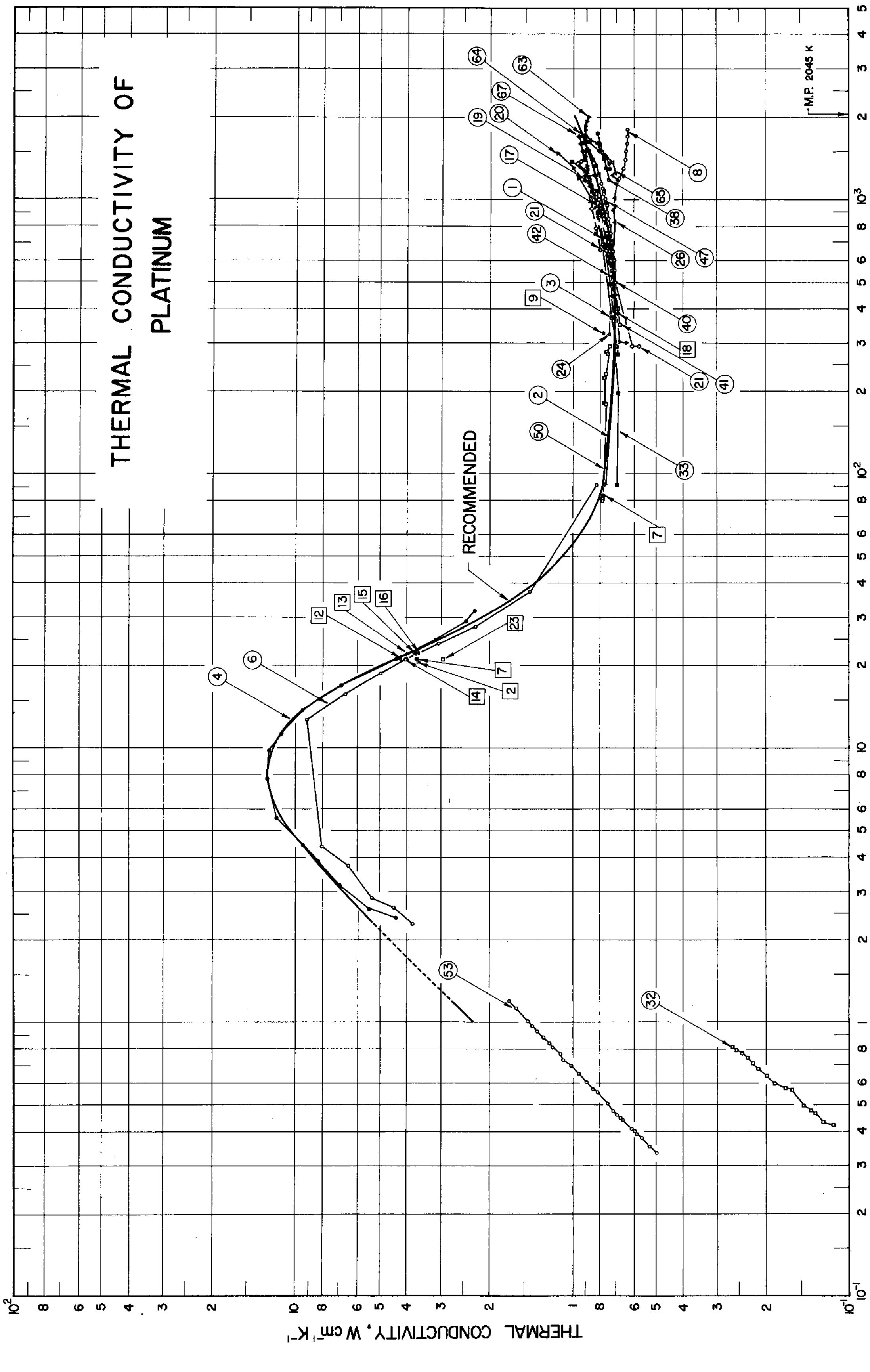

THERMAL CONDUCTIVITY OF
PLATINUM
RECOMMENDED
M.P. 2045 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 126

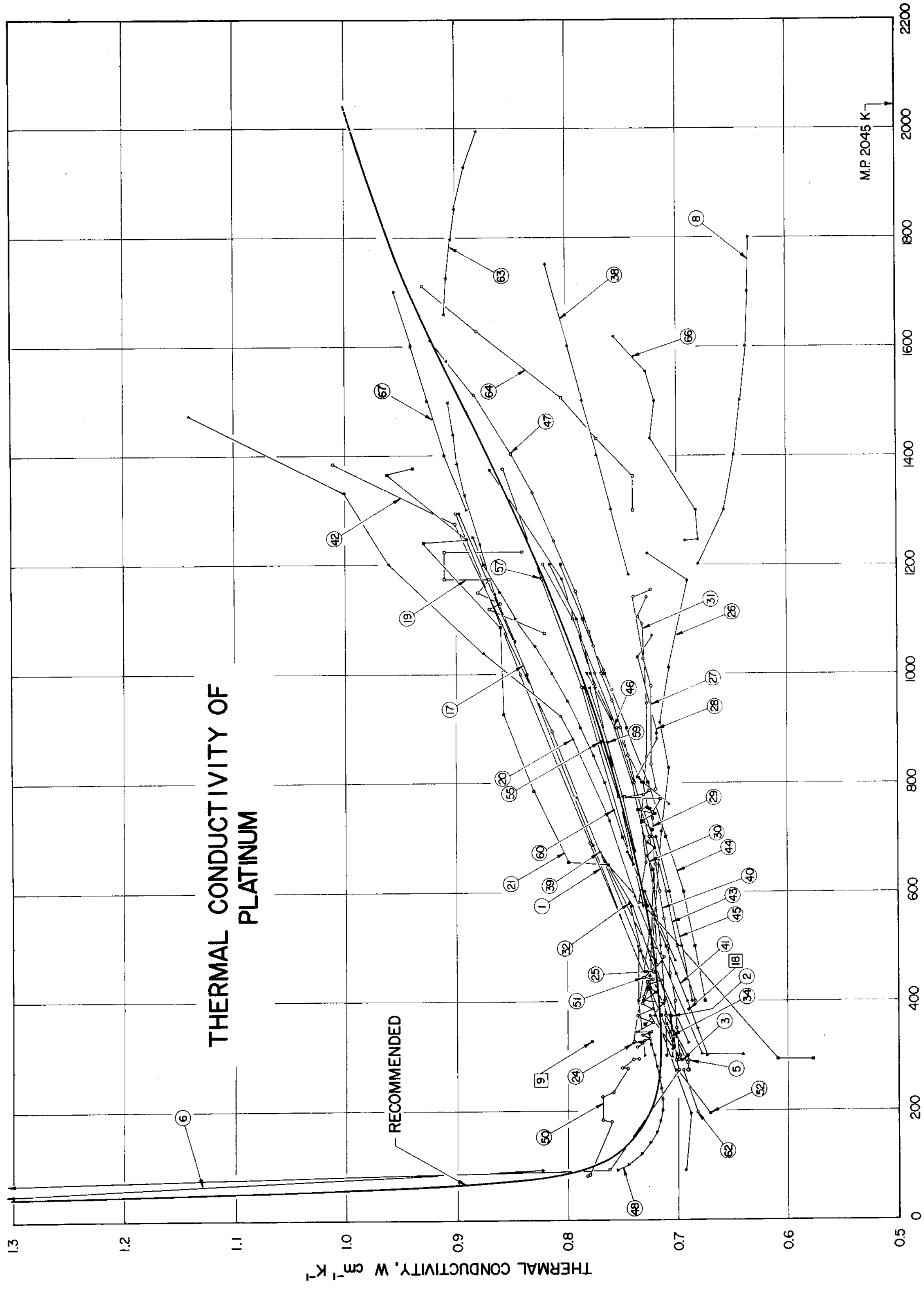

THERMAL CONDUCTIVITY OF PLATINUM
RECOMMENDED
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
M.P. 2045 K
TPRC
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3

FIGURE 127

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	626	Holm, R. and Störmer, R.	1930	E	293-1293		99.95 pure; electrical resistivity 9.90 and 10.805 μohm cm at 0 and 94 C, respectively.
2	920	Meissner, W.	1915	E	21-374		Very high purity; drawn and electrically annealed; electrical conductivity 10.2 and 9.5 x 10^4 ohm^{-1} cm^{-1} at 278.1 and 291 K, respectively.
3	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Pt II	Pure; specimen 1.614 cm in dia and 27.0 cm long; density 21.39 g cm^{-3} at 18 C; electrical conductivity 9.24 and 7.13 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
4	937, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.4-32	Pt I	99.999 pure; supplied by Johnson, Matthey and Co. (JM 2157b); 0.104 cm dia x 2.97 cm long; annealed; $\rho(293K)/\rho(20K) = 202$.
5	116	Barratt, T.	1913/14	F	273-373		Pure; electrical conductivity 10.24 and 7.35 x 10^4 ohm^{-1} cm^{-1} at 273 and 373 K, respectively.
6	1545	White, G. K. and Woods, S. B.	1957	L	2.3-91		99.99$^+$ pure; specimen 1.5 mm in dia; supplied by Baker Platinum Co.; annealed at 1050 C; electrical resistivity 0.0131, 0.0156, 0.0280, 0.056, 0.192, 0.46, 0.77, 1.80, 2.81, 4.81, 6.82, 8.0, 9.81, and 10.66 μohm cm at 6, 10, 15, 20, 30, 40, 50, 75, 100, 150, 200, 225, 273, and 295 K, respectively; residual electrical resistivity 0.0125 μohm cm; $\rho(295K)/\rho_0 = 833$.
7	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	Pt III	Very pure; polycrystal; drawn and electrically annealed; electrical resistivity 0.0650, 2.10, and 9.81 μohm cm at -252, -190, and 0 C, respectively.
8	789	Krishnan, K. S. and Jain, S. C.	1954	E	1200-1800		Spectrographically pure wire; obtained from Johnson, Matthey and Co.
9	525	Gray, J. H.	1894	L	326.2		Pure; specimen 2.0 mm in dia.
10*	682	Johansson, C. H. and Linde, J. O.	1930	C	291.2		Pure; tempered at 800 C and quenched, rolled and drawn; gold used as comparative material (k value 3.09 W cm^{-1} K^{-1}).
11*	117	Barratt, T. and Winter, R. M.	1925	L	290-373		Pure.
12	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.17	Pt IV 33	Quasi-isotropic; electrical resistivity 0.0416 and 9.81 μohm cm at 21.38 and 273.2 K, respectively.
13	555	Grüneisen, E. and Adenstedt, H.	1938	L	22.01	Pt IV 33	The above specimen; 2nd run.
14	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.21	Pt IV 33	The above specimen measured at H = 8750 oersteds; electrical resistivity 0.04578 μohm cm at 21.38 K.
15	555	Grüneisen, E. and Adenstedt, H.	1938	L	22.10	Pt IV 33	The above specimen measured at H = 8750 oersteds.
16	555	Grüneisen, E. and Adenstedt, H.	1938	L	22.15	Pt IV 33	The above specimen measured at H = 12200 oersteds; electrical resistivity 0.04820 μohm cm at 21.38 K.
17	625	Holm, R.	1929	E	293-1293		99.95 pure; electrical resistivity 10.65, 24.90, 35.01, and 43.61 μohm cm at 20, 412, 725, and 1020 C, respectively.
18	1624	Zolotukhin, G. E.	1956	P	384.2		Pure.
19	174	Bode, K. H.	1961	E	1073-1223		99.9 chemically pure; specimen in the form of 0.1 mm dia wire stretched between two heaters; wire surface polished with Viennese chalk or Paris red (crocus, polishing powder); annealed at about 1000 C for 12 hrs.

* Not shown in figure.

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	312	Cutler, M., Snodgrass, H.R., Cheney, G.T., Appel, J., Mallon, C.E., and Meyer, C.H., Jr.	1961	E	301-1473		99.9 pure; electrical resistivity 10.6 μohm cm at 23 C.
21	312	Cutler, M., et al.	1961	E	292-1376		Similar to the above specimen.
22*	1280	Schulze, F.A.	1911	L	298.2		Less than 0.03 impurity.
23	559	Grüneisen, E. and Goens, E.	1927	L	21.2	Pt IV	Pure; polycrystal; annealed; electrical resistivity 0.0899 and 9.83 μohm cm at 21.2 and 273 K, respectively.
24	1141	Powell, R.W., Tye, R.P., and Woodman, M.J.	1962	C, L	323, 523		0.0001 Cu, 0.0001 Fe, and <0.0001 Pd; specimen 0.635 cm in dia and 6.1 cm long; supplied by Johnson, Matthey and Co.; annealed at approx 1000 C; density 21.51 g cm^{-3}; electrical resistivity 0.013 and 9.85 μohm cm at 4.2 and 273 K, respectively; Armco iron used as comparative material; heat out-flow also measured by water-flow calorimeter.
25	1141	Powell, R.W. and Tye, R.P.	1963	C, L	315-503	Pt I	0.0001 Cu, 0.0001 Fe, and <0.0001 Pd; specimen 0.62 cm in dia and 6.1 cm long; density 21.5 g cm^{-3}; machined; annealed at about 1000 C; Armco iron (0.371 cm dia) used as comparative material; heat out-flow also measured by water-flow calorimeter.
26	1141	Powell, R.W. and Tye, R.P.	1963	C	445-1220	Pt I	The above specimen; 0.371 cm dia Armco iron rod used as comparative material.
27	1141	Powell, R.W. and Tye, R.P.	1963	C	787-1153	Pt I	The above specimen; 1.273 cm dia Armco iron rod used as comparative material.
28	1141	Powell, R.W. and Tye, R.P.	1963	C	760-1070	Pt I	The above specimen; 1.273 cm dia Armco iron rod used as comparative material; reassembled.
29	1141	Powell, R.W. and Tye, R.P.	1963	C	335-467	Pt II	0.0001 Si, <0.0001 Ag, <0.0001 Ca, <0.0001 Cu, 0.0001 Fe, <0.0001 Mg, and <0.0001 Pd; specimen 1.269 cm in dia and 10.16 cm in length; annealed at ~1000 C; density 21.5 g cm^{-3}; electrical resistivity after the thermal measurement 9.9, 13.8, 17.4, 21.0, 24.5, 27.9, 31.1, 34.3, 37.3, 40.2, and 43.0 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 C, respectively; Lorenz function at these temps being, respectively, 2.66, 2.70, 2.68, 2.67, 2.65, 2.64, 2.57, 2.54, 2.51, and 2.47 x 10^{-8} V^2 K^{-2}; 1.222 cm dia Armco iron rod used as comparative material.
30	1141	Powell, R.W. and Tye, R.P.	1963	C	575-1141	Pt II	The above specimen; 1.222 cm dia Armco iron rod used as comparative material.
31	1141	Powell, R.W. and Tye, R.P.	1963	C, L	357-800	Pt II	The above specimen; 1.9 cm dia Armco iron rod used as comparative material; energy out flow also measured by water-flow calorimeter.
32	939, 1299	Mendelssohn, K., Sharma, J.K.N., and Yoshida, I.	1965	L	0.42-0.81		99.999 pure; polycrystalline wire specimen; form factor $\ell/a = 7.74 \times 10^3$ cm^{-1}; supplied by Johnson, Matthey and Co.; electrical resistivity 0.08004 μohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 148$; anomalous peak occurred at 0.68 K.
33	704, 705	Kannuluik, W.G. and Carman, E.H.	1951	E	90-579		Wire 11.6 cm long and 1.5 mm in dia.
34	175	Bode, K.H.	1964	L	298-358		99.98 pure; ≈0.0030 Ir, 0.0021-0.0023 Ca, 0.0021-0.0023 Rh, 0.0015-0.0017 Al, 0.0015-0.0017 Pd, 0.0011 Au, 0.0007-0.0009 Mg, 0.0007-0.0009 Ag, 0.0004-0.0006 Cu, and 0.0004-0.0005 Fe; specimen 5.0 cm in dia and 7.0 cm long; cast, cold-pressed and machined; density 21.32 g cm^{-3} at 20 C; held at 600 C for 2 hrs; first run.

* Not shown in figure.

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35*	175	Bode, K. H.	1964	L	294-349		The above specimen; second run.
36*	175	Bode, K. H.	1964	L	294, 365		The above specimen; third run.
37*	175	Bode, K. H.	1964	L	296-363		The above specimen; fourth run.
38	1533	Wheeler, M. J.	1965	P	1180-1750		99.95 Pt sheet of 1 mm thickness; average grain size after test 1000 μ; density 21.5 g cm^{-3}; data calculated from thermal diffusivity measurements using the specific heat data of Kubaschewski, O. and Evans, L. Ll. (Metallurgical Thermochemistry Pergamon Press, 1956).
39	965	Mikryukov, V. E.	1959	E	323-773		99.99 pure; polycrystal.
40	889, 890, 891	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1964	P	300-1150	I	99.999 Pt (nominal); impurities (atomic %): 0.002 Pd, 0.001 Ir, 0.001 Ag, 0.001 Zn, 0.0006 Mo, 0.0006 Os, 0.0006 Ru, 0.0004 In, 0.0002 Re, 0.0002 W, 0.0001 Cu, 0.00007 Rh, and 0.00006 Ta; supplied by J. Bishop and Co.; annealed at 1200 K for at least 1 hr; electrical resistivity given by $\rho = 9.84 (1 + 3.976 \times 10^{-3} T - 0.5843 \times 10^{-6} T^2)$ with T in C, evaluated as 10.90, 14.72, 18.41, 22.00, 25.50, 28.88, 32.11, 35.25, and 38.25 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; $\rho(273K)/\rho(4K) = 900$; thermal conductivity values calculated from thermal diffusivity data using a constant density of 21.37 g cm^{-3} and the specific heat data of Jaeger, F. M. and Rosenbohm, E. (Physica, 6, 1123-5, 1939).
41	889, 891	Martin, J. J. and Sidles, P. H.	1964	P	300-1250	II	99.9 Pt (nominal), impurities (atomic %): 0.35 Rh, 0.24 Ir, 0.05 Pd, 0.04 Ag, 0.034 Ru, 0.015 Cu, 0.006 Zn, 0.001 W, 0.0006 Ta, 0.0005 In, 0.0004 Re, 0.0001 Os, and <0.0001 Mo; supplied by J. Bishop and Co.; annealed at 1200 K for at least 1 hr; electrical resistivity given by $\rho_{TC} = 10.25 (1 + 4.059 \times 10^{-3} T - 0.8551 \times T^{-6} T^2)$ with T in °C, evaluated as 11.36, 15.38, 19.24, 22.91, 26.41, 29.73, 32.88, 35.86, and 38.66 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; data calculated from thermal diffusivity data using a constant density of 21.37 g cm^{-3} and the specific heat data of Jaeger, F. M. and Rosenbohm, E. (Physica, 6, 1123-5, 1939).
42	771, 798	Kobushko, V. S., Merisov, B. A., and Khotkevich, V. I.	1964	E	273-1383		Platinum wire 0.3 mm in dia.
43	890, 891	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1200	B	99.999 Pt (nominal), impurities (atomic %): 0.2 Pd, 0.06 Cu, 0.057 Rh, 0.01 Ag, 0.004 Zn, 0.001 Ir, 0.001 Ru, 0.0006 Os, 0.0002 Re, 0.0002 W, <0.0001 Mo, 0.00007 Ta, and 0.00006 In; rod 0.1875 in. in dia and about 10 in. long; supplied by Engelhard Industries; annealed at 1200 K for at least 1 hr; electrical resistivity 10.95, 14.75, 18.45, 22.10, 25.64, 29.00, 32.20, 35.35, and 38.45 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 100$ determined upon completion of thermal diffusivity measurements; thermal conductivity values calculated from the thermal diffusivity measurements using a constant density of 21.37 g cm^{-3} from Smithsonian Physical Tables (1954) and specific heat data of Jaeger, F. M. and Rosenbohm, E. (1939).

*Not shown in figure.

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
44	890, 891	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1200	C	Similar to above with the specimen having a nominal purity of 99.9; impurities (atomic %): 0.009 Rh, 0.006 Pd, 0.004 Ag, 0.003 Zn, 0.002 Cu, 0.001 Ir, 0.0006 W, 0.0005 In, 0.0004 Re, 0.0003 Os, <0.0003 Mo, 0.0002 Ta, and <0.0002 Ru; electrical resistivity 11.30, 15.13, 18.90, 22.60, 26.14, 29.51, 32.76, 35.86, and 38.89 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; ρ(273K)/ρ(4.2K) = 34.
45	890, 891	Martin, J. J., et al.	1965	P	400-1200	D	Data similarly obtained from another specimen having a nominal purity of 99.999, impurities (atomic %): 0.002 Zn, 0.001 Cu, 0.001 In, 0.001 Ir, 0.001 Pd, 0.001 Ag, 0.0006 Mo, 0.0006 Ru, 0.0002 Re, 0.0002 W, 0.00007 Rh, and 0.00006 Ta; supplied by Sigmund Cohn Corp; electrical resistivity 10.90, 14.68, 18.40, 21.98, 25.45, 28.82, 32.04, 35.10, and 38.13 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; ρ(273K)/ρ(4.2K) = 5000.
46*	820	Laubitz, M. J. and Van der Meer, M. P.	1966	L	300-1000		0.0004 Rh, 0.0003 Fe, <0.0001 each of Al, Pd, and Si, <0.00005 Au, 0.00003 Cu, <0.00003 Mn, 0.00002 Ag, and <0.00001 each of Ca and Mg; a composite rod 1.2 cm dia x 10 cm long supplied by Engelhard Industries, Inc.; machined from a special lot; density 21.452 g cm^{-3} at 19.8 C; electrical resistivity for the range 300 to 1500 K given as $\rho = -1.2935 + 42.257 \times 10^{-3}\ T - 5.755 \times 10^{-6}\ T^2$ (T in K; ρ in μohm cm); ρ(273K)/ρ(4.2K) = 1887.
47	279	Ciszek, T. F.	1966	P	970-1611		Nominal purity 99.9; impurities (given as upper limits): 0.2 each of Au, Rh, and Ru, 0.1 each of Cu, Fe, Pd, Si, and Ag, and 0.01 each of Cr, Mn, and Ni; 0.479 cm dia x 15 cm long; supplied by Engelhard Industries, Inc.; electrical resistivity 34.54, 35.68, 37.90, 40.06, 42.60, 45.01, 46.89, 49.75, and 52.28 μohm cm at 970, 1006, 1078, 1153, 1243, 1331, 1402, 1511, and 1611 K, respectively; thermal conductivity values calculated from the thermal diffusivity measurements using a constant density of 21.37 g cm^{-3} from Forsythe, W. E. (editor, Smithsonian Physical Tables, 9th revised ed.) and the specific heat data taken from Jaeger, F. M. and Rosenbohm, E. (Physica, 6, 1123, 1939).
48	987	Moore, J. P., McElroy, D. L., and Barisoni, M.	1966	L	90-340	E-2 grade, No. 1	99.98 pure; cylindrical specimen supplied by NBS; electrical resistivity 0.0230, 1.867, 6.272, 7.901, 7.911, 9.812, 10.734, 10.757, 10.778, and 11.868 μohm cm at 4.2, 77.5, 183.4, 224.2, 224.6, 273.3, 297.4, 297.8, 298.4, and 327.1 K, respectively; ρ(273K)/ρ(4.2K) = 426.
49*	987	Moore, J. P., et al.	1966	L	90-400		99.999 pure; same specimen measured by Powell, R. W. and Tye, R. P. (see curve No. 25); electrical resistivity 0.0165, 2.388, 6.778, 9.915, and 10.885 μohm cm at 4.2, 77.4, 194.4, 273.2, and 298.0 K, respectively; ρ(273K)/ρ(4.2K) = 600. (Revised thermal conductivity data obtained from the authors in a private communication.)
50	1144, 1145	Powell, R. W., Tye. R. P., and Woodman, M. J.	1966	C	80-294	Pt 1	0.0001 Cu, 0.0001 Fe, and <0.0001 Pd; polycrystalline; specimen 0.635 cm in dia and 6.1 cm long; supplied by Johnson, Matthey and Co., Ltd; annealed at 1273 K; density 21.51 g cm^{-3}; electrical resistivity 2.8, 6.9, 10.92, 14.72, and 18.4 μohm cm at 100, 200, 300, 400, and 500 K, respectively; ρ(273K)/ρ(4.2K) = 740; Lorenz function 2.18, 2.62, 2.69, 2.69, and 2.69 x $10^{-8}\ V^2\ K^{-2}$ at 100, 200, 300, 400, and 500 K, respectively.

* Not shown in figure.

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
51	1144, 1145	Powell, R. W., et al.	1966	C	300-500	Pt 2	0.0001 Fe, 0.0001 Si, <0.0001 each of Ca, Cu, Mg, Hg, and Pd; polycrystalline; specimen 1.269 cm in dia and 10.16 cm long; supplied by Johnson, Matthey and Co., Ltd; annealed at 1250 K; density 21.5 g cm^{-3}; electrical resistivity 2.75, 6.88, 10.92, 14.72, and 18.4 μohm cm at 100, 200, 300, 400, and 500 K, respectively; Lorenz function 2.66, 2.70, and 2.71 x 10^{-8} V^2 K^{-2} at 300, 400, and 500 K, respectively.
52	709	Kannuluik, W. G. and Law, P. G.	1947	E	195-373		Wire specimen 1.438 ±0.003 mm in dia; measured in a vacuum of <10^{-5} mm Hg.
53	64	Anderson, A. C., Peterson, R. E., and Robichaux, J. E.	1968	L	0.34-1.2		99.999 pure; wire specimen 0.051 cm in dia and 10.11 cm long; obtained from Matthey Bishop Inc.; vacuum annealed; strained during mounting; electrical resistivity given as $\rho = (1.687 + 0.0020\ T^2) \times 10^{-8}$ ohm cm for T <1.2 K; electrical resistivity ratio $\rho(300K)/\rho(0K)$ = 633.
54*	448, 449, 450, 1049, 1050	O'Hagan, M. E., Heller, R. B., and Flynn, D. R.	1966	L	372.8		99.987$^+$ Pt, 0.0073 Pd, 0.0039 Fe, <0.0005 Ir, 0.0003 each of Rh, Si and Ag, <0.0002 Au, <0.0001 each of Al, Mg, Mn, and Ni, 0.00004 Ca, and 0.00004 Cu, (no gas analysis made); supplied by Engelhard Industries, Inc.; 0.786 in. dia x 7.25 in. long; prepared by induction-melting in air the commercial purity platinum in a zirconium silicate crucible, cast in a graphite mold into a bar 1.25 in. in dia and 15 in. long; swaged cold to a dia of 1 in., machined to 0.90 in. dia, cut from the middle a piece 12.75 in. long, acid cleaned in hot aqua-regia, annealed at 700 C for 1 hr, machined to 0.805 in. dia x 12.200 in. long, ultrasonically cleaned, pickled in 50% hot nitric acid for 10 min, washed, pickled in 50% hot HCl acid, and washed in distilled water, annealed in air at 770 C for 5.5 hrs, cooled at a rate of ~120 C hr^{-1}, reannealed at 680 C for 1.5 hrs, and cooled at a rate of ~90 C hr^{-1}; its thermal conductivity measured in the NBS Metals Apparatus over the temp range -160-810 C, then machined and ground to 0.786 in. dia, after measurement of electrical resistances at ice and liquid helium temps; the thermal conductivity specimen of 7.25 in. long cut from 1 end of this bar, w/a 0.045 in. dia x 0.130 in. long neck machined in it 1.622 in. from the upper end; density 21.384 g cm^{-3} at 21 C; electrical resistivity 9.85, 13.69, 17.41, 21.02, 24.52, 27.90, 31.17, 34.33, 37.38, 40.28, 43.07, and 45.78 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 C, respectively; $\rho(273K)/\rho(4.2K)$ = 393; measured in air; run one; data corrected for thermal expansion.
55	"	O'Hagan, M. E., et al.	1966	L	373-974		The above specimen measured in 99.99 pure argon at ~1 atm; run 1; data corrected for thermal expansion.
56*	"	O'Hagan, M. E., et al.	1966	L	473-674		The above specimen measured in 99.99 pure helium at ~0.75 atm; run 1; data corrected for thermal expansion.
57	"	O'Hagan, M. E., et al.	1966	L	573-1374		The above specimen measured in 99.99 pure argon at ~0.75 atm; run 2; data corrected for thermal expansion.
58*	"	O'Hagan, M. E., et al.	1966	E	370.0		The above specimen measured in air by an electric method; run 1; data corrected for thermal expansion.
59*	"	O'Hagan, M. E., et al.	1966	E	373-973		The above specimen measured in 99.99 pure argon at ~1 atm; run 1; data corrected for thermal expansion.

*Not shown in figure.

TABLE 118. THERMAL CONDUCTIVITY OF PLATINUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
60	448-450, 1049, 1050	O'Hagan, M. E., Heller, R. B., and Flynn, D. R.	1966	E	473, 673		The above specimen measured in 99.99 pure helium at ~0.75 atm; run 1; data corrected for thermal expansion.
61*	"	O'Hagan, M. E., et al.	1966	E	573-1272		The above specimen measured in 99.99 pure argon at ~0.75 atm; run 2; data corrected for thermal expansion except the last measurement at 1271.7 K.
62	1367	Stops, D. W.	1960	E	196, 273		Commercial wire specimen; 0.01875 cm dia x 10.91 cm long; electrical resistivity 7.19 and 10.41 μohm cm at 194.7 and 273.2 K, respectively.
63	1618, 1621	Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V.	1968	P	1059-1994		Grade PL-O pure platinum; measurements made on three specimens of cross-section 8 x 8 mm and of thicknesses 0.193, 0.245, and 0.288 mm; electrical resistivity ratio $\rho(290K)/\rho(4.2K) \approx 200$, $\rho(373K)/\rho(273K) = 1.3926$; thermal conductivity values calculated from measured thermal diffusivity using specific heat capacity data taken from Kraftmakher, Ya. A. (High-temperature Research, No. 5, Sib. Otd. Akad. Nauk SSSR, Novosibirsk, 1966), density taken from Vargaftik, N. B. (editor, "Thermophysical Properties of Materials," Gosenergoizdat, Moscow-Leningrad, 1956), and linear thermal expansion coefficient taken from Kraftmakher, Ya. A. (Fiz. Tverd. Tela, 9, 1528, 1967); reported values taken from smoothed curve.
64	670	Jain, S. C., Goel, T. C., and Narayan, V.	1969	E	1295-1710	1	99.9 pure; 16 x 0.3 x 0.025 cm; obtained from Johnson, Matthey and Co.; electrical resistivity 39.4, 44.0, 45.8, 46.6, 49.5, 51.4, and 52.9 μohm cm at 1210, 1394, 1452, 1475, 1603, 1678, and 1728 K, respectively; Lorenz function 2.39, 2.41, 2.51, 2.65, and 2.83 x 10^{-8} V^2 K^{-2} at 1202, 1402, 1500, 1600, and 1697 K, respectively.
65	670	Jain, S. C., et al.	1969	E	1249-1712	2	99.99 pure; 0.115 cm dia and 25 cm long; electrical resistivity 41.8, 44.5, 47.7, 49.6, 51.9, and 53.0 μohm cm at 1235, 1333, 1460, 1546, 1612, and 1683 K, respectively; Lorenz function 2.37 and 2.45 x 10^{-8} V^2 K^{-2} at 1202 and 1427 K, respectively.
66*	670	Jain, S. C., et al.	1969	E	1243-1617	3	99.9 pure; 0.2 cm dia x 20 cm long; electrical resistivity 41.8, 43.5, 46.0, 48.1, 50.1, 52.5, and 54.4 μohm cm at 1187, 1267, 1374, 1439, 1531, 1611, and 1694 K, respectively; Lorenz function 2.35, 2.36, and 2.42 x 10^{-8} V^2 K^{-2} at 1202, 1501, and 1600 K, respectively.
67	1136	Powell, R. W. and Tye, R. P.	1963		1275-1700		Thermal conductivity values calculated by the authors from the values of the Lorenz function obtained by Hopkins, M. R. and Griffith, R. L. (Z. Phys., 150, 325-31, 1958) using the mean electrical resistivity values of Holm, R. and Störmer, R. (1930), and Vines, R. F. (1941).
68*	1096	Poltz, H.	1970	L	295-772		99.999 pure; cylindrical specimen 50 mm in diameter and 90 mm long; recrystallized at 250 C; density 21.285 g cm^{-3}.

* Not shown in figure.

Plutonium

The thermal conductivity of plutonium has only been measured over the temperature range 62 to 413 K, and a fairly wide choice of values is presented. Andrew [67] made determinations on four samples, two of which contained preferential orientation of monoclinic crystals of α-plutonium respectively parallel (curve 9) and perpendicular (curve 10) to the long axis of the specimen. The others were cast-annealed and had more randomly oriented grains and many (curve 7) or few (curve 8) microcracks. The observed values increased strongly with temperature and only differed by up to 11.5 percent at 80 K and 4.7 percent at 300 K. Andrew included electrical resistivity data for each sample and obtained Lorenz functions of $(3.44 \pm 0.06)\ 10^{-8}\ V^2\ K^{-2}$ at 195 K and $(3.15 \pm 0.06)\ 10^{-8}\ V^2\ K^{-2}$ at 300 K. Since the Debye temperature is about 173 K these values seem reasonable, whereas the data of Sandenaw and Gibney [1241] (curves 1–3) gave considerably higher Lorenz values whilst the data of Waldron, et al. [1500] (curves 4–6) and of R. F. Powell [1099] (curve 15) indicate low values of about $2.0 \times 10^{-8}\ V^2\ K^{-2}$ at room temperature.

The present provisional curve has been drawn through the upper region of the band of values obtained by Andrew. No attempt has been made to extend this curve to lower temperatures, nor above 390 K into the region where phase transformations occur. Further experimental determinations are required in both of these areas. The uncertainty of the provisional values is of the order of ±25 percent.

TABLE 119. Provisional thermal conductivity of plutonium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline	
T	k
0	0
80	0.0306
90	0.0318
100	0.0332
123.2	0.0361
150	0.0399
173.2	0.0432
200	0.0476
223.2	0.0516
250	0.0568
273.2	0.0616
298.2	0.0670
300	0.0674
323.2	0.0726
350	0.0790

†For well-annealed high-purity polycrystalline plutonium.

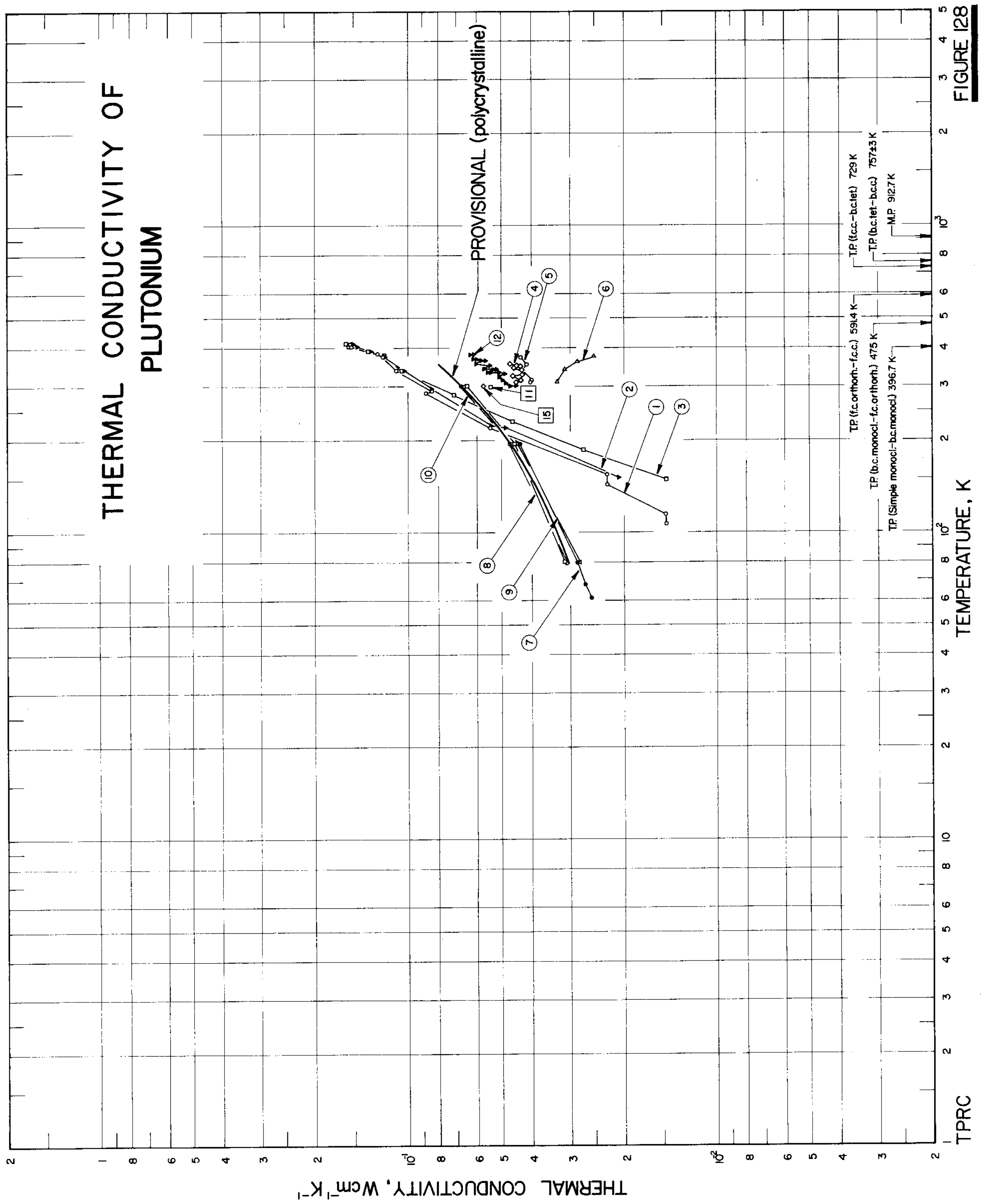

THERMAL CONDUCTIVITY OF PLUTONIUM
FIGURE 128
PROVISIONAL (polycrystalline)
T.P. (f.c.orthorh.-f.c.c.) 591.4 K
T.P. (b.c.monocl.-f.c.orthorh.) 475 K
T.P. (Simple monocl.-b.c.monocl.) 396.7 K
T.P. (f.c.c.-b.c.tet.) 729 K
T.P. (b.c.tet.-b.c.c.) 757±3 K
M.P. 912.7 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm^{-1}K^{-1}
TPRC

TABLE 120. THERMAL CONDUCTIVITY OF PLUTONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1240, 1241	Sandenaw, T.A. and Gibney, R.B.	1957	L	108–413	1	99.95 pure; isotopic content: 94.76 Pu-239, 4.91 Pu-240, 0.29 Pu-241 and 0.04 Pu-242; specimen 0.231 in. in dia and 3.50 in. long; heat generation 0.01067 cal $sec^{-1}cm^{-3}$; density 19.58 g cm^{-3}; phase transformation (α to β) at 397.0 ± 0.2 K; electrical resistivity 61.1, 128.0, 157.0, 153.5, 146.3, 141.0, 107.5, 107.0, 106.2, 105.0, 97.7, 98.5, 99.4, and 107.1 μohm cm at 27.2, 50, 100, 150, 273, 380, 420, 475, 505, 590, 625, 725, 735, and 774 K, respectively.
2	1240, 1241	Sandenaw, T.A. and Gibney, R.B.	1957	L	152–413	2	99.97 pure; isotopic content: 95.35 Pu-239; 4.37 Pu-240, 0.26 Pu-241 and 0.03 Pu-242; specimen 0.250 in. in dia and 3.50 in. long; heat generation 0.01034 cal $sec^{-1}cm^{-3}$; density 19.56 g cm^{-3}; phase transformation (α to β) at 396.4 ± 0.1 K; electrical resistivity 68.5, 128.0, 156.8, 153.5, 146.6, 141.8, 109.5, 110.0, 109.5, 109.3, 103.0, 104.0, 104.8, 114.0, and 114.1 μohm cm at 25.8, 50, 100, 150, 273, 380, 420, 475, 505, 590, 625, 725, 735, 774, and 787 K, respectively.
3	1240, 1241	Sandenaw, T.A. and Gibney, R.B.	1957	L	148–413	3	99.98 pure; isotopic content: 95.33 Pu-239, 4.39 Pu-240, 0.28 Pu-241 and 0.06 Pu-242; specimen 0.227 in. in dia and 3.75 in. long; heat generation 0.01034 (assumed) cal $sec^{-1}cm^{-3}$; density 19.53 g cm^{-3}.
4	1500	Waldron, M.B., Garstone, J., Lee, J.A., Mardon, P.G., Marples, J.A.C., Poole, D.M., and Williamson, G.K.	1958	L	309–357		Impurities 0.025; α-phase; specimen 1 in. in dia and 5 in. long; zone refined; self heating used as source of power during measurement; data extracted from two runs.
5	1500	Waldron, M.B. et.al.	1958	E	309–374		Impurities 0.025; α-phase; 1.6 in. long; 0.08 in. dia; zone refined; cast.
6	1500	Waldron, M.B. et.al.	1958	E	309–374		The above specimen, data corrected for emissivity (assumed to be 0.3).
7	67	Andrew, J.F.	1967	E	62–300	α-Plutonium	99.98^{+} pure; monoclinic crystalline; specimen 0.25 in. in dia and 1.81 in. long; arc-melted and induction cast into an MgO mold; density 19.62 g cm^{-3}; specimen had randomly oriented grains and a large number of microcracks.
8	67	Andrew, J.F.	1967	E	80–300	α-Plutonium	99.98^{+} pure; monoclinic crystalline; specimen 0.25 in. in dia and 1.81 in. long; arc-melted and cast into a mold at -40 C, then annealed at 110 C; density 19.77 g cm^{-3}; specimen had randomly oriented grains and very few microcracks.
9	67	Andrew, J.F.	1967	E	80–300	α-Plutonium	99.98^{+} pure; specimen 0.25 in. in dia and 1.80 in. long with long axis parallel to preferential alignment of the (020) plane in the monoclinic crystals; prepared by heating the cast ingot into the beta-phase temperature range and then cooling it to room temperature under a compressive load of 60,000 psi; density 19.77 g cm^{-3}.
10	67	Andrew, J.F.	1967	E	80–300	α-Plutonium	Similar to the above specimen except the long axis aligned perpendicular to the (020) plane of the monoclinic crystal.

TABLE 120. THERMAL CONDUCTIVITY OF PLUTONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
11	111	Ball, J.G., Lee, J.A., Mardon, P.G., and Robertson, J.A.L.	1960	E	298	α-Plutonium	0.51-1.02 mm dia x 152.4 mm long; electrical resistivity at 30 C given as 50 μohm cm, but this appears to be a typographical error for 150 μohm cm, (measuring temp assumed at 25 C).
12	827	Lee, J.A. and Mardon, P.G.	1961	→	303-381		99.8$^+$ pure; α-phase; 1 in. dia x 5 in. long; measured by using the self-heating of the specimen as the source of power; specimen oxidized during run due to poor vacuum.
13*	827	Lee, J.A. and Mardon, P.G.	1961	→	310-350		Similar to above; specimen demounted after run, no oxidation found.
14*	827	Lee, J.A. and Mardon, P.G.	1961	→	328-357		The above specimen reloaded for another run.
15	544, 1099	Grison, E., Lord, W.B.H., and Fowler, R.D. (editors)	1961	C	298.2		Measurement made by Powell, R.F. using a thermal comparator; Lorenz function reported as 1.98 x 10^{-8} V^2 K^{-2} at 21 C.

* Not shown in figure.

Polonium

No information is available for the thermal conductivity of polonium. However, the electrical resistivity of thin films of ^{210}Po deposited on glass has been measured by Maxwell [904a] (see also [912]), and is about 47 $\mu\Omega$ cm at 300 K. This value is probably high since his samples were impure, lead being the major impurity which increases by about 1/2 percent a day for a new sample. If the theoretical Lorenz number is used, the thermal conductivity of polonium is calculated to be 0.16 W cm^{-1} K^{-1} at 300 K. This value is probably too low for pure polonium.

By assuming a Lorenz function of 3.2×10^{-8} V^2 K^{-2} at 300 K, which is comparable to that of polycrystalline bismuth, the calculated thermal conductivity is 0.20 W cm^{-1} K^{-1}. This value is adopted as the provisional value for the thermal conductivity of polonium at 300 K, and is probably good to ±30 percent.

Potassium

At low temperatures the recommended values for a sample having $\rho_0 = 0.00220$ $\mu\Omega$ cm are based on the measurements (curve 102) of Archibald, et al. [92] and were calculated to fit their data to 1.5 T_m by using equation (7) and using $m = 2.10$, $n = 2.00$, $a'' = 0.00180$, and $\beta = 0.0820$. This curve has been extended to follow the data (curve 30) of Stauder and Mielczarek [1360] to about 9 K and then continued in close agreement with the data (curve 5) of MacDonald, et al. [873] to reach their value of 1.13 W cm^{-1} K^{-1} near 40 K. From 40 K to room temperature is a region demanding further experimental investigation. The only available values in this subnormal region are those (curve 5) of MacDonald, et al. to 91 K. The value at their upper limit is about 2 percent greater than that at 40 K, suggesting that potassium may be another metal having a gentle maximum in this unexamined region.

Uncertainty also exists at room temperature and on to the melting point. The sets of measured values agree that the temperature coefficient above room temperature is negative, but at 320 K give thermal conductivities of 0.81, 0.92, and 1.08 W cm^{-1} K^{-1}, so cover a range of 33 percent. The highest (curve 7) of these values is due to Khalileev [755] whose curve continued to increase with decrease in temperature, and at 297 K was only about 2 percent below the proposed curve at 40 K. If both curves prove correct, minimum and maximum values are possible within the range 40 to 300 K. Since from the recent electrical resistivity measurements of Tepper, et al. [1401] and the theoretical Lorenz function a value of 1.01 W cm^{-1} K^{-1} at 320 K is obtained, a smooth curve with no such inflections has been drawn from this region to the aforementioned 40 K point as a very tentative completion to the most probable curve for the thermal conductivity of solid potassium.

More attention has been devoted to the thermal conductivity of liquid potassium and the agreement between the several experimental values and most derived values is reasonably satisfactory. There appears to be strong evidence that the Lorenz function is below the theoretical value. For instance, the measurements (curves 10–22) of Deem and Matolich [328] gave values close to 2.14×10^{-8} V^2 K^{-2} throughout the range 400 to 1000 K, whilst the consistently higher curve (curve 33) derived by Tepper, et al. [1211] in terms of a Lorenz function of 2.45×10^{-8} V^2 K^{-2} would be in better agreement had 2.14×10^{-8} been used.

Grosse [546, 548] has found the electrical resistivity data to 1450 K of Lemmon, et al. [836] to be in good agreement with the form of reduced conductivity-reduced temperature correlation which he has proposed. This has enabled him to derive estimated values (curve 106) for the thermal conductivity using 2.16×10^{-8} V^2 K^{-2} as the Lorenz function. These estimated values extend right up to the critical point, 2450 K as estimated by him, at which the assumed thermal conductivity is 0.0008 W cm^{-1} K^{-1}, in agreement with the value estimated for the thermal conductivity of the saturated vapor (curve 105).

The most probable curve for the liquid state commences at a value of 0.548 W cm^{-1} K^{-1}, giving a value of 1.8 for k_S/k_L, and follows smoothly through the upper zone of the experimental data to link on with the estimated curve due to Grosse.

The recommended values are thought to be accurate to within ±10 percent for the solid state, ±5 percent for the liquid state below 1000 K, and ±10 percent from 1000 to 1500 K. The values above 1500 K are provisional. At temperatures below 50 K, the values are, of course, applicable only to a sample having $\rho_0 = 0.00220$ $\mu\Omega$ cm.

TABLE 121. Recommended thermal conductivity of potassium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	k	T	k	T	k	T	k
0	0	60	1.10	336.8	0.548	1500	0.192*
1	11.9*	70	1.09	350	0.542	1573.2	0.176*
2	20.4*	80	1.08	373.2	0.532	1600	0.170*
3	22.1	90	1.075	400	0.520	1673.2	0.155*
4	19.1	100	1.070*	473.2	0.490	1700	0.149*
5	14.4	123.2	1.058*	500	0.479	1773.2	0.134*
6	10.8	150	1.050*	573.2	0.449	1800	0.128*
7	8.33	173.2	1.046*	600	0.439	1873.2	0.113*
8	6.62	200	1.043*	673.2	0.413	1900	0.108*
9	5.42	223.2	1.042*	700	0.404	1973.2	0.0932*
10	4.58	250	1.040*	773.2	0.380	2000	0.0880*
11	3.97	273.2	1.036*	800	0.371	2073.2	0.0737*
12	3.47	298.2	1.025	873.2	0.348	2100	0.0680*
13	3.06	300	1.024	900	0.340	2173.2	0.0541
14	2.74	323.2	1.003	973.2	0.320	2200	0.0490*
15	2.48	336.8	0.985	1000	0.313	2273.2	0.0346*
16	2.26			1073.2	0.294	2300	0.0290*
18	1.91			1100	0.287	2373.2	0.0151*
20	1.67			1173.2	0.269	2400	0.0100*
25	1.33			1200	0.263	2423.2	0.0053*
30	1.23			1273.2	0.245	2450	0.0008*
35	1.18			1300	0.239		
40	1.15			1373.2	0.222		
45	1.13			1400	0.215		
50	1.12			1473.2	0.199		

†The values are for high-purity potassium and those below 50 K are applicable only to a specimen having $\rho_o = 0.00220$ μΩ cm. The values above 1500 K are provisional.

*Extrapolated, interpolated, or estimated.

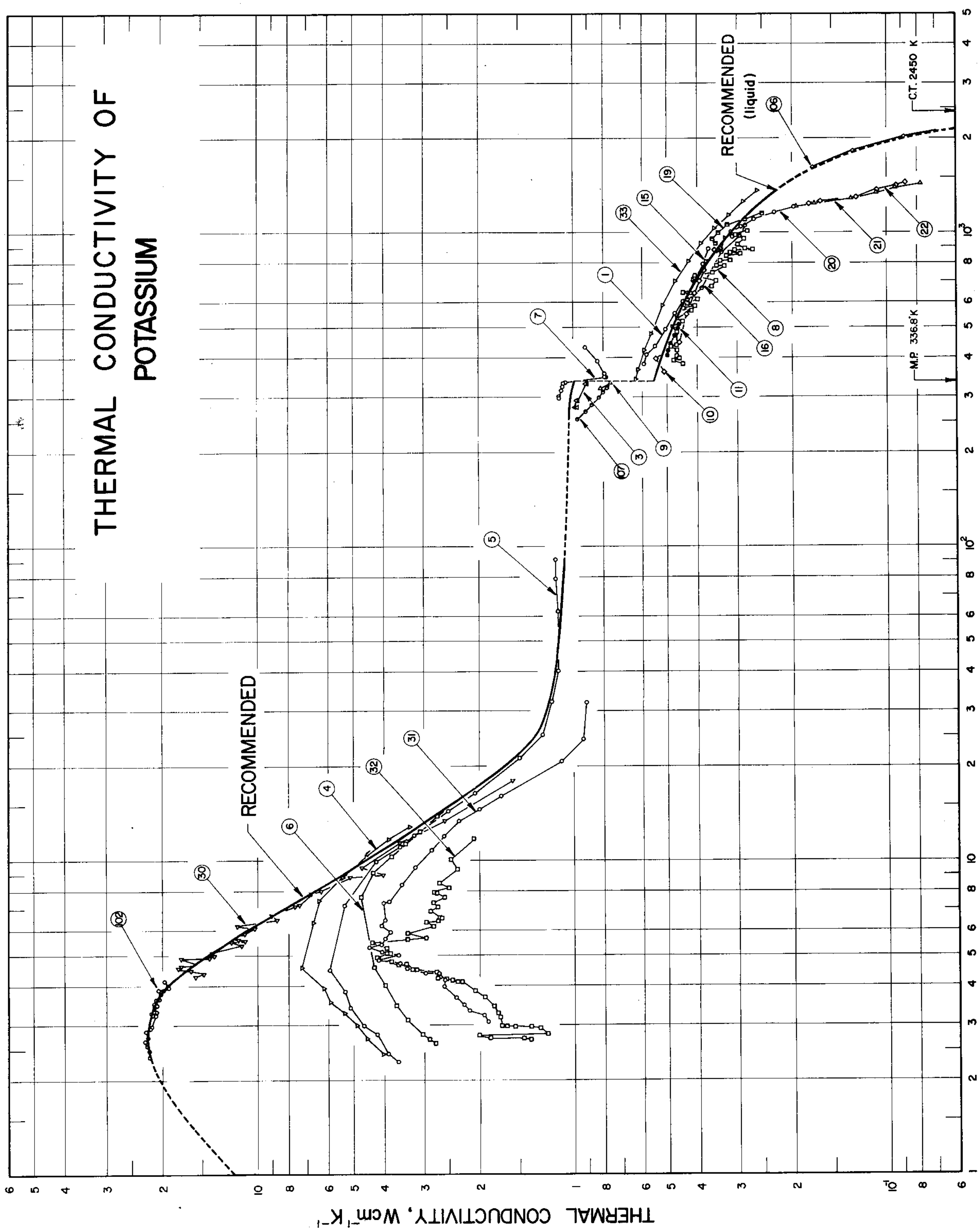

THERMAL CONDUCTIVITY OF POTASSIUM
RECOMMENDED
RECOMMENDED (liquid)
M.P. 336.8 K
C.T. 2450 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, $W cm^{-1} K^{-1}$
TPRC

FIGURE 129

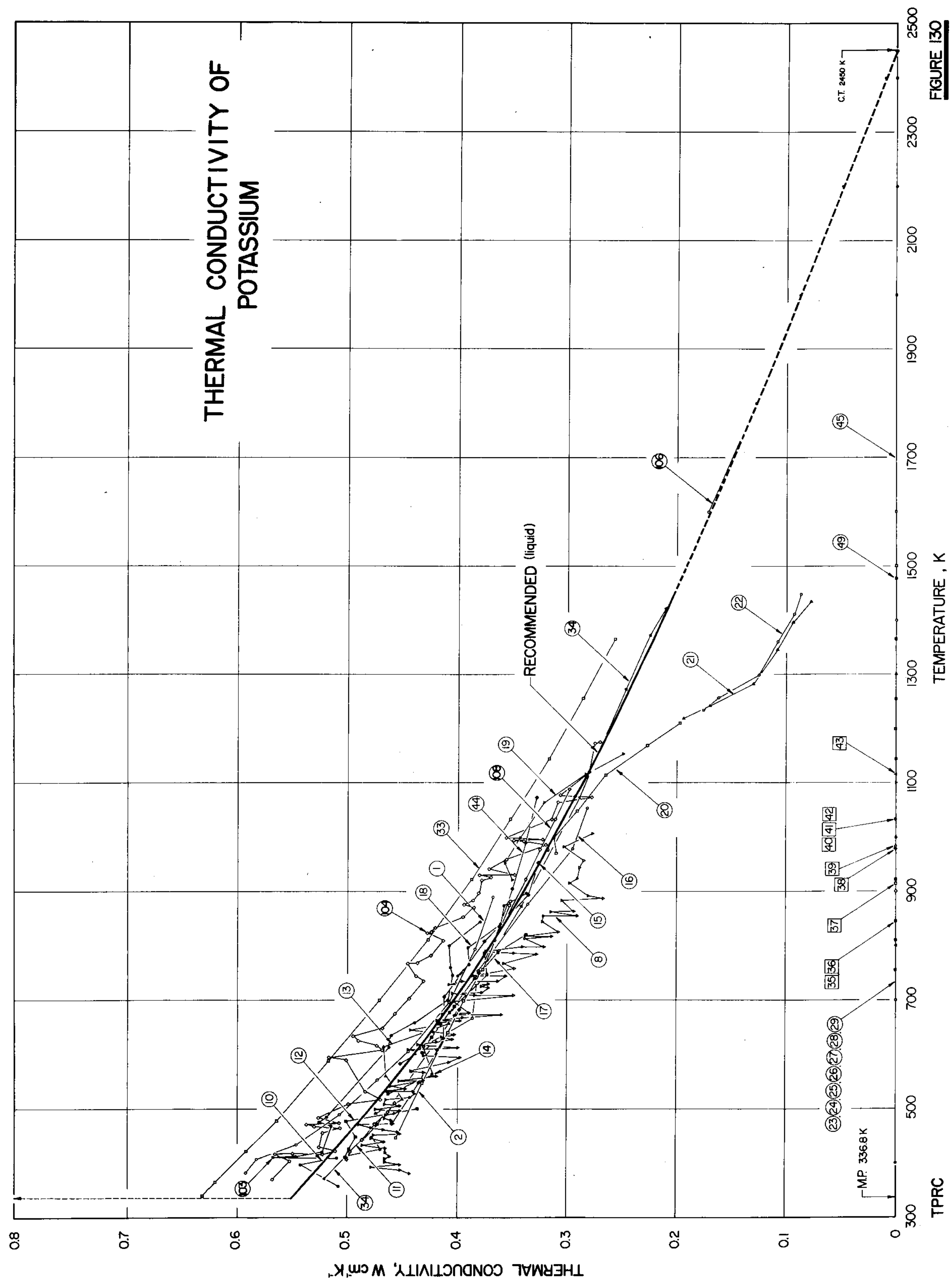

THERMAL CONDUCTIVITY OF POTASSIUM
RECOMMENDED (liquid)
M.P. 336.8 K
C.T. 2450 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 130

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1044	Novikov, I.I., Solovyev, A.N., Khabakhnasheva, E.M., Gruzdev, V.A., Pridantsev, A.I., and Vasenina, M.Ya.	1956	P	384-891		Pure; in liquid state; thermal conductivity values calculated from measured (in argon) thermal diffusivity data using the specific heat and density values given in "Liquid Metals Handbook" (Lyon, R., Editor, 2nd Edition, 1952).
2	405, 414	Ewing, C.T., Grand, J.A., and Miller, R.R.	1951	L	448-883		<0.001 O, <0.00001 each of Na, Ca, Al, Rb, and Li; distilled; in liquid state.
3	635	Hornbeck, J.W.	1913	E	278-331		Pure; trace of Na; supplied by Eimer and Amend; electrical resistivity reported as 6.492, 6.442, 7.015, 7.035, 6.980, 8.353, and 8.338 μohm cm at 5.0, 5.0, 20.6, 20.7, 20.9, 57.4, and 57.8 C, respectively.
4	873	MacDonald, D.K.C., White, G.K., and Woods, S.B.	1956	L	2.4-13	K1	Very pure; specimen 1.3 mm dia; electrical resistivity ratio $\rho(295 K)/\rho_0 = 532$ (using Hackspill's value $\rho(295 K) = 7.08$ μohm cm); Lorenz function L(0 K) = 2.55 x 10^{-8} V^2 K^{-2}.
5	873	MacDonald, D.K.C., et al.	1956	L	2.3-91	K2	Very pure; specimen 2.1 mm dia; electrical resistivity ratio $\rho(295)/\rho_0 = 513$ (using Hackspill's value $\rho(295 K) = 7.08$ μohm cm); Lorenz function L(0 K) = 2.31 x 10^{-8} V^2 K^{-2}.
6	873	MacDonald, D.K.C., et al.	1956	L	2.6-18	K4	Very pure; specimen 1.3 mm dia; electrical resistivity ratio $\rho(295K)/\rho_0 = 325$ (using Hackspill's value $\rho(295 K) = 7.08$ μohm cm); Lorenz function L(0 K) = 2.49 x 10^{-8} V^2 K^{-2}.
7	755	Khalileev, P.A.	1940	L	298-433		Doubly distilled; measured below and above melting point (approx 62 C).
8	805, 1036	Kutateladze, S.S., Borishanskii, V.M., Novikov, I.I., and Fedynskii, O.S.	1958	L	382-1007		M.P. 63.7 C; specimen in liquid state; measured in vacuum of ~4 x 10^{-4} mm Hg.
9	328	Deem, H.W. and Matolich, J., Jr.	1963	C	319, 333		0.1 Na, 0.0050 Rb, 0.0035 O, 0.0030 Li, <0.0010 each of Cs, Zr, Fe, Co, and Ni; Nb-1 Zr alloy used as comparative material.
10	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	360-449		Liquid state; same pretest impurities as the above specimen; additonal impurities after test: 0.00105 Nb and 0.00015 Zr (contaminated from specimen container, made of Nb-1 Zr alloy); electrical resistivity reported as 15.4, 21.5, 28.4, 35.8, 44.4, 54.7, 66.4, 79.5, 93.8, 110, 131, 145, and 153 μohm cm at 373, 473, 573, 673, 773, 873, 973, 1073, 1173, 1273, 1373, 1423, and 1448 K, respectively; Nb-1 Zr alloy used as comparative material; run A, equilibrium 1.
11	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	408-511		Run A, equilibrium 2 of the above specimen.
12	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	412-501		Run A, equilibrium 3 of the above specimen.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	491-658		Run A, equilibrium 4 of the above specimen.
14	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	529-787		Run A, equilibrium 5 of the above specimen.
15	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	584-953		Run A, equilibrium 6 of the above specimen.
16	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	611-1054		Run A, equilibrium 7 of the above specimen.
17	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	604-822		Same specimen as above; run B, equilibrium 1.
18	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	745-897		Run B, equilibrium 2 of the above specimen.
19	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	922-1154		Run B, data set 3, reading 1 of the above specimen.
20	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	970-1210		Run B, data set 3, reading 2 of the above specimen.
21	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	1219-1435		Run B, data set 3, reading 14 of the above specimen.
22	328, 902, 835, 836	Deem, H.W. and Matolich, J., Jr.	1963	C	1234-1449		Run B, data set 3, reading 15 of the above specimen.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
23	1362	Stefanov, B.I., Timrot, D.L., Totskii, E.E., and Chu, W.H.	1966		700-1500		Vapor; measured in the 1 mm gap between concentric cylinders 900 mm long; vapor pressure = 0.01 kg cm^{-2}.
24	1362	Stefanov, B.I., et al.	1966		800-1500		Similar to the above except vapor pressure = 0.05 kg cm^{-2}.
25	1362	Stefanov, B.I., et al.	1966		900-1500		Similar to the above except vapor pressure = 0.1 kg cm^{-2}.
26	1362	Stefanov, B.I., et al.	1966		1000-1500		Similar to the above except vapor pressure = 0.5 kg cm^{-2}.
27	1362	Stefanov, B.I., et al.	1966		1100-1500		Similar to the above except vapor pressure = 1.0 kg cm^{-2}.
28	1362	Stefanov, B.I., et al.	1966		1100-1500		Similar to the above except vapor pressure = 2.0 kg cm^{-2}.
29	1362	Stefanov, B.I., et al.	1966		700-1100		Similar to the above except measured on saturation curve.
30	1360	Stauder, R.F. and Mielczarek, E.V.	1967	L	4.3-18	K-9	99.97 pure; single crystal; rectangular specimen with length/cross-sectional area = 12 cm^{-1}; material obtained from Mine Safety Appliances Corp; prepared by growing from the bulk material using the Bridgman technique.
31	1360	Stauder, R.F. and Mielczarek, E.V.	1967	L	3.1-32	ZK-1	Originally 99.97 pure; single crystal; rectangular specimen with length to cross-sectional area ratio = 12 cm^{-1}; material obtained from Mine Safety Appliances Corp; prepared by melting in a stainless steel boat, zone refined at a rate of 1 in. hr^{-1} for 16 passes, grown by using the Bridgman technique. The zone refining technique is believed to have introduced impurities not present in the original bulk material.
32	1360	Stauder, R.F. and Mielczarek, E.V.	1967	L	2.7-12	ZK-2	Similar to the above specimen.
33	1211, 1212, 1401	Tepper, F., Zelenak, J., Roehlich, F., and May, V.	1965	→	341-1366		Specimen in liquid state; density reported as 0.7851, 0.7434, 0.7161, 0.6887, 0.6664, 0.6276, 0.6024, and 0.5861 g cm^{-3} at 520.5, 701.3, 827.7, 944.3, 1048, 1206, 1302, and 1374 K, respectively; electrical resistivity reported as 7.02, 7.32, 7.54, 8.05, 15.05, 17.96, 20.31, 24.83, 28.34, 32.64, 37.84, 41.43, 47.70, 51.81, 58.51, 65.94, 71.44, 81.18, 87.82, 98.61, 106.63, 119.87, and 130.61 µohm cm at 296, 309, 314, 329, 376, 431, 476, 541, 591, 648, 712, 755, 822, 863, 926, 988, 1031, 1102, 1144, 1210, 1253, 1319, and 1365 K, respectively; thermal conductivity values calculated from measured electrical resistivity data and the Lorenz number 2.45 x 10^{-8} V^2 K^{-2}.
34	328, 836	Deem, H.W. and Matolich, J., Jr.	1963	→	373-1423		Thermal conductivity values calculated from the measurements of electrical resistivity, reported as 15.4, 21.5, 28.4, 35.8, 44.4, 54.7, 66.4, 74.2, 79.5, 93.8, 110, 131, and 145 µohm cm at 100, 200, 300, 400, 500, 600, 700, 760, 800, 900, 1000, 1100, and 1150 C, respectively, Lorenz number assumed to be 2.14 x 10^{-8} V^2 K^{-2} based upon experimental information.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35	1400	Tepper, F. and Roehlich, F.	1966	→	845.2	Run No. 1	Vapor specimen filled in a test cell 8 in. long connected with a boiler; boiler pressure ~10 mm Hg; thermal conductivity measured by using the dynamic hot-wire method.
36	1400	Tepper, F. and Roehlich, F.	1966	→	847.2	Run No. 2	Same as above except boiler pressure 37 mm Hg.
37	1400	Tepper, F. and Roehlich, F.	1966	→	914.2	Run No. 3	Same as above except boiler pressure 72 mm Hg.
38	1400	Tepper, F. and Roehlich, F.	1966	→	978.2	Run No. 4	Same as above except boiler pressure 80 mm Hg.
39	1400	Tepper, F. and Roehlich, F.	1966	→	983.2	Run No. 5	Same as above; in different run.
40	1400	Tepper, F. and Roehlich, F.	1966	→	1034	Run No. 6	Same as above except boiler pressure 78 mm Hg.
41	1400	Tepper, F. and Roehlich, F.	1966	→	1035	Run No. 7	Same as above except boiler pressure 1417 mm Hg.
42	1400	Tepper, F. and Roehlich, F.	1966	→	1036	Run No. 8	Same as above; in different run.
43	1400	Tepper, F. and Roehlich, F.	1966	→	1116	Run No. 9	Same as above except boiler pressure 1144 mm Hg.
44	712	Kapelner, S. M. and Bratton, W. D.	1962	→	473-1073		0.32 Na, 0.02 Fe, and 0.004 O (post test); molten specimen contained in a type 347 stainless steel tube; supplied by Fisher Scientific Co.; electrical resistivity 8.07, 8.24, 8.59, 8.82, 9.47, 9.81, 14.77, 15.48, 17.90, 21.86, 26.06, 29.57, 34.11, 38.32, 43.30, 48.47, 54.04, 59.47, 60.02, 66.75, and 74.30 μohm cm at 25.3, 29.4, 38.3, 51.4, 58.3, 59.2, 79.4, 91.9, 140.8, 205.0, 256.4, 313.9, 373.6, 429.2, 481.9, 542.8, 593.3, 646.9, 651.4, 706.7, and 764.2 C, respectively; thermal conductivity values calculated from measured electrical resistivity data and the Lorenz function of 2.07, 2.11, 2.14, 2.17, 2.21, 2.29, and 2.34 x 10^{-8} V^2 K^{-2} at 200, 300, 400, 500, 600, 700, and 750 C, respectively, the first five values being derived from the thermal conductivity measurements of Ewing, C. T. and Grand, J. A. (NRL Report 3835, 1951) and the author's own electrical resistivity data.
45	1414	Timrot, D. L. and Totskii, E. E.	1967	→	997		Vapor state; contained in the annulus between two concentric thin-walled hollow cylinders; measuring method based on thermal expansion of the coaxial cylinders; measured at a potassium vapor pressure of 0.022 kg cm^{-2}.
46*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	857-1107		Similar to above but potassium vapor pressure 0.023 kg cm^{-2}.
47*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1004		Similar to above but potassium vapor pressure 0.048 kg cm^{-2}.
48*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	859, 885		Similar to above but potassium vapor pressure 0.049 kg cm^{-2}.
49	1414	Timrot, D. L. and Totskii, E. E.	1967	→	919		Similar to above but potassium vapor pressure 0.050 kg cm^{-2}.
50*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	921, 1004		Similar to above but potassium vapor pressure 0.140 kg cm^{-2}.
51*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1112		Similar to above but potassium vapor pressure 0.142 kg cm^{-2}.
52*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1250		Similar to above but potassium vapor pressure 0.303 kg cm^{-2}.
53*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1003		Similar to above but potassium vapor pressure 0.304 kg cm^{-2}.
54*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1111		Similar to above but potassium vapor pressure 0.308 kg cm^{-2}.
55*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1003-1244		Similar to above but potassium vapor pressure 0.550 kg cm^{-2}.

* Not shown in figure.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
56*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1070-1246		Similar to above but potassium vapor pressure 0.940 kg cm^{-2}.
57*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	898.4		99.8 pure; in vapor state; contained in the annulus between two coaxial hollow cylinders of 200 mm high with 12.92 mm I. D. and 14.08 mm O. D.; measured at a potassium vapor pressure of 0.005 atm.
58*	1476	Vargaftik and Voshchinin	1967	R	806,1077		Similar to above but potassium vapor pressure 0.007 atm.
59*	1476	Vargaftik and Voshchinin	1967	R	1085		Similar to above but potassium vapor pressure 0.026 atm.
60*	1476	Vargaftik and Voshchinin	1967	R	1008		Similar to above but potassium vapor pressure 0.027 atm.
61*	1476	Vargaftik and Voshchinin	1967	R	914.0		Similar to above but potassium vapor pressure 0.033 atm.
62*	1476	Vargaftik and Voshchinin	1967	R	1016,1088		Similar to above but potassium vapor pressure 0.034 atm.
63*	1476	Vargaftik and Voshchinin	1967	R	1077		Similar to above but potassium vapor pressure 0.037 atm.
64*	1476	Vargaftik and Voshchinin	1967	R	806.8		Similar to above but potassium vapor pressure 0.042 atm.
65*	1476	Vargaftik and Voshchinin	1967	R	817.9		Similar to above but potassium vapor pressure 0.044 atm.
66*	1476	Vargaftik and Voshchinin	1967	R	898.5		Similar to above but potassium vapor pressure 0.045 atm.
67*	1476	Vargaftik and Voshchinin	1967	R	1073		Similar to above but potassium vapor pressure 0.047 atm.
68*	1476	Vargaftik and Voshchinin	1967	R	999.3		Similar to above but potassium vapor pressure 0.057 atm.
69*	1476	Vargaftik and Voshchinin	1967	R	898.4		Similar to above but potassium vapor pressure 0.095 atm.
70*	1476	Vargaftik and Voshchinin	1967	R	1009		Similar to above but potassium vapor pressure 0.100 atm.
71*	1476	Vargaftik and Voshchinin	1967	R	895.8		Similar to above but potassium vapor pressure 0.106 atm.
72*	1476	Vargaftik and Voshchinin	1967	R	1000		Similar to above but potassium vapor pressure 0.128 atm.
73*	1476	Vargaftik and Voshchinin	1967	R	896.4		Similar to above but potassium vapor pressure 0.170 atm.
74*	1476	Vargaftik and Voshchinin	1967	R	1077		Similar to above but potassium vapor pressure 0.172 atm.
75*	1476	Vargaftik and Voshchinin	1967	R	1080		Similar to above but potassium vapor pressure 0.180 atm.
76*	1476	Vargaftik and Voshchinin	1967	R	1087		Similar to above but potassium vapor pressure 0.185 atm.
77*	1476	Vargaftik and Voshchinin	1967	R	1001		Similar to above but potassium vapor pressure 0.196 atm.
78*	1476	Vargaftik and Voshchinin	1967	R	1076		Similar to above but potassium vapor pressure 0.204 atm.
79*	1476	Vargaftik and Voshchinin	1967	R	1011		Similar to above but potassium vapor pressure 0.206 atm.
80*	1476	Vargaftik and Voshchinin	1967	R	1072		Similar to above but potassium vapor pressure 0.213 atm.
81*	1476	Vargaftik and Voshchinin	1967	R	1015		Similar to above but potassium vapor pressure 0.305 atm.
82*	1476	Vargaftik and Voshchinin	1967	R	1001		Similar to above but potassium vapor pressure 0.318 atm.
83*	1476	Vargaftik and Voshchinin	1967	R	1014		Similar to above but potassium vapor pressure 0.336 atm.
84*	1476	Vargaftik and Voshchinin	1967	R	1080		Similar to above but potassium vapor pressure 0.357 atm.
85*	1476	Vargaftik and Voshchinin	1967	R	1074		Similar to above but potassium vapor pressure 0.388 atm.

* Not shown in figure.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
86*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1075		Similar to above but potassium vapor pressure 0.490 atm.
87*	1476	Vargaftik and Voshchinin	1967	R	1088		Similar to above but potassium vapor pressure 0.500 atm.
88*	1476	Vargaftik and Voshchinin	1967	R	1000		Similar to above but potassium vapor pressure 0.503 atm.
89*	1476	Vargaftik and Voshchinin	1967	R	1014		Similar to above but potassium vapor pressure 0.505 atm.
90*	1476	Vargaftik and Voshchinin	1967	R	1077		Similar to above but potassium vapor pressure 0.564 atm.
91*	1476	Vargaftik and Voshchinin	1967	R	1069		Similar to above but potassium vapor pressure 0.580 atm.
92*	1476	Vargaftik and Voshchinin	1967	R	1055		Similar to above but potassium vapor pressure 0.758 atm.
93*	1476	Vargaftik and Voshchinin	1967	R	1072		Similar to above but potassium vapor pressure 0.790 atm.
94*	1476	Vargaftik and Voshchinin	1967	R	1087		Similar to above but potassium vapor pressure 0.912 atm.
95*	1476	Vargaftik and Voshchinin	1967	R	1074		Similar to above but potassium vapor pressure 0.948 atm.
96*	1476	Vargaftik and Voshchinin	1967	R	1074		Similar to above but potassium vapor pressure 1.030 atm.
97*	1476	Vargaftik and Voshchinin	1967	R	1069		Similar to above but potassium vapor pressure 1.040 atm.
98*	1476	Vargaftik and Voshchinin	1967	R	1076		Similar to above but potassium vapor pressure 1.080 atm.
99*	1476	Vargaftik and Voshchinin	1967	R	1067		Similar to above but potassium vapor pressure 1.170 atm.
100*	1476	Vargaftik and Voshchinin	1967	R	1086		Similar to above but potassium vapor pressure 1.286 atm.
101*	1476	Vargaftik and Voshchinin	1967	R	1075		Similar to above but potassium vapor pressure 1.300 atm.
102	92	Archibald, M. A., Dunick, J. E., and Jericho, M. H.	1967	L	2.4-4.2		Obtained from J. T. Baker Chemical Co.; 1 mm dia x 4 cm long; material melted, pressurized in helium, evacuated, remelted, repeated the cycle several times, then cast in a nylon tube; residual electrical resistivity 0.0022 μohm cm; electrical resistivity ratio $\rho(296K)/\rho_0$ = 2800.
103	784, 1307	Shpil'rain, E. E. and Krainova, I. F.	1969	C	411-844		99.97 pure; liquid specimen held in a cylindrical container 15 mm in dia and 90 mm long; 1Kh 18 N9T steel used as comparative material.
104	784, 1307	Shpil'rain, E. E. and Krainova, I. F.	1969	C	372-1175		The above specimen 2nd run.
105*	546, 548, 549	Grosse, A. V.	1964	→	400-2450		Saturated vapor potassium; thermal conductivity values calculated from simple kinetic theory using the author's estimates of saturated vapor viscosity of potassium (Science, 147, 1438-41, 1965); critical temp estimated to be 2450 K.
106	546, 548, 549	Grosse, A. V.	1964	→	1600-2450		Liquid potassium; estimated values, based upon the electrical conductivity data up to 1450 K of Deem, H. and Matolich, J., Jr., (BMI Rept. BATT-4673-T6, NASA CR-52315, 1963), the author's estimated values up to the critical temp of 2450 K, and a Lorenz function of 2.16×10^{-8} V^2K^{-2}.
107	232	Caldwell, R. T. and Walley, D. M.	1966	→	255-336		Solid potassium; thermal conductivity values estimated from electrical resistivity data of Deem, H. W. and Matolich, J., Jr. (BMI Rept. BATT-4673-T6, NASA CR-52315, 1963) by using a Lorenz number about 18% lower than the theoretical value.

* Not shown in figure.

TABLE 122. THERMAL CONDUCTIVITY OF POTASSIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
108	1509	Weatherford, W. D., Jr., Tyler, J. C., and Ku, P. M.	1961		700-1089		Liquid state; recommended values.
109*	1509	Weatherford, W. D., Jr. et al.	1961		734-1515		Saturated vapor; recommended values calculated from the frozen specific heat and the viscosity of saturated vapor assuming a constant Prandtl number of 0.73.

* Not shown in figure.

Praseodymium

The thermal conductivity measurements reported for praseodymium are limited to those of Devyatkova, Zhuze, Golubkov, Sergeeva, and Smirnov [359] (curve 1) for the range 83 to 380 K, and of Legvold and Spedding [831] (curve 2) and Jolliffe, Tye, and Powell [690] (curve 3) at normal temperatures. These last two values are of the order of 10 percent below the curve of Devyatkova, et al., and the present recommended curve has been drawn in an intermediate position. The curve has been tentatively extrapolated to 1000 K by deriving the electronic component from published electrical resistivity data and the theoretical Lorenz number, and the lattice component from AT^{-1}, a value of 3.78 being used for A as derived from the data of Jolliffe, et al. at 291 K.

Owing to the complete lack of thermal conductivity measurements below 83 K, the curve has not been extended to lower temperatures. A value of 0.8 $\mu\Omega$ cm has been reported by Meaden [912] for the residual electrical resistivity, and this indicates that the thermal conductivity of praseodymium at 4 K is likely to be not less than 0.128 W cm^{-1} K^{-1}. This is close to the value at room temperature, and would suggest that the curve has a maximum and a minimum in the intermediate temperature region.

The recommended values are thought to be accurate to within ±5 percent of the true values near room temperature and ±10 to ±15 percent at other temperatures.

TABLE 123. Recommended thermal conductivity of praseodymium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	373.2	0.134
80	0.0692*	400	0.136*
90	0.0732	473.2	0.144*
100	0.0769	500	0.147*
123.2	0.0844	573.2	0.154*
150	0.0926	600	0.157*
173.2	0.0987	673.2	0.166*
200	0.106	700	0.169*
223.2	0.110	773.2	0.180*
250	0.116	800	0.184*
273.2	0.120	873.2	0.196*
298.2	0.125	900	0.200*
300	0.125	973.2	0.212*
323.2	0.128	1000	0.216*
350	0.132		

†For well-annealed high-purity praseodymium.
*Extrapolated.

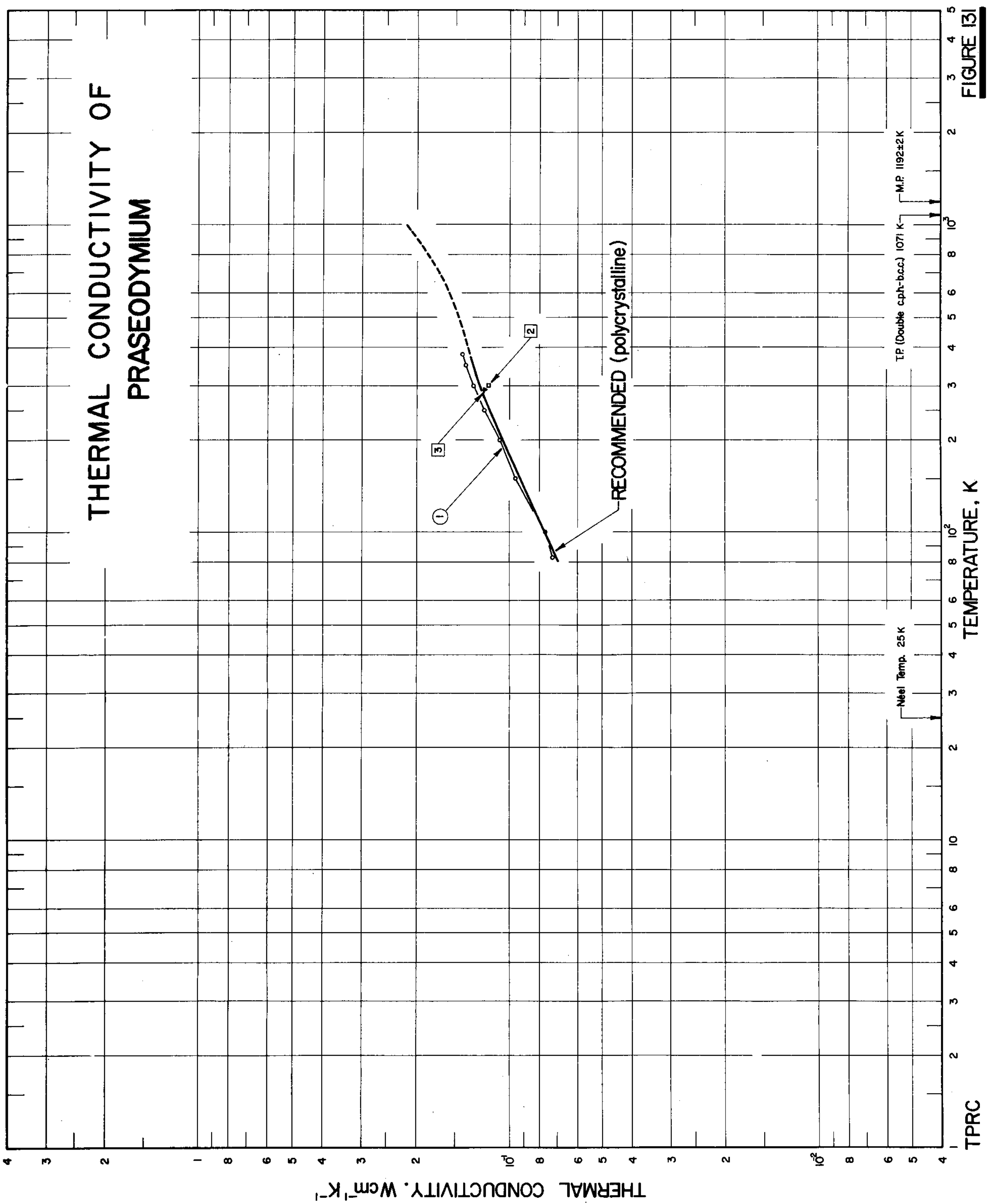

THERMAL CONDUCTIVITY OF
PRASEODYMIUM
FIGURE 131
RECOMMENDED (polycrystalline)
T.P. (Double c.p.h-b.c.c.) 1071 K
M.P. 1192±2 K
Neel Temp. 25 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

TABLE 124. THERMAL CONDUCTIVITY OF PRASEODYMIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	359	Devyatkova, E.D., Zhuze, V.P., Golubkov, A.V., Sergeeva, V.M., and Smirnov, I.A.	1964	L	83-380		0.5 La, 0.04 Cu, 0.03 Fe, and 0.01 Ca; prepared by briquetting powder under a pressure of approx 8000 Kg cm^{-2} and annealing in vacuo (~1 x 10^{-4} mm Hg) for 1-2 hrs at 1600-1800 C; measured in vacuo of ~5 x 10^{-5} mm Hg; data taken from smoothed curve of measurements on several specimens.
2	831	Legvold, S and Spedding, F.H.	1954		301		No details reported.
3	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	C	291		~0.1 Ta, <0.1 other rare earth metals, and ~0.03 other base metals; high purity polycrystalline specimen 1 cm in dia, 1.2 cm long; electrical resistivity 66 μohm cm at 291 K; data obtained by the author from measurements of 2 different thermal comparators.

Promethium

No measurements have been reported for either the thermal or electrical conductivity of promethium, but Williams and McElroy [1565] have derived estimated values for both conductivities for the solid and molten states. Estimates for the electrical resistivity of solid promethium were obtained from plots of electrical resistivity isotherms against atomic number. The probable change in resistivity on fusion and the temperature coefficient in the molten phase were also derived from the corresponding data for other rare earth elements. Having derived their estimated electrical resistivity values for the solid (ρ_S) and liquid (ρ_L) states Williams and McElroy then calculated the corresponding thermal conductivities.

For the solid they used the equation

$$k_T = \frac{2.443 \times 10^{-8} T}{\rho_S} + \frac{16}{T}.$$

The various procedures adopted for the estimation of liquid promethium yielded a mean curve from which the extreme estimates deviated by 42 percent at 1353 K and by 56 percent at 2253 K.

The mean estimated curves obtained in this way for the thermal conductivity of promethium over the range 300 to 2253 K are reproduced in the figure, and provide the only information for the thermal conductivity of this element.

For the time being, these estimated values are adopted as provisional values for the thermal conductivity of high-purity promethium. These are probably good to ±30 percent for solid and ±40 percent for molten promethium.

TABLE 125. Provisional thermal conductivity of promethium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline		Liquid	
T	k	T	k
300	0.179*	1353	0.175*
323.2	0.181*	1373.2	0.177*
350	0.182*	1400	0.178*
373.2	0.184*	1473.2	0.182*
400	0.184*	1500	0.184*
473.2	0.185*	1573.2	0.188*
500	0.185*	1600	0.190*
573.2	0.186*	1673.2	0.194*
600	0.187*	1700	0.196*
673.2	0.190*	1773.2	0.200*
700	0.191*	1800	0.202*
773.2	0.194*	1873.2	0.206*
800	0.195*	1900	0.208*
873.2	0.198*	1973.2	0.212*
900	0.201*	2000	0.214*
973.2	0.205*	2073.2	0.212*
1000	0.207*	2173.2	0.225*
1073.2	0.213*	2200	0.226*
1100	0.215*	2253	0.229*
1173.2	0.221*		
1185	0.222*		
1185	0.213*		
1200	0.214*		
1273.2	0.220*		
1300	0.223*		
1353	0.230*		

†The provisional values are for high-purity promethium and those for solid are for a polycrystalline sample.

*Estimated.

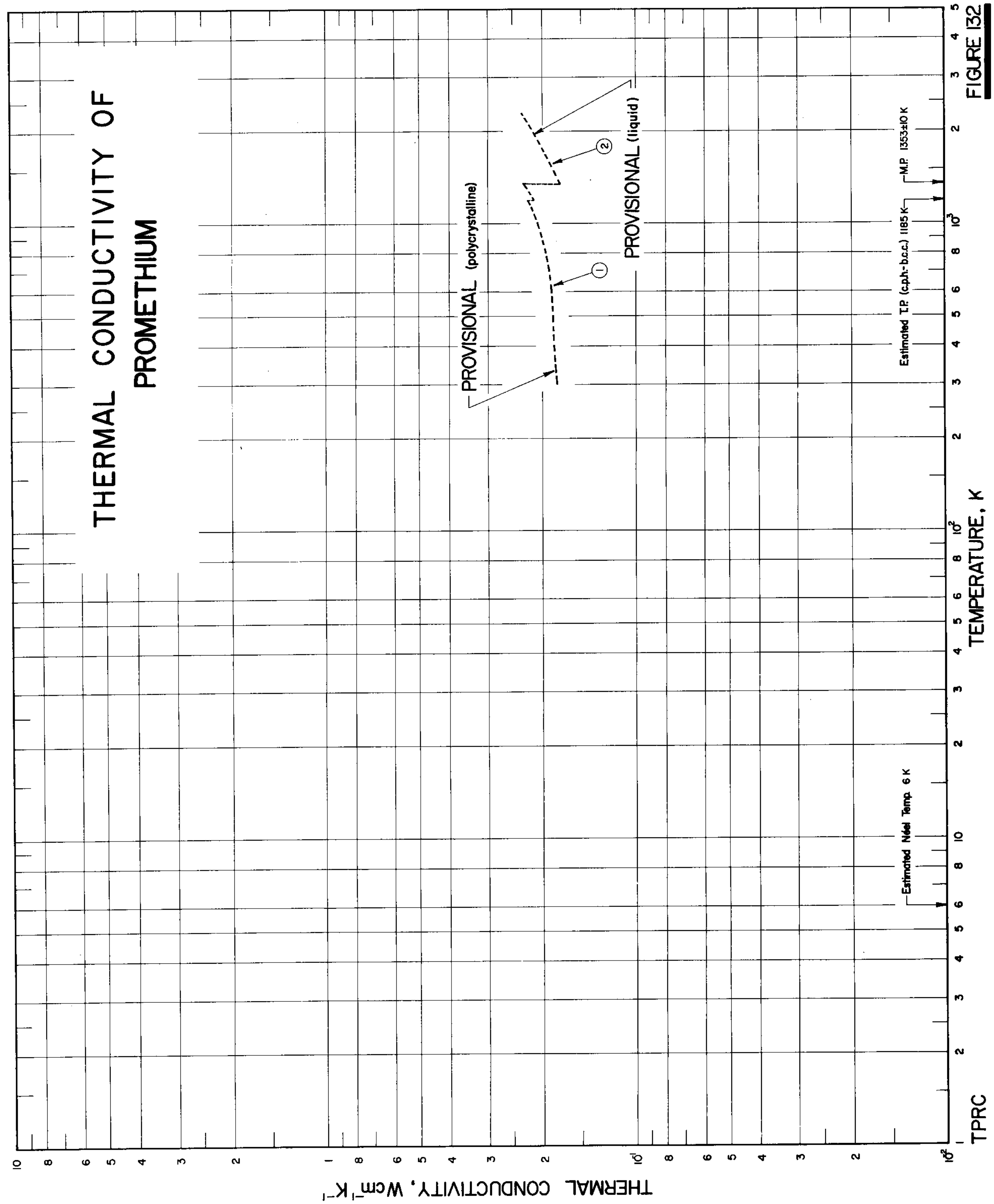

THERMAL CONDUCTIVITY OF PROMETHIUM
PROVISIONAL (polycrystalline)
PROVISIONAL (liquid)
Estimated T.P. (c.p.h-b.c.c.) 1185 K
M.P. 1353±10 K
Estimated Néel Temp. 6 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 132

TABLE 126. THERMAL CONDUCTIVITY OF PROMETHIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1565	Williams, R.K. and McElroy, D.L.	1966	→	300-1353		Solid state; estimated thermal conductivity values given as the sum of electronic thermal conductivity and lattice thermal conductivity with electronic thermal conductivity values calculated from the theoretical Lorenz number $L_0 = 2.443 \times 10^{-8} V^2 K^{-2}$ and the estimated electrical resistivity reported as 54.0, 68.0, 80.0, 92.0, 102.0, 111.5, 120.5, 128.0, 134.5, 139.0 (α), 146.0 (β), 149.0, and 152.0 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1185, 1185, 1300, and 1353 K, respectively; and lattice thermal conductivity calculated from the emprical equation $k_L = 16 T^{-1}$; c.p.h. to b.c.c. transformation temp estimated to be 1185 K; Néel temp estimated to be 6 K.
2	1565	Williams, R.K. and McElroy, D.L.	1966	→	1353-2253		Liquid state; estimated thermal conductivity values given as the sum of electronic thermal conductivity and phonon conductivity with electronic thermal conductivity values calculated from estimated values of Lorenz number, and electrical resistivity, whereas phonon conductivity values ranging from 0.004 to 0.012 W $cm^{-1} C^{-1}$ being based on predictions due to Rao, M.R. (Phys. Rev., 59, 212, 1941), Turnbull, A.G. (Aust. J. Appl. Sci., 12, 324-29, 1961) and Powell, R.W., et al. ("Advances in Thermophysical Properties at Extreme Temperatures and Pressures", ASME, 289-95, 1965); approx mean conductivity values given by $k = 0.110 + 6.0 \times 10^{-5} T$ (°C) W $cm^{-1} C^{-1}$.

Protactinium

No information on the thermal conductivity of protactinium is available. The electrical resistivity of protactinium has been measured between 4 and 300 K by Griffin, Mendelssohn, and Mortimer [541] and is approximately equal to 1.9, 2.0, 2.5, 10.7, 13.7, 16.4, and 19.3 $\mu\Omega$ cm at 4.2. 10, 20, 150, 200, 250, and 300 K, respectively. Using the theoretical Lorenz number, Meaden [914] has calculated the electronic thermal conductivity of protactinium to be 0.055, 0.122, 0.373, and 0.380 W cm^{-1} K^{-1} at 4.2, 10, 250, and 300 K, respectively. However, since these values are low, Meaden [914] assumed that the Lorenz function of protactinium be the same as that of thorium for which the Lorenz function had been reported to be about 2.8×10^{-8} V^2 K^{-2} at liquid-helium temperatures and about 3.0×10^{-8} V^2 K^{-2} around room temperature [574], and has estimated the thermal conductivity of protactinium to be 0.062, 0.140, 0.457, and 0.466 W cm^{-1} K^{-1} at 4.2, 10, 250, and 300 K, respectively.

For the time being, these estimated higher values are adopted as provisional values for the thermal conductivity of protactinium. These are probably good to ±30 percent. The values below 250 K are applicable only to a specimen having an electrical resistivity of 1.9 $\mu\Omega$ cm at 4.2 K.

It is interesting to note that, if a smooth curve is drawn through the three points representing the thermal conductivity values at 300 K of thorium, uranium, and neptunium in a large working graph similar to figure 15, the intercept of this curve at atomic number 91 gives a value of 0.434 W cm^{-1} K^{-1} for protactinium at 300 K, which is only about 7 percent lower than the estimated value of Meaden.

Radium

Although no information appears to have been published regarding the electrical resistivity of radium, a value attributed to Chirkin [274] for the room-temperature thermal conductivity of radium does appear in a Handbook of the Physicochemical Properties of the Elements edited by Samsonov [1239]. Neither the basis of this value nor its probable reliability is known.

TABLE 127. Provisional thermal conductivity of radium

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid	
T	k
0	0
293	0.186

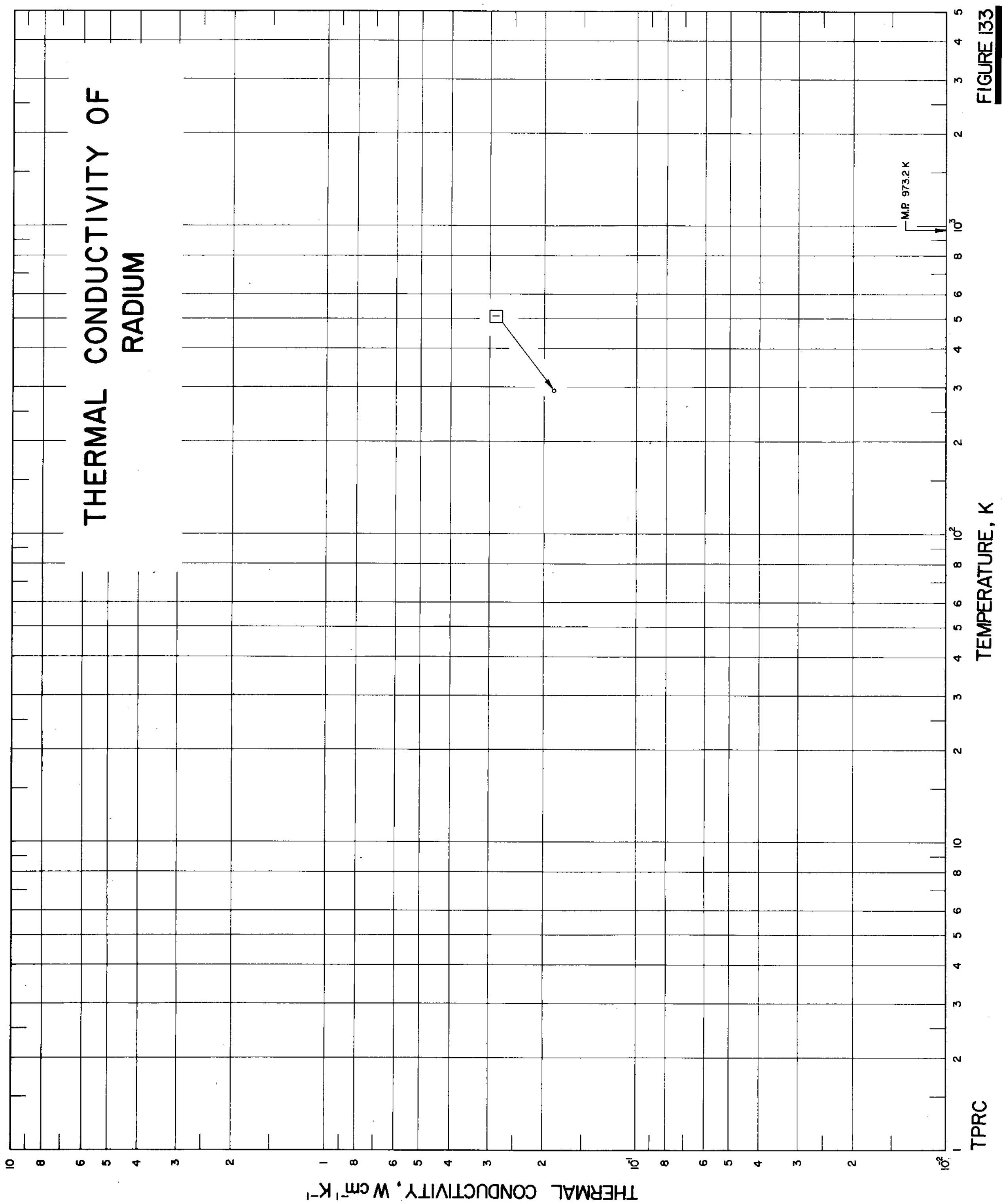


FIGURE 133
THERMAL CONDUCTIVITY OF RADIUM
M.P. 973.2 K
1
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

TABLE 128. THERMAL CONDUCTIVITY OF RADIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	274	Chirkin, V. S.	1962		293		No details given.

Radon

No experimental data are available for the thermal conductivity of radon. The estimated thermal conductivity for the saturated liquid, saturated vapor, and gaseous states are discussed separately below.

Saturated Liquid

No experimental data or estimates were found for the thermal conductivity of saturated liquid radon. The values here presented were obtained using the generalized correlation of Owens and Thodos [1058] for the thermal conductivity of monatomic liquids and vapors. It was necessary to obtain values of the critical parameters for this substance. While the critical temperature of 377.16 K was cited in the literature, no value of the critical thermal conductivity was located. A plausible result is (3.30 ± 0.45) 10^{-5} cal cm^{-1} s^{-1} K^{-1}. The critical parameters were then used together with the correlation to obtain the tabulated values.

The accuracy of the values is difficult to assess. Based upon the uncertainty in the original correlation, in the estimation of the value at the critical point and in the validity of the principle of corresponding states, an uncertainty of about twenty-five percent would seem to be a reasonable estimate. The values here presented must be considered as provisional and in need of experimental verification.

Saturated Vapor

No experimental data or estimates were found for the thermal conductivity of saturated radon vapor. The values here presented were obtained using the generalized correlation of Owens and Thodos [1058] for the thermal conductivity of monatomic liquids and vapors. It was necessary to obtain values of the critical parameters for this substance. While the critical temperature of 377.16 K was cited in the literature, no value of the critical thermal conductivity was located. A plausible result is (3.30 ± 0.45) 10^{-5} cal cm^{-1} s^{-1} K^{-1}. These critical parameters were then used together with the correlation to obtain the tabulated values.

The accuracy of the values is difficult to assess. Based upon the uncertainty in the original correlation, in the estimation of the value at the critical point and in the validity of the principle of corresponding states, an uncertainty of about twenty-five percent would seem to be a reasonable estimate. The values here presented must be considered as provisional and in need of experimental verification.

Gas

No experimental values were found for the thermal conductivity of radon gas at atmospheric pressure. Values were obtained in two ways: first, by using the generalized correlation of Owens and Thodos [1058] with the critical temperature of 377.16 K and critical thermal conductivity of 3.30×10^{-5} cal cm^{-1} s^{-1} K^{-1} and, secondly, by using the Lennard-Jones 6–12 potential function with molecular parameters quoted by [251]. Surprisingly good agreement was obtained in the results of the two methods. At 300 K, the values agreed to 0.5 percent, at 600 K to 0.7 percent, and at 1000 K to 2.5 percent. No preference can be assigned for the better method. The generalized correlation approach relies on the principle of corresponding states and the estimated critical thermal conductivity while the Lennard-Jones approach relies upon the molecular parameters estimated from thermal diffusion studies.

The values here presented are the mean of the two sets of values derived above. In view of the complete lack of experimental data they must be regarded as provisional and of uncertain accuracy. Possibly five percent uncertainty below 500 K and ten percent to 1000 K would prove a reasonable error estimate.

TABLE 129. Recommended thermal conductivity of radon

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Saturated liquid		Saturated vapor		Gas (at 1 atm)	
T	$k \times 10^3$	T	$k \times 10^3$	T	$k \times 10^3$
				211	0.0256*
				220	0.0266*
				230	0.0279*
				240	0.0291*
202	0.604*			250	0.0303*
210	0.586*	211	0.026*	260	0.0315*
220	0.562*	220	0.028*	270	0.0327*
230	0.540*	230	0.030*	280	0.0339*
240	0.518*	240	0.032*	290	0.0351*
250	0.498*	250	0.034*	300	0.0364*
260	0.477*	260	0.035*	310	0.0376*
270	0.456*	270	0.038*	320	0.0387*
280	0.437*	280	0.040*	330	0.0398*
290	0.417*	290	0.042*	340	0.0410*
300	0.396*	300	0.045*	350	0.0422*
310	0.375*	310	0.047*	360	0.0433*
320	0.353*	320	0.051*	370	0.0445*
330	0.330*	330	0.055*	380	0.0457*
340	0.305*	240	0.060*	390	0.0468*
350	0.278*	350	0.065*	400	0.0480*
360	0.249*	360	0.073*	410	0.0490*
370	0.213*	370	0.089*	420	0.0501*
377	0.138*‡	377	0.138*‡	430	0.0512*
				440	0.0523*
				450	0.0534*
				460	0.0544*
				470	0.0555*
				480	0.0566*
				490	0.0576*
				500	0.0586*
				550	0.0643*
				600	0.0690*
				650	0.0740*
				700	0.0789*
				750	0.0832*
				800	0.0874*
				850	0.0915*
				900	0.0964*
				950	0.0997*
				1000	0.1042*

*Estimated or extrapolated.
‡Pseudo-critical value.

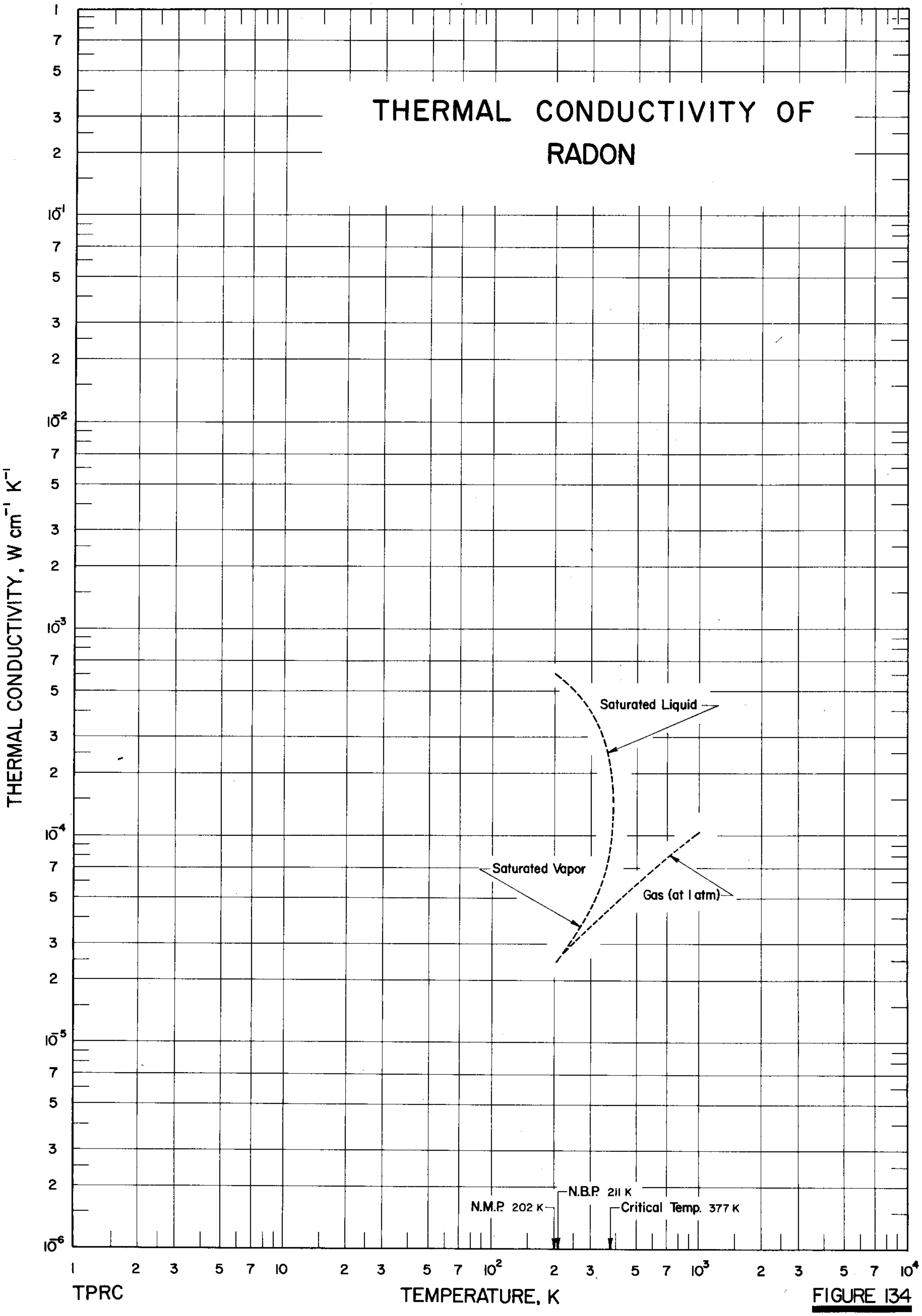

THERMAL CONDUCTIVITY OF RADON
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
Saturated Liquid
Saturated Vapor
Gas (at 1 atm)
N.M.P. 202 K
N.B.P. 211 K
Critical Temp. 377 K
TEMPERATURE, K
TPRC

FIGURE 134

Rhenium

At low temperatures the maxima of the available thermal conductivity curves for both single crystals and polycrystalline samples fall on one and the same straight line, and all the curves appear to be of the same family. In this case, the thermal conductivity data for a single crystal can be considered also for a polycrystalline sample as long as the two samples have the same residual electrical resistivity. The recommended values at cryogenic temperatures for a polycrystalline sample having $\rho_0 = 0.00366$ $\mu\Omega$ cm are based on the highest (curve 13) of the three sets of data obtained by Schriempf [1274]. The values below 1.5 T_m were calculated to fit the data by using the three-term equation (10) and using $n = 2.20$, $\alpha = 0.0000648$, $\beta = 0.150$, and $\gamma = 0.000282$. It is because equation (7) does not fit this curve well, the maximum difference being about 9 percent. Based upon the fact that the maximum difference, in fitting the second highest curve 12 by using equations (7) and (10), is less than 4 percent, it is concluded that equation (7) together with the constants listed in table 1 is adequate for curves lower than curve 12.

The calculated curve has been extended to follow curve 13 to 19 K and follow the general shape of curve 3 to 65 K. It then continues smoothly to pass through a value at 83 K (curve 5) of Powell, Tye, and Woodman [1142] and to fit their data (curve 6) to 523 K. Over the range 273 to 523 K, Powell, et al. had found the Lorenz function to have an almost constant value of 3.1×10^{-8} V^2 K^{-2}, and the value at higher temperatures might be expected to remain above the theoretical value. The only other experimental determinations of the thermal conductivity of rhenium have been by Rudkin, Parker, and Jenkins [1229] (curve 4) for the range 1700 to 2650 K and Jun and Hoch [699] (curve 7) from 1577 to 2397 K. The former group of workers also included determinations of the electrical resistivity, and these would suggest that their thermal conductivity values are low since the Lorenz function decreases from 1.89×10^{-8} to 1.32×10^{-8} V^2 K^{-2} over the range of their measurements. By using the same electrical resistivity data the thermal conductivity determinations of Jun and Hoch yield Lorenz functions which decrease from 2.75×10^{-8} V^2 K^{-2} at 1577 K to 1.87×10^{-8} V^2 K^{-2} at 2397 K. The tentatively recommended curve has accordingly been continued from 523 to 2600 K passing through the 1577 K point of Jun and Hoch. This line corresponds to a Lorenz function that has been assumed to change from 3.1×10^{-8} to 2.75×10^{-8} V^2 K^{-2} between 523 and 1577 K and to 2.5×10^{-8} V^2 K^{-2} by 2600 K. No electrical resistivity data for rhenium are available to higher temperatures, nor is there any information relating to the conductivity of molten rhenium. Rhenium is clearly a metal for which considerable uncertainty exists and further experiments are needed.

The recommended values are thought to be accurate to within ±10 percent below 100 K, ± 5 percent from 100 to 500 K, and ±15 percent above 500 K. The values at temperatures below 100 K are, of course, applicable only to a sample having $\rho_0 = 0.00366$ $\mu\Omega$ cm.

TABLE 130. Recommended thermal conductivity of rhenium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	350	0.470
1	6.65*	373.2	0.466
2	13.2*	400	0.461
3	19.4	473.2	0.451
4	25.0	500	0.449
5	29.7	573.2	0.444*
6	33.3	600	0.442*
7	35.6	673.2	0.441*
8	36.6	700	0.440*
9	36.6	773.2	0.440*
10	35.6	800	0.441*
11	34.0	873.2	0.442*
12	31.7	900	0.443*
13	28.9	973.2	0.445*
14	26.0	1000	0.446*
15	23.1	1073.2	0.450*
16	20.3	1100	0.451*
18	15.4	1173.2	0.455*
20	11.6	1200	0.457*
25	6.02	1273.2	0.462*
30	3.39	1300	0.464*
35	2.19	1373.2	0.469*
40	1.56	1400	0.471*
45	1.21	1473.2	0.476*
50	0.986	1500	0.478*
60	0.774	1573.2	0.483
70	0.678	1600	0.485
80	0.629	1673.2	0.490
90	0.606	1700	0.492
100	0.589	1773.2	0.498
123.2	0.561	1800	0.500
150	9.538	1873.2	0.507
173.2	0.524	1900	0.509
200	0.510	1973.2	0.516
223.2	0.501	2000	0.519
250	0.492	2073.2	0.526
273.2	0.486	2173.2	0.536
298.2	0.480	2200	0.539
300	0.479	2273.2	0.547
323.2	0.475	2400	0.563
		2473.2	0.573
		2600	0.592

†The recommended values are for well-annealed high-purity rhenium, and those below 100K are applicable only to a specimen having residual electrical resistivity of 0.00366 $\mu\Omega$ cm.

*Extrapolated or interpolated.

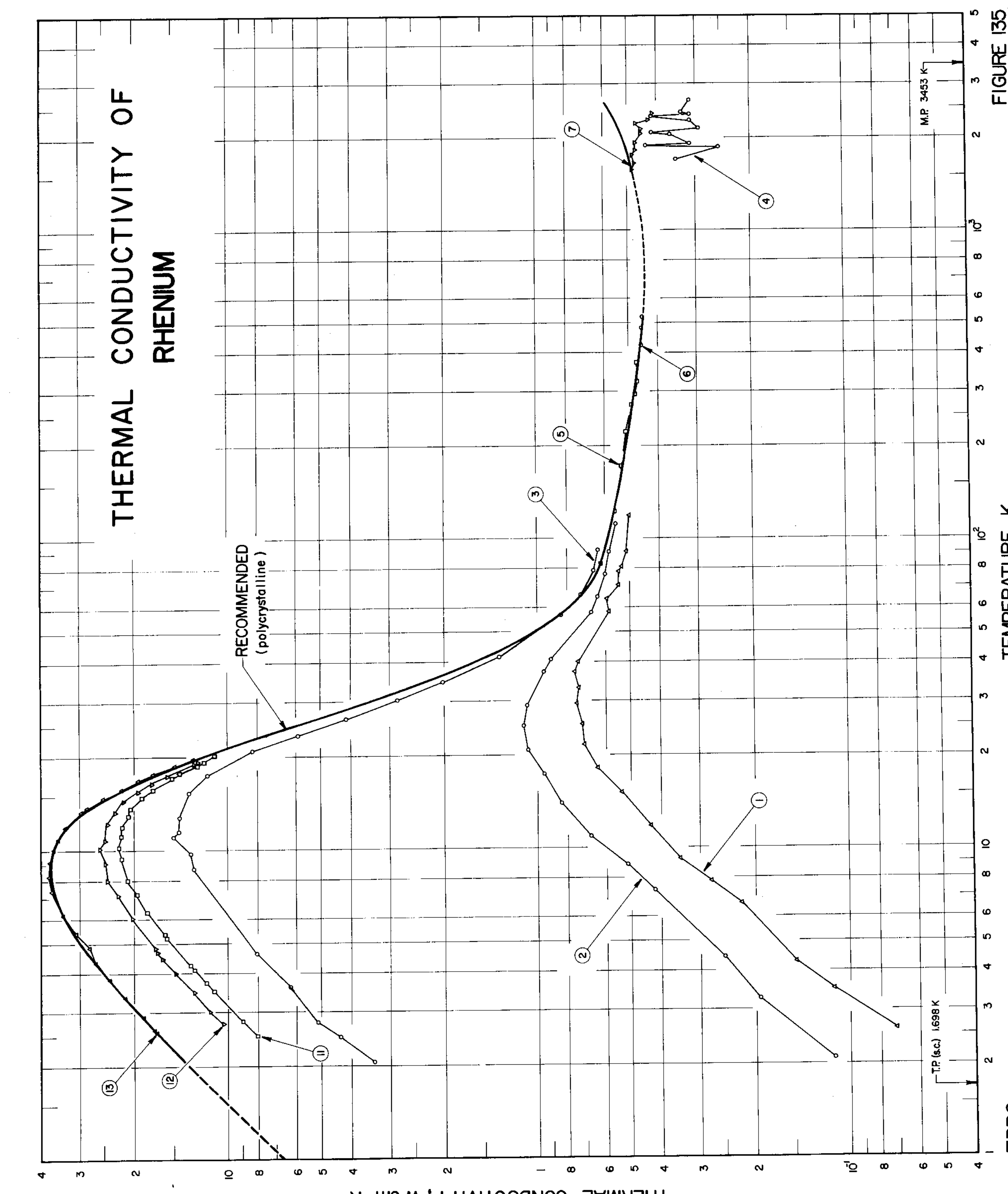

THERMAL CONDUCTIVITY OF
RHENIUM
RECOMMENDED
(polycrystalline line)
M.P. 3453 K
T.P. (s.c.) 1.698 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 135

TABLE 131. THERMAL CONDUCTIVITY OF RHENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1547, 1550	White, G.K. and Woods, S.B.	1957	L	2.6-118	Re 1	99.5$^+$ Re, total metallic impurities <0.1, consisting of Cu, Fe, and Mo; 1 x 0.075 cm in cross section and 5 to 8 cm long; cut from a rolled sheet 0.75 mm thick supplied by A. D. Mackay Inc.; density 21.3 g cm^{-3} at room temp; residual electrical resistivity 0.787 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0$ = 24.9.
2	1547, 1550	White, G.K. and Woods, S.B.	1957	L	2.1-112	Re 2	Cut from the same sheet as the above specimen; annealed in vacuo at 700 C for 2 hrs; residual electrical resistivity 0.469 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0$ = 40.7.
3	1547	White, G.K. and Woods, S.B.	1957	L	2.1-92	Re 4	Total impurities <0.01; prepared by zone-melting rhenium powder in an argon arc furnace; 6 mm in dia and 5 to 8 cm long; residual electrical resistivity 0.0139 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0$ = 1357.
4	1229	Rudkin, R.L., Parker, W.J., and Jenkins, R.J.	1962	E	1700-2650		Spectrographically pure; 0.10 in. in dia; electrical resistivity reported as 75.2, 84.9, 92.0, 95.2, 100.0, 103.9, 106.5, 108.3, 109.5, and 110.1 μohm cm at 1130, 1410, 1630, 1815, 1975, 2115, 2250, 2370, 2495, and 2605 K, respectively; measured in a vacuum of <10^{-5} mm Hg.
5	1142	Powell, R.W., Tye, R.P., and Woodman, M.J.	1963	L	83-373		High purity; traces of noble metals; 7.0 cm long, 0.486 cm in dia; supplied by Johnson, Matthey and Co., Ltd; heat treated at 1390 C; electrical resistivity reported as 2.9, 5.8, 9.6, 13.3, 17.2, 18.8, 21.2, 24.9, 28.8, 32.6, and 36.1 μohm cm at 83, 123, 173, 223, 273, 293, 323, 373, 423, 473, and 523 K, respectively; residual electrical resistivity 0.078 μohm cm; density 20.98 g cm^{-3}; data taken from smoothed curve.
6	1142	Powell, R.W., et al.	1963	C	423-523		The above specimen measured by comparative method using Armco iron as comparative material; data taken from smoothed curve.
7	699	Jun, C.K. and Hoch, M.	1966	→	1577-2397		0.0047 C and 0.001116 O; hexagonal; specimen 1.0711 cm in dia and 0.1582 cm thick; density 20.97 g cm^{-3}; thermal conductivity derived from the temp distribution on the flat surface of the cylindrical disc specimen heated in high vacuum (10^{-5} mm Hg) by high frequency induction generating localized heating within 0.003 in. of the surface at current frequency of 500,000 cps with heat lost only by radiation; the cylindrical surface being assumed isothermal, and the temp gradient along the radius was analytically correlated to the thermal conductivity.
8*	1299	Sharma, J.K.N.	1967	L	0.40-0.96		99.994 pure; single crystal; supplied by Materials Research Corp, New York; specimen form factor (ℓ/a) = 1.6 x 10^2 cm^{-1}; electrical resistivity ratio $\rho(293K)/\rho(1.5)$ = 2000; in superconducting state.
9*	1299	Sharma, J.K.N.	1967	L	0.43-0.95		The above specimen in superconducting state; second run.
10*	1299	Sharma, J.K.N.	1967	L	0.42-0.97		The above specimen in normal state; anomalous peak observed at 0.75 K.
11	1271, 1274	Schriempf, J.T.	1967	L	2.5-20	Specimen 2	99.9 pure; single crystal; specimen 0.07586 cm^2 in cross-sectional area and 8.36 cm long; supplied by Chase Brass & Copper Co.; specimen axis oriented 77° from c-axis; prepared by electron-beam zone-refining in a vacuum of about 10^{-8} torr; residual electrical resistivity 0.00754 μohm cm; electrical resistivity ratio $\rho(297K)/\rho_0$ = 2490; Lorenz number L_0 = 2.46 x 10^{-8} V^2 K^{-2}; Lorenz function reported as 2.43, 2.41, 2.38, 2.38, 2.34, 2.29, 2.24, 2.15, 2.09, 1.92, 1.84, 1.70, 1.63, 1.50, 1.45, 1.33, 1.26, 1.13, 1.12, 1.07, 1.05, and 1.05 x 10^{-8} V^2 K^{-2} at 2.6, 3.5, 3.8, 4.3, 5.2, 5.4, 6.4, 7.2, 8.1, 9.4, 10.2, 11.1, 11.8, 12.8, 13.5, 14.6, 15.0, 17.0, 17.6, 18.5, 18.6, and 19.1 K, respectively.

* Not shown in figure.

TABLE 131. THERMAL CONDUCTIVITY OF RHENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
12	1274	Schriempf, J. T.	1967	L	2.7-19	Specimen 3	99.9 pure; single crystal; same supplier and fabrication method as the above specimen; 0.07518 cm^2 in cross-sectional area and 2.22 cm long; specimen axis oriented 37° from c-axis; residual electrical resistivity 0.00645 μohm cm; electrical resistivity ratio $\rho(297K)/\rho_0$ = 2510; Lorenz number L_0 = 2.46 x 10^{-8} V^2 K^{-2}; Lorenz function reported as 2.44, 2.44, 2.40, 2.37, 2.35, 2.36, 2.35, 2.32, 2.21, 2.13, 2.04, 1.88, 1.81, 1.66, 1.50, 1.38, 1.29, 1.18, 1.12, 1.00, 0.99, and 0.98 x 10^{-8} V^2 K^{-2} at 2.9, 3.1, 4.1, 4.6, 4.6, 4.8, 4.8, 4.9, 6.1, 7.0, 8.0, 9.0, 9.9, 10.9, 12.0, 13.3, 14.5, 15.6, 16.6, 18.5, 19.2, and 19.4 K, respectively.
13	1271, 1274	Schriempf, J. T.	1967	L	2.5-19	Specimen 60	Single crystal; 0.03618 cm^2 in cross-sectional area and 8.65 cm long; specimen axis oriented 90° from c-axis; prepared by Dr. R. Soden of Bell Telephone Laboratories by zone-refining compacted powder specimen; residual electrical resistivity 0.00366 μohm cm; electrical resistivity ratio $\rho(297K)/\rho_0$ = 5041; Lorenz number L_0 = 2.46 x 10^{-8} V^2 K^{-2}; Lorenz function reported as 2.42, 2.39, 2.37, 2.34, 2.30, 2.25, 2.21, 2.13, 1.97, 1.85, 1.70, 1.56, 1.45, 1.32, 1.18, 1.14, 1.06, 0.98, 0.95, 0.91, 0.89, and 0.90 x 10^{-8} V^2 K^{-2} at 2.8, 3.0, 3.5, 3.9, 4.4, 4.9, 5.3, 6.2, 7.4, 8.2, 9.3, 10.2, 11.0, 12.0, 13.3, 13.8, 14.9, 16.0, 17.0, 17.8, 18.8, and 19.9 K, respectively.

Rhodium

At low temperatures the recommended values for a sample having $\rho_0 = 0.00840$ $\mu\Omega$ cm are based on the measurements (curve 4) of White and Woods [1545]. The recommended curve has been fitted to these data for the region of maximum conductivity by using equation (7) and using $m = 3.00$, $n = 2.80$, $\alpha'' = 1.32 \times 10^{-6}$, and $\beta = 0.344$. The curve continues to follow their data up to 65 K, and then passes centrally through the region 112 to 118 K in which six determinations by four groups of workers, White and Woods [1545], Kemp, Klemens, and Tainsh [737] (curves 6 and 7), Powell and Tye [1129] (curve 8), and Powell, Tye and Woodman [1145] (curve 10), all agree to within 2.5 percent. From this region the recommended curve has been drawn to pass approximately through the higher set of values (curve 11) due to Powell, Tye, and Woodman, which terminates at 591 K.

No thermal conductivity measurements have been made between 591 and 1500 K. The recommended curve at moderate temperatures has been extended smoothly in this region to higher temperatures to pass through the mean of the recent data of Sorokin, Trukhanova, and Filippov [1343] (curve 13).

No information is available for the thermal conductivity of molten rhodium.

The recommended values are thought to be accurate to within ±5 percent at moderate temperatures and ±10 percent at low and high temperatures. The values at temperatures below 150 K are, of course, applicable only to a sample having $\rho_0 = 0.00840$ $\mu\Omega$ cm.

TABLE 132. Recommended thermal conductivity of rhodium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	1.52
1	2.91*	273.2	1.51
2	5.81	298.2	1.50
3	8.69	300	1.50
4	11.6	323.2	1.49
5	14.5	350	1.48
6	17.3	373.2	1.47
7	20.1	400	1.46
8	22.8	473.2	1.43
9	25.4	500	1.41
10	27.8	573.2	1.37
11	29.9	600	1.36*
12	32.1	673.2	1.32*
13	33.8	700	1.31*
14	35.3	773.2	1.28*
15	36.3	800	1.27*
16	37.0	873.2	1.25*
18	37.3	900	1.24*
20	36.4	973.2	1.21*
25	30.5	1000	1.21*
30	21.6	1073.2	1.19*
35	14.5	1100	1.18*
40	10.2	1173.2	1.17*
45	7.47	1200	1.16*
50	5.70	1273.2	1.15*
60	3.78	1300	1.14*
70	2.89	1373.2	1.13*
80	2.38	1400	1.12*
90	2.06	1473.2	1.11*
100	1.86	1500	1.10
123.2	1.63	1573.2	1.10
150	1.58	1600	1.10
173.2	1.56	1673.2	1.10
200	1.54	1700	1.10
223.2	1.53	1773.2	1.10
		1800	1.10
		1873.2	1.11
		1900	1.11
		1973.2	1.12
		2000	1.12

†The recommended values are for well-annealed high-purity rhodium, and those below 150 K are applicable only to a specimen having $\rho_0 = 0.00840$ $\mu\Omega$ cm.

*Extrapolated or interpolated.

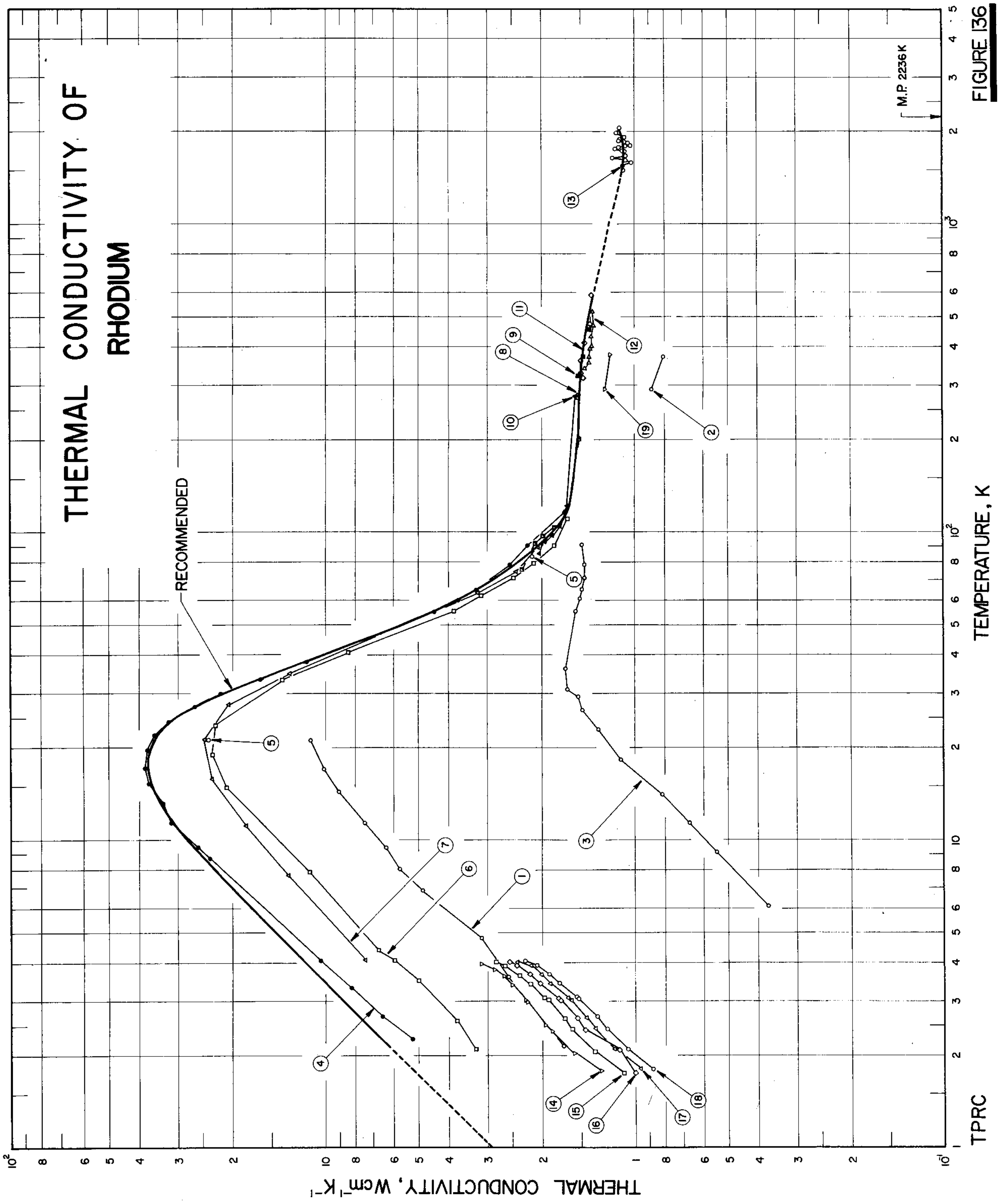

THERMAL CONDUCTIVITY OF
RHODIUM
RECOMMENDED
M.P. 2236 K
FIGURE 136
TEMPERATURE, K
THERMAL CONDUCTIVITY, $W cm^{-1} K^{-1}$
TPRC

TABLE 133. THERMAL CONDUCTIVITY OF RHODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.2-21	JM 2357; Rh 1	99.995 pure; 1-2 mm dia x 5 cm long; supplied by Johnson, Matthey and Co., Ltd.
2	116	Barratt, T.	1914	F	290, 373		Pure; 0.1030 x 0.1030 x 10.0 cm; electrical resistivity reported as 4.811 and 6.211 μohm cm at 0 and 100 C, respectively; specific gravity 12.505.
3	1545	White, G.K. and Woods, S.B.	1957	L	6.1-91	Rh 1	99.9$^+$ pure; 1.5 mm dia; supplied by Baker Platinum Co.; annealed at 1050 C; residual electrical resistivity 0.44 μohm cm; electrical resistivity ratio $\rho(295\ K)/\rho\ (0\ K) = 12$.
4	1545	White, G.K. and Woods, S.B.	1957	L	2.3-116	JM 8208; Rh 2	99.997$^+$ Rh, 0.002 Fe, and 0.0005 Cu; 1.5 mm dia; supplied by Johnson Matthey & Co., Ltd; annealed at 1300 C; ideal electrical resistivity reported as 0.00075, 0.0022, 0.0124, 0.048, 0.107, 0.42, 0.87, 1.91, 2.93, 4.38, 4.78, and 5.8 μohm cm at 15, 20, 30, 40, 50, 75, 100, 150, 200, 273, 295, and 350 K, respectively; residual electrical resistivity 0.0084 μohm cm; $\rho(295\ K)/\rho(0\ K) = 570$.
5	559	Grüneisen, E. and Goens, E.	1927	L	21, 83		Pure; supplied by Heraeus; rolled into square wire; annealed in vacuum at 1030 C for 10 min; electrical resistivity reported as 0.01635, 0.595, and 4.58 μohm cm at 21.2, 83.2, and 273.2 K, respectively.
6	737	Kemp, W.R.G., Klemens, P.G., and Tainsh, R.J.	1959	L	2.1-111	1	Specimen 7.5 x 0.15 x 0.15 cm; made from the specimen used by Grüneisen and Goens, 1927; electrical resistivity reported as 0.0155, 0.0160, 0.0167, 0.0188, 0.0318, 0.0581, 0.170, 0.380, 0.524, 0.751, 1.178, and 5.043 μohm cm at 4.2, 14.3, 18.7, 23.2, 32.9, 40.8, 54.7, 70.1, 78.8, 90.2, 110.6, and 292.3 K, respectively.
7	737	Kemp, W.R.G., et al.	1959	L	4.1-90	2	Same source as the above specimen; dimensions 3.4 x 0.15 x 0.15 cm; annealed in vacuum at 1400 C for 5 hrs and cooled slowly; residual electrical resistivity 0.0148 μohm cm.
8	1129	Powell, R.W. and Tye, R.P.	1955	L	86-282		0.03-0.1 Ir, 0.005 Fe, 0.002-0.005 Ag, and 0.001-0.003 Pd; 5 cm long, 0.349 cm dia; supplied by Johnson Matthey Co.; annealed in vacuum at 1336 C; density 12.45 g cm^{-3}; electrical resistivity reported as 0.63, 0.765, 0.86, 1.02, 1.16, 1.265, 1.34, 2.95, 2.99, 3.155, 4.44, and 4.51 μohm cm at 85.8, 92.4, 97.1, 104.9, 112.2, 117.6, 121.6, 202.6, 204.8, 213.8, 277.8, and 281.6 K, respectively.
9	1141	Powell, R.W., Tye, R.P., and Woodman, M.J.	1962	C	323-458		The above specimen measured by comparative method using Armco iron as comparative material; residual electrical resistivity 0.024 μohm cm; electrical resistivity ratio $\rho(273\ K)/\rho_0 = 182$.
10	1145	Powell, R.W., Tye, R.P., and Woodman, M.J.	1967	L	84-282	Rh 1	0.03-0.1 Ir, 0.005 Fe, 0.002-0.005 Ag, and 0.001-0.003 Pd; specimen 0.348 cm in dia and 5 cm long supplied by Johnson Matthey Co.; annealed at 1610 K; density 12.44 g cm^{-3}; electrical resistivity reported as 0.92, 2.9, 4.90, 6.95, and 9.15 μohm cm at 100, 200, 300, 400, and 500 K, respectively; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 180$.
11	1145	Powell, R.W., et al.	1967	C	318-591	Rh 1	The above specimen measured by comparative method using Armco iron as comparative material.

TABLE 133. THERMAL CONDUCTIVITY OF RHODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
12	1145	Powell, R.W., Tye, R.P., and Woodman, M. J.	1967	C	310–521	Rh 2	0.001 Fe, 0.0002 Ag, 0.0001 Cu, and 0.0001 Pd; specimen 0.6 cm in dia, 6 cm long; supplied by Johnson,Matthey and Co.; density 12.22 g cm^{-3}; electrical resistivity reported as 0.9, 2.95, 4.95, 7.05, and 9.22 μohm cm at 100, 200, 300, 400, and 500 K, respectively; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 233$.
13	1343	Sorokin, A. G., Trukhanova, L. N., and Filippov, L. P.	1969	E	1500–2031		99.99 pure; 0.2 mm in dia and 11 to 12 cm long; annealed at 1900 K for 2 hrs; electrical resistivity 26.7, 29.5, 32.4, 35.2, 38.0, 40.9, 43.4, 46.3, and 48.8 μohm cm at 1250, 1350, 1450, 1550, 1650, 1750, 1850, 1950, and 2050 K, respectively; measured in a vacuum of 10^{-5} torr. (Correction of data received from Filippov, L. P., Feb. 28, 1970.)
14	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8–4.0	JM 2357	99.995 pure; supplied by Johnson, Matthey and Co., Ltd; strained; residual electrical resistivity $\rho_0 = 0.020$ μohm cm; electrical resistivity reported as 0.0227, 0.0266, 0.0290, 0.0304, 0.0318, 0.0337, and 0.0344 μohm cm at 1.55, 2.35, 2.82, 3.18, 3.48, 3.76, and 4.15 K, respectively.
15	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8–4.0		The above specimen measured in a magnetic field of 7.2 kilooersteds.
16	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8–4.0		The above specimen measured in a magnetic field of 10.7 kilooersteds.
17	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8–4.0		The above specimen measured in a magnetic field of 13.1 kilooersteds.
18	1012	Natarajan, N. S. and Chari, M. S. R.	1970	L	1.8–4.0		The above specimen measured in a magnetic field of 17.5 kilooersteds.
19	617	Holborn, L., Scheel, K., and Henning, F. (editors)	1919	E	291,373		Cast rod; electrical conductivity 16.6 and 12.6 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively; thermal conductivity data measured by Jaeger, W. and Diesselhorst, H.

Rubidium

Experimental determinations of the thermal conductivity of rubidium in the solid phase are limited to the measurements from about 2 to 70 K of MacDonald, White, and Woods [873] (curve 1) and from 281 to 361 K of Khalileev [755] (curve 2). These offer little choice but to fit the recommended curve to the observations at low temperature region mathematically by using equation (7) and using $n = 2.00$, $\alpha' = 0.00930$, and $\beta = 1.50$, and to those at higher temperatures graphically. In the temperature interval between them this gives a curve of the usual form of gradually decreasing thermal conductivity with increase in temperature. The recommended values at temperatures below 40 K are applicable only to a sample having $\rho_0 = 0.0384\ \mu\Omega$ cm.

However, it would seem that the sample studied by Khalileev was very impure since he stated that the melting point of his sample was 8 degrees below that of pure rubidium, and therefore his values could be expected to be low, and an increase of only 6 percent would yield a room-temperature value equal to that of MacDonald, et al. at 70 K. A larger increase would necessitate a minimum at an intermediate temperature. There is a strong case for further determinations of the thermal conductivity of rubidium to be undertaken from liquid nitrogen temperatures to the melting point.

In the liquid state the data of Khalileev appear to be decidedly abnormal in that they indicate a high value for the Lorenz function and one that increases sharply over the short range studied. Two other experimental determinations by Russian workers are available, whilst several previous estimations had been made on the basis of electrical resistivity values and assumed values for the Lorenz function. Of these two experimental measurements, that of Shpil-rain and Krainova [1306] (curves 7, 8, 9) is for a much purer sample and employs an acceptable comparative longitudinal heat flow method. The linear equation proposed by those workers as fitting their results, $k = 29.2 - 0.0161\ t$, with k in kcal m^{-1} h^{-1} C^{-1} and t in C, extrapolated to a zero value at 1814 C, that is, 2087 K which is only 13 K below the accepted critical temperature of 2100 K. At temperatures of 400 to 600 K this line is some 6 to 10 percent below the estimated values derived through the theoretical Lorenz function, suggesting that rubidium resembles the other alkali metals in having a lower than theoretical Lorenz function. The recommended curve has been drawn through the Shpil'rain and Krainova data but with a little less slope so as to lie close to the estimated curve due to Grosse [546] above about 1300 K and then to continue in a position slightly below Grosse's curve to the critical point.

Experimental determinations are required on rubidium for the solid phase from about 70 to 300 K and throughout the liquid range. The uncertainty of the recommended values is of the order of 10 percent at temperatures below 1000 K and 15 percent at 1300 K. The values above 1300 K are provisional.

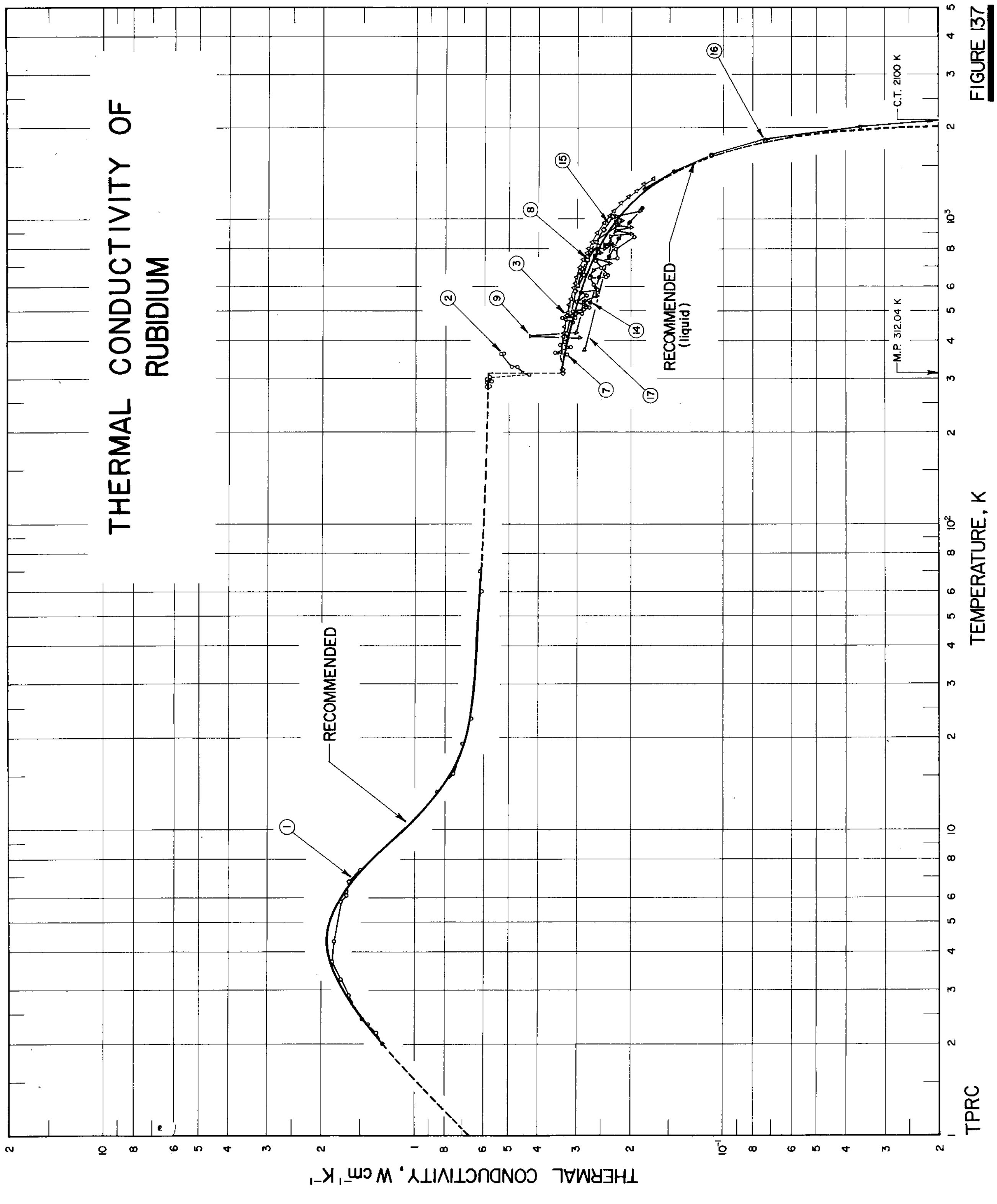
TABLE 134. Recommended thermal conductivity of rubidium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Liquid	
T	k	T	k
0	0	312.04	0.333
1	0.663*	323.2	0.331
2	1.27	350	0.325
3	1.71	373.2	0.321
4	1.91	400	0.318
5	1.88	473.2	0.306
6	1.73	500	0.302
7	1.56	573.2	0.289
8	1.38	600	0.285
9	1.22	673.2	0.273
10	1.09	700	0.268
11	0.991	773.2	0.256
12	0.919	800	0.251
13	0.859	873.2	0.239
14	0.810	900	0.234
15	0.772	973.2	0.222
16	0.746	1000	0.218
18	0.710	1073.2	0.205
20	0.685	1100	0.201
25	0.657	1173.2	0.188
30	0.647	1200	0.184
35	0.640	1273.2	0.172
40	0.635	1300	0.167
45	0.630	1373.2	0.155*
50	0.627	1400	0.150*
60	0.620	1473.2	0.137*
70	0.615	1500	0.132*
80	0.611*	1573.2	0.118*
90	0.607*	1600	0.113*
100	0.603*	1673.2	0.0987*
123.2	0.599*	1700	0.0933*
150	0.594*	1773.2	0.0787*
173.2	0.592*	1800	0.0730*
200	0.589*	1873.2	0.0580*
223.2	0.587*	1900	0.0516*
250	0.586*	1973.2	0.0339*
273.2	0.583*	2000	0.0272*
298.2	0.582	2073.2	0.0079*
300	0.582		
312.04	0.581		

†The values are for well-annealed high-purity rubidium, and those below 40 K are applicable only to a specimen having $\rho_0=0.0384$ $\mu\Omega$ cm. The values above 1300 K are provisional.

*Extrapolated, interpolated, or estimated.


THERMAL CONDUCTIVITY OF RUBIDIUM
FIGURE 137
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
RECOMMENDED
RECOMMENDED (liquid)
M.P. 312.04 K
C.T. 2100 K
TPRC

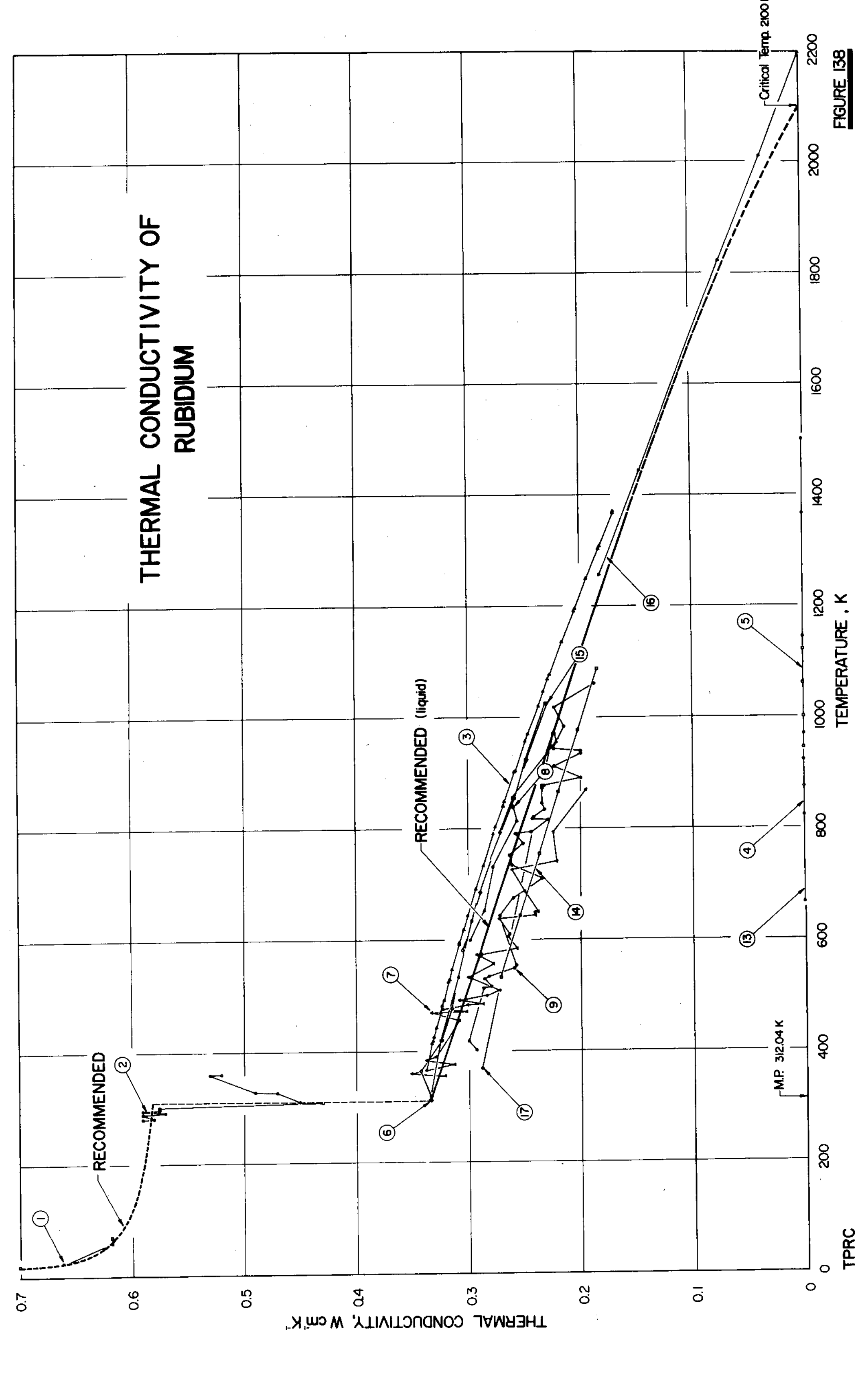

THERMAL CONDUCTIVITY OF
RUBIDIUM
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TEMPERATURE , K
RECOMMENDED
RECOMMENDED (liquid)
M.P. 312.04 K
Critical Temp. 2100 K
TPRC
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

FIGURE 138

TABLE 135. THERMAL CONDUCTIVITY OF RUBIDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	873	MacDonald, D.K.C., White, G.K., and Woods, S.B.	1956	L	2.0-70	Rb 1	High purity; 1.65 mm dia; supplied by A.D. MacKay (New York); electrical resistivity ratio $\rho(295K)/\rho_0$ = 380 (using electrical resistivity $\rho(295K)$ = 14.6 μohm cm).
2	755	Khalileev, P.A.	1940	L	281-361		Supplied by Ukraine Chemical Institute of Odessa; specific resistance 35% greater than that of pure Rb; M.P. 8 degrees lower than that of pure Rb.
3	1212, 1398, 1399	Tepper, F., Murchison, A., Zelenak, J.S., and Roehlich, F.	1964	→	367-1370		99.5 pure; electrical resistivity measured in argon and reported as 11.28, 12.51, 26.55, 30.12, 30.88, 32.82, 35.39, 35.90, 40.56, 42.70, 47.03, 47.48, 54.49, 58.01, 60.70, 69.82, 77.44, 85.30, 86.05, 96.59, 105.82, 117.59, 129.96, 144.17, 144.27, 159.55, 174.96, 196.97, and 197.36 μohm cm at 273.2, 302.6, 366.5, 414.3, 418.7, 442.1, 469.3, 482.6, 524.3, 547.1, 592.1, 595.4, 643.7, 691.5, 734.8, 790.9, 848.7, 901.5, 903.7, 969.3, 1020.9, 1076.5, 1135.4, 1190.9, 1195.4, 1249.8, 1303.7, 1367.6, and 1369.8 K, respectively; thermal conductivity values calculated from electrical resistivity data using theoretical Lorenz number 2.45 x 10^{-8} V^2 K^{-2}.
4	18	Achener, P.Y.	1967	→	822-969		Specimen in vapor state; measuring method based on the study of the laminar flow in a long tube with a constant wall temp, combined with the heat exchange theory; thermal conductivity values calculated from the measured temp and flow rate with the specific heat data of the vapor taken from Achener, P.Y., et al., (USAEC Rept. AGN-8192, 1967).
5	521	Gottlieb, M., Zollweg, R.J., DeSteese, J.G., Taylor, C.R., and Ennulat, D.F.	1962		944-1121		Vapor specimen; atomic dia σ = 12.7 Å; thermal conductivity data estimated.
6	712	Kapelner, S.M. and Bratton, W.D.	1962	→	312-1025		0.32 Cs, 0.06 K, and 0.05 Na; composition after testing: 0.39 Cs, 0.13 Na, 0.11 K, 0.03 Ca, 0.008 Fe, 0.005 O, 0.002 Ni, <0.001 each of Cr and Li; molten specimen contained in a type 347 stainless steel tube; supplied by American Potash and Chemical Corp; electrical resistivity reported as 13.85, 14.67, 22.84, 22.93, 23.35, 25.96, 31.62, 37.06, 42.30, 46.59, 46.61, 52.45, 58.01, 59.37, 64.61, 71.48, 72.49, 81.06, 91.29, 99.05, and 109.31 μohm cm at 25.6, 37.5, 39.2, 41.7, 46.4, 91.7, 146.7, 204.2, 260.3, 308.3, 309.4, 361.7, 412.5, 426.1, 463.1, 520.3, 528.9, 581.7, 650.1, 697.2, and 751.7 C, respectively; thermal conductivity values calculated from measured electrical resistivity data and the theoretical Lorenz number 2.45 x 10^{-8} V^2 K^{-2}.
7	1306	Shpil'rain, E.E. and Krainova, I.F.	1968	C	360-873		99.96 Rb, 0.03 K, 0.005 Cs, <0.005 Ca, and 0.0005 Na; in liquid state; obtained from State Rare-Metals Institute; molten specimen contained in a 1Kh 18N9T steel tube 4.4 mm in dia and 90 mm long; 1Kh 18N9T steel used as comparative material.
8	1306	Shpil'rain, E.E. and Krainova, I.F.	1968	C	605-973		2nd run of the above specimen.
9	1306	Shpil'rain, E.E. and Krainova, I.F.	1968	C	408-1062		3rd run of the above specimen.

TABLE 135. THERMAL CONDUCTIVITY OF RUBIDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
10*	20	Achener, P.Y. and Jouthas, J.T.	1968	→	824-1127		<0.0100 O; in vapor state; measuring method based on the study of laminar flow in a long tube with a constant wall temp combined with the heat exchange theory; thermal conductivity values calculated from measured temp and flow rate with specific heat capacity data taken from Achener, P.Y., et al. (USAEC AGN-8195, vol. 1, 1968); measured at test pressure of 0.209, 0.353, 0.578, 0.693, 0.986, 1.74, 2.97, 3.71, and 3.45 atm at the respective (in increasing order) measuring temps.
11*	825	Lee, C.S. and Bonilla, C.F.	1968	E	1045		99.8$^+$ Rb, 0.07 Cs, 0.05 K, 0.007 Na, and 0.001 Li; in vapor state; supplied by Kawecki; measured at 0.0882 atm pressure.
12*	825	Lee, C.S. and Bonilla, C.F.	1968	E	1099		Similar to the above specimen except measured at 0.0829 atm pressure.
13	1509	Weatherford, W.D., Jr., Tyler, J.C., and Ku, P.M.	1964		655-1516		Vapor state; calculated from the frozen specific heat and the viscosity of saturated vapor assuming a constant Prandtl number of 0.73.
14	1509	Weatherford, W.D., Jr., et al.	1964		612-1115		Liquid state; recommended values based on values of Oak Ridge National Laboratory and of Ai Research Manufacturing Co. of Arizona (authors' data source No. 716 and 721, respectively); no details given.
15	546, 548	Grosse, A.V.	1964		312-1025		Liquid state; electrical resistivity reported as 22.83, 23.35, 25.96, 31.99, 37.06, 46.59, 58.01, 71.48, 91.29, and 109.3 μohm cm at 312.0, 319.6, 364.9, 419.9, 477.4, 581.5, 685.7, 793.5, 923.3, and 1024.9 K, respectively; data calculated from electrical resistivity values of Kapelner, S.M. and Bratton, W.E. (USAEC Rept. PWAC-376, 1962) and the Lorenz number $L = 2.443 \times 10^{-8}$ W ohm K^{-2}.
16	546, 548	Grosse, A.V.	1964		1256-2200		Liquid state; data calculated from electrical resistivity values obtained from the semi-theoretically derived equation $\rho = 19.522 + 7.885 \times 10^{-2}\, t + 1.301 \times 10^{-5}\, t^2 + 5.441 \times 10^{-8}\, t^3$ where ρ in μohm cm and t in C and the Lorenz number $L = 2.443 \times 10^{-8}$ W ohm K^{-2} (this equation given by the author does not give the reported values, however).
17	1035	Nikol'skii, N. A.	1959		373, 973		3.8 K, 0.49 Cs, 0.006 Na, and 0.0005 Ca.

* Not shown in figure.

Ruthenium

At low temperatures the recommended curve for a polycrystalline sample having $\rho_0 = 0.0158\ \mu\Omega$ cm has been fitted to the upper set of the data (curve 2) of White and Woods [1553] up to 25 K by using equation (7) and using $m = 5.80$, $n = 2.60$, $\alpha'' = 3.21 \times 10^{-10}$, and $\beta = 0.647$ and continues to follow their data to 80 K. From 80 to 600 K it lies in an intermediate position between the data of Powell, Tye, and Woodman [1145] (curves 4–7) for two single crystal samples and up to 10 percent above their data (curves 8, 9) for a presumably less pure polycrystalline sample. Powell, et al. found the ratio $k_{\parallel}/k_{\perp}$ for the two single crystal samples to decrease from about 1.27 at 100 K to 1.24 at 500 K. Also, their values for $k_{\perp}$ tended to agree with those for their two polycrystalline samples.

Ruthenium has been reported by Jaeger and Rosenbohm [665] to undergo phase transformations at temperatures of about 1308, 1473, and 1773 K. In addition their measurements of electrical resistance indicate a strong maximum in the rate of change with increase in temperature at 583 K, which would require a drop in thermal conductivity of the order of 30 percent should the Lorenz function remain constant. This led Powell, Groot, and Taylor [1123] (curve 13) to make a determination of the electrical resistivity to nearly 2000 C. No anomalies occurred and Powell, Groot, and Taylor [1123] have estimated the thermal conductivity of ruthenium from their electrical resistivity data by assuming the Lorenz function to be 2.76, 2.74, and 2.63 $\times 10^{-8}$ V^2 K^{-2} at 1000, 1500, and 2000 K, respectively. The recommended curve has been extended smoothly to pass through these values and extrapolated to the melting point.

Further measurements on both thermal and electrical conductivity are required from 500 K upwards for single crystal and polycrystalline ruthenium. It seems likely that considerable interest should be associated with this additional information. For instance, the phase transformations in Figure 139 receive no support from the electrical resistivity measurements of [1123]. Furthermore Rhys [1192b] was able to retain to room temperature single crystals grown from the melt and therefore regarded any phase changes as unlikely to occur within this range of temperature.

The uncertainty of the recommended values is of the order of ± 5 percent at temperatures below 500 K and increases to ± 15 percent at the highest temperatures. The recommended values below 200 K are applicable only to a specimen having $\rho_0 = 0.0158\ \mu\Omega$ cm.

TABLE 136. Recommended thermal conductivity of ruthenium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	350	1.16
1	1.55*	373.2	1.15
2	3.09*	400	1.14
3	4.64	473.2	1.12
4	6.18	500	1.11
5	7.71	573.2	1.08
6	9.23	600	1.08
7	10.7	673.2	1.06
8	12.2	700	1.05
9	13.6	773.2	1.03
10	15.0	800	1.02
11	16.3	873.2	1.01
12	17.5	900	0.997
13	18.7	973.2	0.982
14	19.7	1000	0.976
15	20.5	1073.2	0.962
16	21.3	1100	0.957
18	22.3	1173.2	0.944
20	22.6	1200	0.939
25	21.3	1273.2	0.928
30	17.8	1300	0.923
35	13.3	1373.3	0.913
40	9.53	1400	0.909
45	6.88	1473.2	0.899
50	5.10	1500	0.895
60	3.10	1573.2	0.885
70	2.26	1600	0.882
80	1.86	1673.2	0.873
90	1.65	1700	0.870
100	1.54	1773.2	0.862
123.2	1.38	1800	0.859
150	1.28	1873.2	0.851
173.2	1.23	1900	0.848
200	1.18	1973.2	0.841
223.2	1.17	2000	0.838
250	1.17	2073.2	0.831*
273.2	1.17	2173.2	0.822*
298.2	1.17	2200	0.820*
300	1.17	2273.2	0.813*
323.2	1.16	2400	0.803*
		2473.2	0.798*
		2500	0.796*

†The recommended values are for well-annealed high-purity ruthenium, and those below 200 K are applicable only to a specimen having $\rho_0 = 0.0158$ $\mu\Omega$ cm.

*Extrapolated.

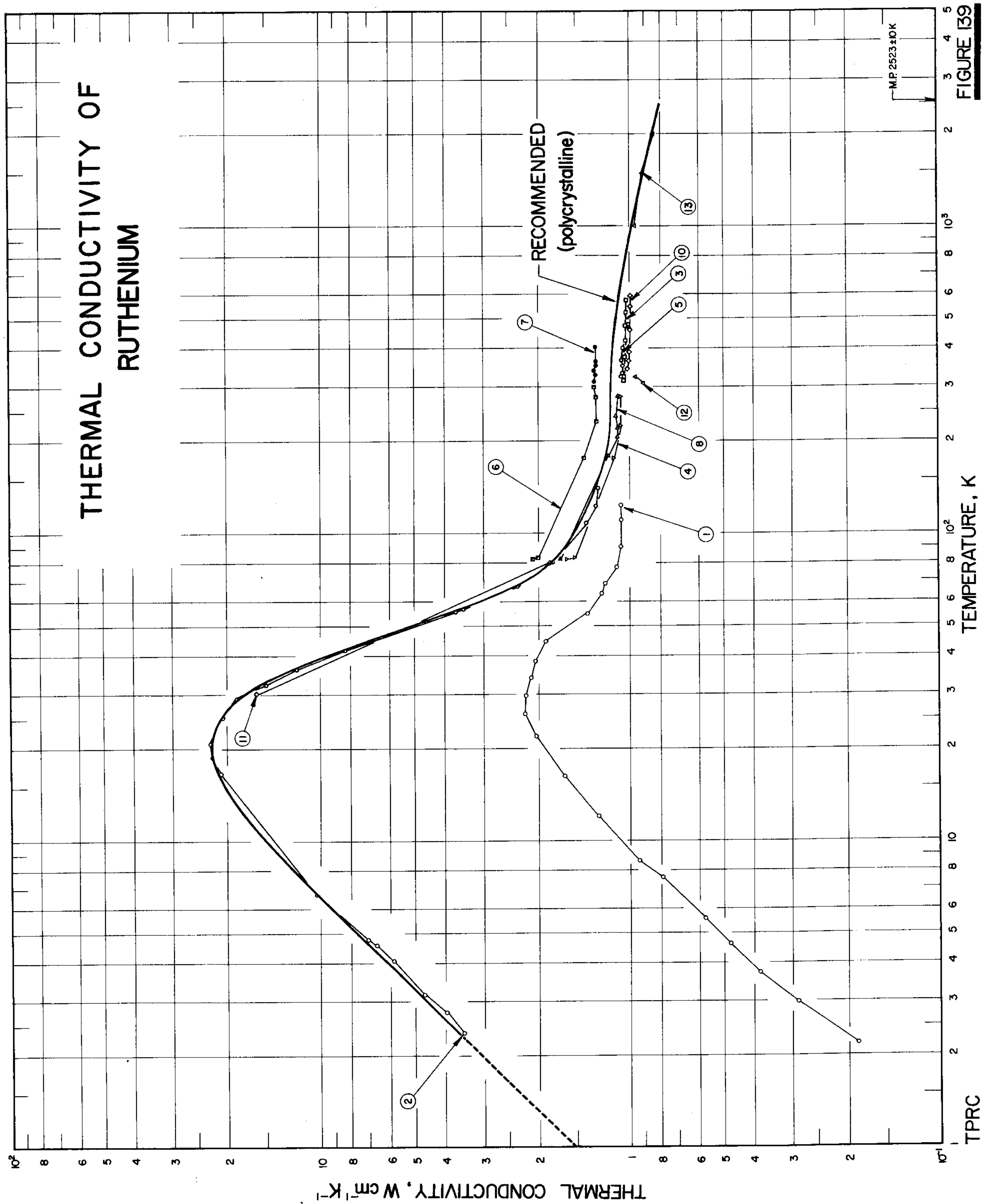

THERMAL CONDUCTIVITY OF
RUTHENIUM
RECOMMENDED
(polycrystalline)
M.P. 2523±10 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
1
2
3
4
5
6
7
8
10
11
12
13

FIGURE 139

TABLE 137. THERMAL CONDUCTIVITY OF RUTHENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1553	White, G.K. and Woods, S.B.	1958	L	2.0–124	Ru 2	99.995⁺ pure; polycrystalline; grain size 1 mm; approx 6 mm in dia and 7 cm long; Ru powder supplied by Baker Platinum Co.; specimen prepared by arc-melting pressed pellets of powder in an inert atmosphere; specific gravity 12.0 at 22 C; ideal electrical resistivity reported as 0.034, 0.067, 0.19, 0.38, 1.07, 1.90, 3.61, 5.26, 6.85, 7.60, and 8.27 μohm cm at 25, 30, 40, 50, 75, 100, 150, 200, 250, 273, and 295 K, respectively; residual electrical resistivity 0.235 μohm cm; $\rho(295\ K)/\rho_0 = 36.1$; Lorenz function $2.40 \times 10^{-8}\ V^2\ K^{-2}$ at 0 K.
2	1553	White, G.K. and Woods, S.B.	1958	L	2.0–140	Ru 3	Similar to the above specimen except dimensions approx 5 mm in dia and 6 cm long; specific gravity 12.25 at 22 C; ideal electrical resistivity reported as 0.005, 0.010, 0.037, 0.11, 0.54, 1.25, 2.80, 4.38, 5.76, 6.69, and 7.37 μohm cm at 25, 30, 40, 50, 75, 100, 150, 200, 250, 273, and 295 K, respectively; residual electrical resistivity 0.0158 μohm cm; $\rho(295\ K)/\rho_0 = 467$; Lorenz function $2.46 \times 10^{-8}\ V^2\ K^{-2}$ at 0 K.
3	1141	Powell, R.W., Tye, R.P., and Woodman, M.J.	1962	C, L	313–573		0.1 Fe, 0.03 Rh, 0.002 Pt, 0.001 Cu, 0.001 Ni, and 0.0005 Pd; 2.5 cm long, 0.660 cm in dia; supplied by Johnson Matthey Co.; argon-arc melted and ground; density 12.36 g cm^{-3}; electrical resistivity reported as 0.566 and 7.13 μohm cm at liquid helium and ice temp, respectively; Armco iron used as comparative material; heat outflow also measured by water-flow calorimeter.
4	1145	Powell, R.W., Tye, R.P., and Woodman, M.J.	1967	L	83–280	a	99.96 Ru (by difference), 0.03 Os, 0.006 Fe, 0.003 Ni, and 0.001 Pd; single crystal; specimen 0.65 cm in dia, 10 cm long; axis of specimen perpendicular to prism axis of crystal; supplied by the International Nickel Co. Ltd. (Mond); as received; density 12.38 g cm^{-3}; electrical resistivity reported as 1.42, 4.58, 7.62, 10.5, and 13.3 μohm cm at 100, 200, 300, 400, and 500 K, respectively; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 94$.
5	1145	Powell, R.W., et al.	1967	C, L	322–476	a	The above specimen measured by comparative method using Armco iron as comparative material; heat outflow also measured by water-flow calorimeter.
6	1145	Powell, R.W., et al.	1967	L	83–298	b	Same purity and supplier as the above specimen; 0.68 cm in dia, 10 cm long; single crystal; axis of the specimen parallel to prism axis of crystal; as received; density 12.38 g cm^{-3}; electrical resistivity reported as 1.07, 3.46, 5.82, 8.15, and 10.4 μohm cm at 100, 200, 300, 400, and 500 K, respectively; electrical resistivity ratio $\rho(273\ K)/\rho(4.2\ K) = 76.5$.
7	1145	Powell, R.W., et al.	1967	C, L	310–404	b	The above specimen measured by comparative method using Armco iron as comparative material; heat outflow also measured by water-flow calorimeter.
8	1145	Powell, R.W., et al.	1967	L	83–277	c	0.03 Os, 0.006 Fe, 0.003 Ni, and 0.001 Pd; polycrystalline bar 0.635 cm in dia, 10 cm long; supplied by the International Nickel Co.; pressed at 20 ton $in.^{-2}$; sintered in vacuo at 1920 K and hot forged; as received; density 12.24 g cm^{-3}; electrical resistivity reported as 1.30, 4.38, 7.43, 10.4, and 13.2 μohm cm at $\rho(273\ K)/\rho(4.2\ K) = 388$.
9*	1145	Powell, R.W., et al.	1967	C, L	365–510	c	The above specimen measured by comparative method using Armco iron as comparative material; heat outflow also measured by water-flow calorimeter.

* Not shown in figure.

TABLE 137. THERMAL CONDUCTIVITY OF RUTHENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
10	1145	Powell, R.W., et al.	1967	C, L	341-592	d	0.03 Rh, 0.01 Fe, 0.002 Pt, 0.001 Cu, 0.001 Ni, and 0.0005 Pd; polycrystalline; 0.66 cm in dia, 2.5 cm long; supplied by Johnson, Matthey and Co.; arc-melted and ground; as received; density 12.36 g cm^{-3}; electrical resistivity reported as 1.83, 4.83, 7.85, 10.74, and 13.4 μohm cm at 100, 200, 300, 400, and 500 K, respectively; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 12.6$; Armco iron used as comparative material; heat outflow also measured by water-flow calorimeter.
11	1385	Tainsh, R.J. and White, G.K.	1964	L	30, 80		0.02 Os, 0.007 Rh, 0.0025 Fe, and 0.001 each of Sb and Pd; polycrystalline; supplied by International Nickel Co.; 4 mm dia x 7 mm long; prepared from a sintered bar by hot-working and centerless grinding; annealed in vacuo at 1100 C for 4 hrs; electrical resistivity ratio $\rho(295K)/\rho_0 \cong 400$; residual electrical resistivity 0.0184 μohm cm; electrical resistivity 0.95 and 6.74 μohm cm at 90 and 273 K, respectively; Lorenz function 2.45 x 10^{-8} V^2 K^{-2} at 4.2 K.
12	1063	Panteleimonov, L.A. and Nesterova, O.P.	1966		308, 323		99.91 pure.
13	1123	Powell, R.W., Groot, H., and Taylor, R.E.	1970	→	1000-2000		Polycrystalline; thermal conductivity values calculated from the measured electrical resistivity data using the derived Lorenz function values of 2.76, 2.74, and 2.63 x 10^{-8} V^2 K^{-2} at 1000, 1500, and 2000 K, respectively.

Samarium

The thermal conductivity of samarium has been measured by Arajs and Dunmyre [84] (curve 1) over the range 6 to 196 K. A minimum is observed at about 13 K, which is probably associated with the Curie temperature. The maximum at about 32 K is thought to be the usual maximum in the electronic thermal conductivity, the rather high temperature at which this occurs and its small size suggesting the sample to be somewhat impure. At about 100 K the data again assume a definite positive temperature coefficient, and it is probably significant that this change in slope occurs in the region for which the Néel transition from the antiferromagnetic to the paramagnetic state has been reported. The room-temperature determination by Powell and Jolliffe [1127] (curve 2) lies on a reasonable extrapolation of the Arajs and Dunmyre curve and it seems appropriate to accept this curve as representing the most probable curve for the thermal conductivity of samarium at the present time. The only other measurements, due to Devyatkova, Zhuze, Golubkov, Sergeeva, and Smirnov [359] (curve 3) and covering the range 83 to 397 K, are much lower, and the reported chemical analyses show this sample to contain much larger amounts of calcium and europium. The proposed curve has been extrapolated to pass through the mean value of Powell and Jolliffe and on to 600 K. To obtain these estimated values the electrical resistivity data of Meaden [912] have been adjusted to pass through the room temperature value of Powell and Jolliffe and then extrapolated to 600 K. The electronic component has been calculated as equal to $2.443 \times 10^{-8}\ T\ \rho^{-1}$ and the lattice component deduced from the relation AT^{-1}, and using a value for A of 16.6, as derived from the data of Powell and Jolliffe.

The proposed values are provisional and are thought to be accurate to within ±15 percent of the true values near room temperature, ±20 percent above room temperature, and ±25 percent below room temperature. The values below room temperature are applicable only to samarium having an electrical resistivity of 6.73 $\mu\Omega$ cm at 4.2 K.

TABLE 138. Provisional thermal conductivity of samarium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
6	0.0555	100	0.0735
7	0.0591	123.2	0.0820
8	0.0611	150	0.0924
9	0.0618	173.2	0.101
10	0.0607	200	0.113
11	0.0586	220	0.123
12	0.0557	223.2	0.124
13	0.0542	250	0.132
14	0.0551	273.2	0.133
15	0.0566	298.2	0.133
16	0.0580	300	0.133
17	0.0598	323.2	0.133
18	0.0623	350	0.133
19	0.0659	373.2	0.133
20	0.0692	400	0.133
25	0.0754	473.2	0.134*
30	0.0770	500	0.135*
35	0.0768	573.2	0.139*
40	0.0754	600	0.141*
45	0.0742		
50	0.0732		
60	0.0714		
70	0.0708		
80	0.0709		
90	0.0714		

†The provisional values are for well-annealed high-purity samarium, and those below room temperature are applicable only to a specimen having electrical resistivity of 6.73 $\mu\Omega$ cm at 2.4 K.
*Extrapolated.

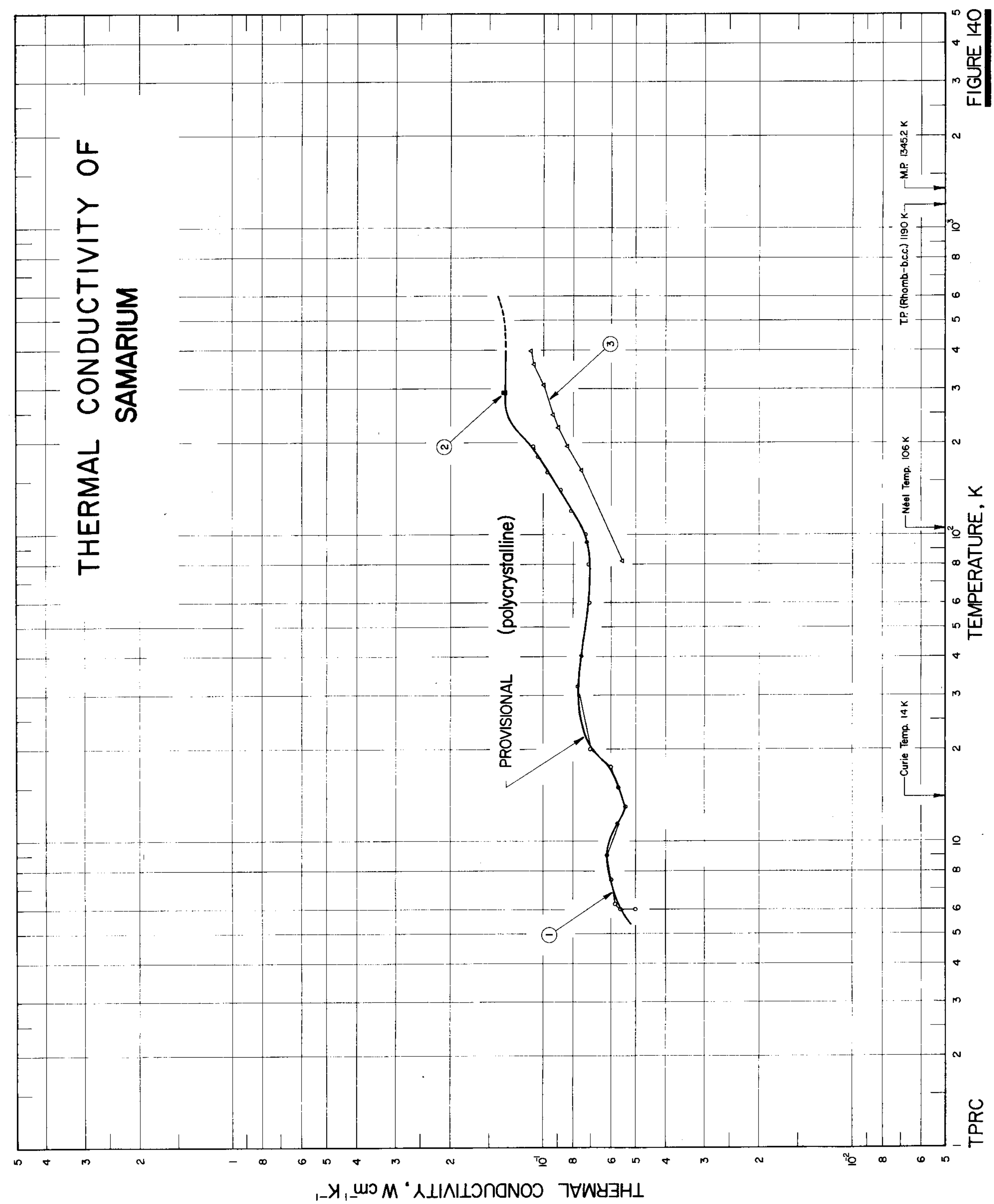

THERMAL CONDUCTIVITY OF SAMARIUM
PROVISIONAL (polycrystalline)
FIGURE 140
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
Curie Temp. 14 K
Néel Temp. 106 K
T.P. (Rhomb-b.c.c.) 1190 K
M.P. 1345.2 K

TABLE 139. THERMAL CONDUCTIVITY OF SAMARIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	84, 85	Arajs, S. and Dunmyre, G. R.	1965	L	6.0-196		0.05 Eu, 0.02 Ca, 0.01 Gd, 0.01 Mg, and 0.005 Si; polycrystalline; 0.479 cm dia, 6 cm long; Sm supplied by Research Chemicals; arc-melted in 100 torr argon atmosphere and machined; electrical resistivity reported as 6.73, 7.90, 12.1, 15.1, 16.3, 18.2, 28.2, 39.6, 51.3, 61.8, 62.3, 63.0, 64.7, 70.5, 82.5, and 93.4 μohm cm at 4.17, 8.12, 13.8, 16, 20, 40, 60, 80, 100, 105, 110, 120, 160, 240, and 308 K, respectively; data taken from smoothed curve.
2	1127	Powell, R.W. and Jolliffe, B.W.	1965	C	291		High purity; polycrystalline; 0.25 in. in dia, 0.25 in. long; supplied by Johnson Matthey and Co.; electrical resistivity 94 μohm cm at 18 C; thermal conductivity values obtained from two measurements using different thermal comparators; Monel metal used as comparative material.
3	359	Devyatkova, E.D., Zhuze, V.P., Golubkov, A.V., Sergeeva, V.M., and Smirnov, I.A.	1964	L	83-397		Impurities: 0.5 Eu, 0.18 Ca, 0.02 Gd, 0.01 Nd, and 0.01 Y; prepared by briquetting powder under a pressure of ~8000 Kg cm^{-2} and annealing in vacuo (~1 x 10^{-4} mm Hg) for 1-2 hrs at 1600-1800 C; measured in vacuo of ~5 x 10^{-5} mm Hg; data taken from smoothed curve of measurements on several specimens.

Scandium

Although the solid phase of scandium persists to about 1800 K no measurements of the thermal conductivity of this metal are available above room temperature. At room temperature there are two discordant values and two sets of data extending from lower temperatures. Unfortunately, the values of Arajs and Colvin [81] (curve 3) which cover the full range from 5 to 316 K appear to be subject to uncertainty above about 100 K.

Three groups of workers have reported electrical resistivity values for their thermal conductivity samples. At 4.2 K, whereas the sample studied by Arajs and Colvin had a residual electrical resistivity of 10.6 $\mu\Omega$ cm, that of Aliev and Volkenshtein [47] (curve 1) was 7.4 $\mu\Omega$ cm. Arajs and Colvin's data leads to a Lorenz function of the order of 7×10^{-8} V^2 K^{-2}, indicating an appreciable lattice component, whereas the data of Aliev and Volkenshtein yield a Lorenz function which is only about 20 percent greater than the theoretical value.

Quite independently of this analysis, doubts have previously been expressed by Powell [1121] regarding Arajs and Colvin's thermal conductivity values at normal temperatures for gadolinium, terbium, and dysprosium. These doubts should be extended to scandium since the measurements appear to have been made in the same apparatus and also yield abnormally high values for the Lorenz function which are strongly increasing with increase in temperature.

On the basis of these results and considerations, the very tentative most probable curve for the thermal conductivity of scandium has been drawn smoothly through Arajs and Colvin's data over the range 5 to 100 K and then continued to the 291 K point of Powell and Jolliffe [1127] (curve 2). The recommended values near room temperature should be good to within ±5 percent. The values below 200 K are only for scandium having a residual electrical resistivity of 10.6 $\mu\Omega$ cm and are probably good to within ±15 percent.

Scandium is another metal for which further thermal and electrical conductivity measurements are required over the full temperature range of the solid phase. Since scandium has a hexagonal crystal structure, both single and polycrystalline samples should be studied.

TABLE 140. Recommended thermal conductivity of scandium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1} K^{-1})

Solid Polyctystalline					
T	*k*	*T*	*k*	*T*	*k*
0	0	13	0.0855	70	0.138
1	0.00706*	14	0.0910	80	0.139
2	0.0140	15	0.0960	90	0.141
3	0.0208	16	0.101	100	0.143
4	0.0276	18	0.109	123.2	0.146
5	0.0344	20	0.117	150	0.149
6	0.0412	25	0.130	173.2	0.151
7	0.0479	30	0.137	200	0.153
8	0.0545	35	0.138	223.2	0.154
9	0.0612	40	0.138	250	0.156
10	0.0678	45	0.136	273.2	0.157
11	0.0738	50	0.135	298.2	0.158
12	0.0797	60	0.136	300	0.158

†The recommended values are for well-annealed high-purity scandium, and those below 200 K are applicable only to a specimen having $\rho_o = 10.6$ $\mu\Omega$ cm.

*Extrapolated.

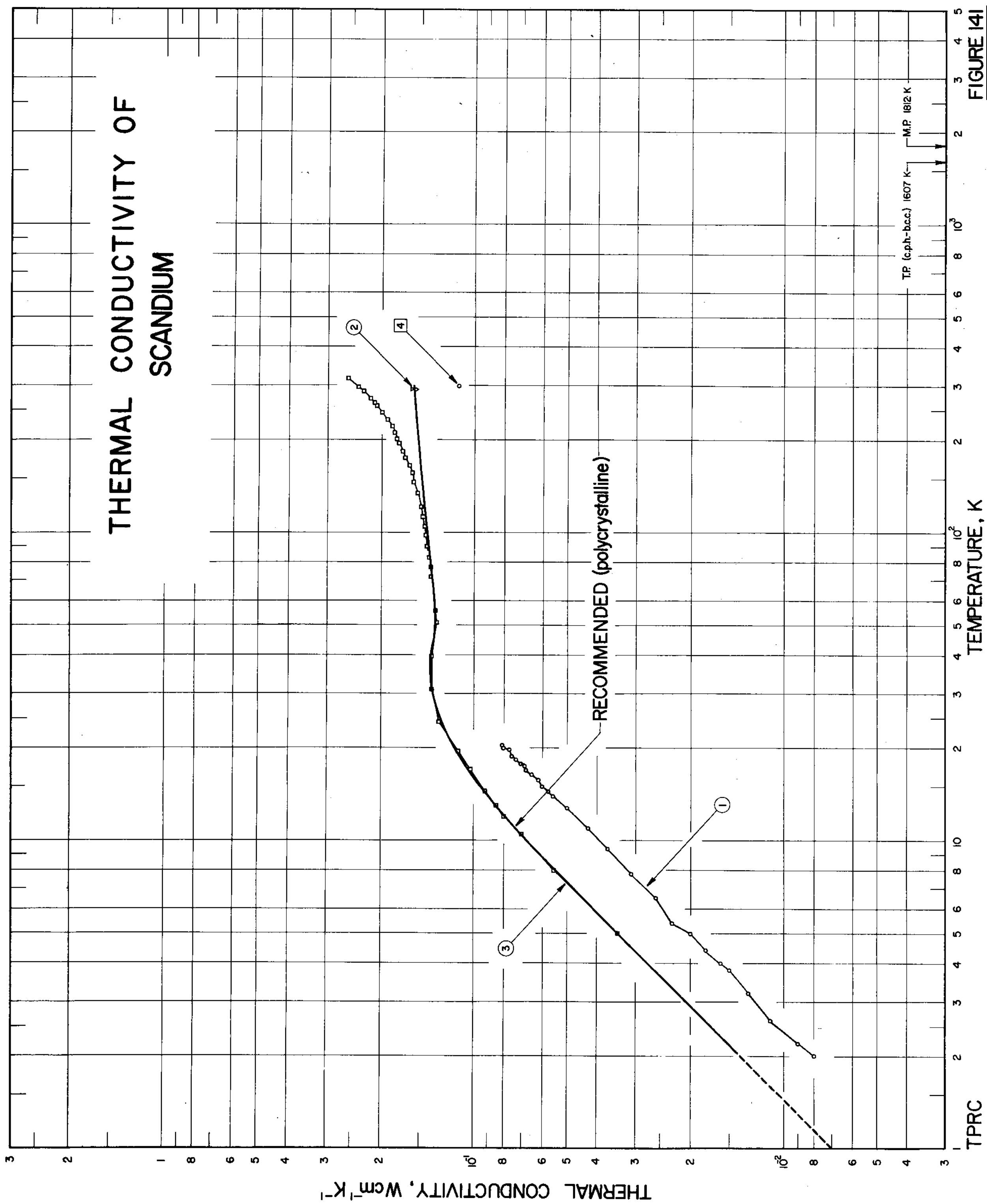

THERMAL CONDUCTIVITY OF SCANDIUM
RECOMMENDED (polycrystalline)
T.P. (c.p.h.-b.c.c.) 1607 K
M.P. 1812 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 141

TABLE 141. THERMAL CONDUCTIVITY OF SCANDIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	47	Aliev, N.G. and Volkenshtein, N.V.	1965	L	2.0-21		Approx 99.9 pure; flat specimen 0.25 mm thick; electrical resistivity 71 μohm cm at 293 K; electrical resistivity ratio $\rho(293\ K)/\rho(4.2\ K) = 9.59$; Lorenz number $2.96 \times 10^{-8}\ V^2\ K^{-2}$ at 4.2 K.
2	690, 1127	Powell, R.W. and Jolliffe, B.W.	1965	C	291.2		High purity; polycrystalline; specimen 0.25 in. in dia and 0.25 in. long; supplied by Johnson Matthey Co.; electrical resistivity 52 μohm cm at 18 C; Monel metal used as comparative material; thermal conductivity values obtained from two measurements using different thermal comparators.
3	81	Arajs, S. and Colvin, R.V.	1964	L	5-316		High purity, traces of Ta, Ca, and Fe; polycrystalline; specimen 0.486 cm in dia and 6.35 cm long; supplied by St. Eloi Corp; electrical resistivity reported as 10.7, 12.0, 18.0, 25.5, 32.8, 40.1, 47.9, 54.8, and 61.8 μohm cm at 6.2, 40, 80, 120, 160, 200, 240, 280, and 320 K, respectively; residual electrical resistivity ~10.6 μohm cm; measured in a vacuum of 6×10^{-6} mm Hg.
4	883	Mardon, P.G., Nichols, J.L., Pearce, J.H., and Poole, D.M.	1961	→	298.2		≤0.1 Ta, ≤0.02 Cu, ≤0.01 Ag, ≤0.002 Fe, and ≤0.01 other rare earth metals; melting point 1522 ± 5 C; electrical resistivity reported as 67, 91, 112, 131, 146, 159, 172, 183, 193, 203, 212, and 215 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, and 1360 C, respectively; thermal conductivity value calculated from the measured electrical resistivity and the Lorenz function taken as $2.7 \times 10^{-8}\ V^2\ K^{-2}$.

Selenium

The thermal conductivity of an amorphous solid is invariably much lower than that of the crystalline form and this helps to account for the wide range of values, 0.000418 to 0.045 W cm^{-1} K^{-1} that have been reported for selenium at normal temperature. The thermal conductivity of the amorphous form decreases with decrease in temperature whereas that of the crystalline form rises typically to a maximum value before decreasing rapidly. Selenium is therefore an element for which it is appropriate to deal separately with the two forms.

White, Woods, and Elford [1555] have made determinations (curve 70) over the range 1.9 to 95 K on a sample of vitreous selenium which link on reasonably well with several determinations (curves 86–88, 100–105) made by Abdullaev and various coworkers [3, 10, 293] on other amorphous samples at temperatures which increase from about 88 K. On the basis of these determinations as represented by curves 70, 86, 87, and 100, the recommended curve for the thermal conductivity of amorphous selenium has been drawn. An unusual feature of the thermal conductivity of amorphous selenium is that at the vitrification temperature (also known as glass point) discontinuity with a sharp peak occurs.

In the case of crystalline selenium use has been made of the determinations over the range 1.8 to about 100 K reported by Adams, Baumann, and Stuke [22] (curves 109–111) for three single crystal selenium samples, two cut in directions parallel and perpendicular to the *c*-axis from the same crystal and another for the parallel direction cut from a different crystal. This last sample yielded the highest thermal conductivity data and a curve fitted to these values has been chosen as the proposed curve for selenium in a direction parallel to the *c*-axis up to about 100 K. From the values for the other two samples the ratio $k_{\perp}/k_{\parallel}$ was derived at each temperature, and these values were also assumed to hold for their other samples and were used in deriving the corresponding curve for the perpendicular direction.

The best conducting of the polycrystalline samples tested by White, et al. yielded intermediate values between the curves proposed for the two main crystal directions at temperatures above 30 K, although the conductivity maximum is low and the temperature of this maximum is higher, suggesting the polycrystalline sample to be rather less pure. At about 95 K, the upper limit of the measurements of White, et al., there is reasonable agreement with curve 132 of Abdinov and Aliev [1], and the form of this curve has been accepted as typical of crystalline selenium up to the melting point. This curve shows a minimum at about 320 K followed by a steep rise to the melting point. The proposed curves for the two main crystal directions have been extrapolated from 100 K to the melting point so as to give the same type of temperature variation. It should however be pointed out that the ratio so obtained for $k_{\parallel}/k_{\perp}$ at the minimum is 4.1 whereas Abdullaev, Dzhalilov, and Aliev [8] (curves 98 and 99) obtained a corresponding ratio of only 1.25. These two proposed curves for $k_{\parallel}$ and $k_{\perp}$ above 80 K are recommended curves, and below 80 K they are considered only as typical curves.

Only two sets of measurements have been extended into the liquid state. These indicate k_S/k_L to be 2.0 and 2.3. But, since the values for k_L near the melting point are respectively 0.0197 and 0.00285 W cm^{-1} K^{-1} and differ so much, no proposal is made at present regarding the thermal conductivity of molten selenium. There is need for further determinations on selenium above about 300 K and well into the liquid phase.

The electrical conductivity of liquid selenium [1002] is approximately only 10^{-8} Ω^{-1} cm^{-1} and there is evidence [252] that the electrons remain tightly bound to the atoms as covalent pairs and are not free for electrical conduction.

The values for selenium single crystal at temperatures above 80 K are recommended values and are thought to be accurate to within ±10 to ±20 percent. The values below 80 K are merely typical values. The values for amorphous selenium are recommended values and are thought to be accurate to within ±10 percent except for those values from 301 to 309 K which are provisional and their uncertainty may be as high as ±25 percent.

TABLE 142. Recommended thermal conductivity of selenium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to c-axis k	⊥ to c-axis k	T	∥ to c-axis k	⊥ to c-axis k
0	0	0	60	0.168	0.0480
1	0.0563*	0.00865*	70	0.144	0.0411
2	0.353	0.0600	80	0.126	0.0360
3	0.855	0.160	90	0.112	0.0320
4	1.41	0.268	100	0.103	0.0294
5	1.75	0.348	123.2	0.0880	0.0253
6	1.92	0.395	150	0.0762	0.0218
7	1.90	0.410	173.2	0.0681	0.0195
8	1.78	0.407	200	0.0608	0.0174
9	1.61	0.390	223.2	0.0555	0.0161
10	1.42	0.359	250	0.0513	0.0147
11	1.26	0.329	273.2	0.0481	0.0137
12	1.12	0.301	298.2	0.0452	0.0131
13	1.01	0.276	300	0.0452	0.0130
14	0.919	0.253	323.2	0.0448	0.0127
15	0.844	0.234	350	0.0461	0.0132
16	0.778	0.217	373.2	0.0483	0.0139
18	0.672	0.189	400	0.0538	0.0154
20	0.588	0.166	473.2	0.0696	0.0198
25	0.448	0.127	490.2	0.0747	0.0213
30	0.362	0.103			
35	0.303	0.0866			
40	0.260	0.0743			
45	0.228	0.0651			
50	0.203	0.0580			

†The values are for high-purity selenium. Those for crystalline selenium below 80 K are merely typical values, and those for amorphous selenium from 301 to 309 K are provisional.

*Extrapolated.

TABLE 142. Recommended thermal conductivity of selenium†—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid
Amorphous

T	k	T	k
0	0	250	0.00360
1	0.000130*	273.2	0.00428
2	0.000236	290	0.00484
3	0.000290	295	0.00504
4	0.000323	298.2	0.00519
5	0.000342	299.2	0.00524
6	0.000358	300	0.00528
7	0.000374	300.2	0.00529
8	0.000390	301	0.00533
9	0.000405	301.2	0.00534
10	0.000420	302	0.00538
11	0.000435	302.2	0.00539
12	0.000450	303	0.00544
13	0.000465	303.2	0.00545
14	0.000480	303.5	0.00547
15	0.000494	304	0.00732
16	0.000508	304.5	0.00681
18	0.000532	304.7	0.00671
20	0.000560	305	0.00657
25	0.000619	305.2	0.00650
30	0.000675	305.5	0.00640
35	0.000730	305.7	0.00635
40	0.000788	306	0.00627
45	0.000843	306.2	0.00623
50	0.000900	306.5	0.00619
60	0.00102	306.7	0.00619
70	0.00113	307	0.00619
80	0.00125	307.2	0.00621
90	0.00136	307.5	0.00625
100	0.00148	308	0.00631
123.2	0.00173	309	0.00644
150	0.00204	310	0.00656
173.2	0.00230	313.2	0.00696
200	0.00263	320	0.00782
223.2	0.00299	323.2	0.00818

†The values are for high-purity selenium. Those for amorphous selenium from 301 to 309 K are provisional.

*Extrapolated.

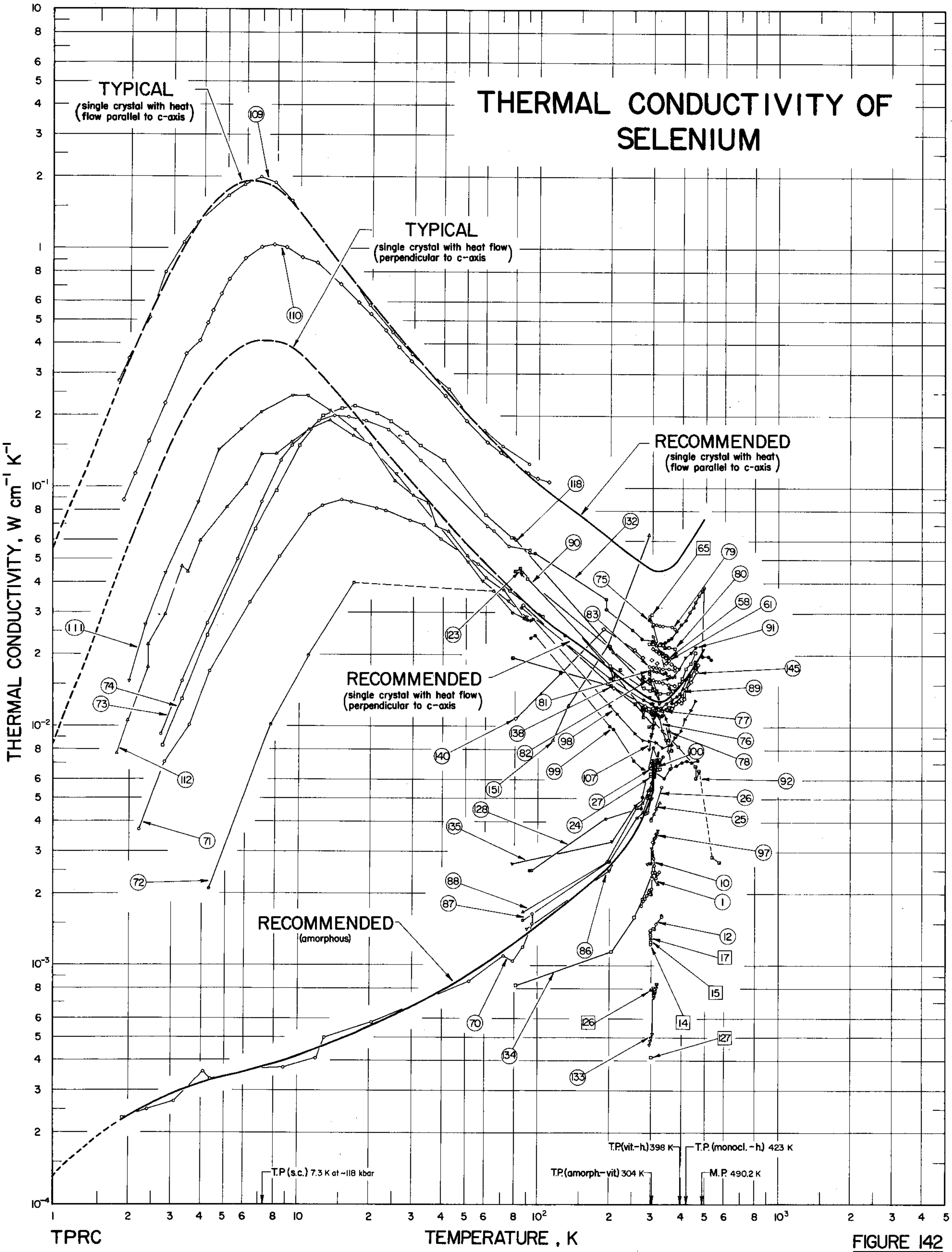

THERMAL CONDUCTIVITY OF SELENIUM
TYPICAL (single crystal with heat flow parallel to c-axis)
TYPICAL (single crystal with heat flow perpendicular to c-axis)
RECOMMENDED (single crystal with heat flow parallel to c-axis)
RECOMMENDED (single crystal with heat flow perpendicular to c-axis)
RECOMMENDED (amorphous)
T.P.(vit.-h.) 398 K
T.P.(monocl.-h) 423 K
T.P.(amorph.-vit) 304 K
M.P. 490.2 K
T.P.(s.c.) 7.3 K at ~118 kbar
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 142

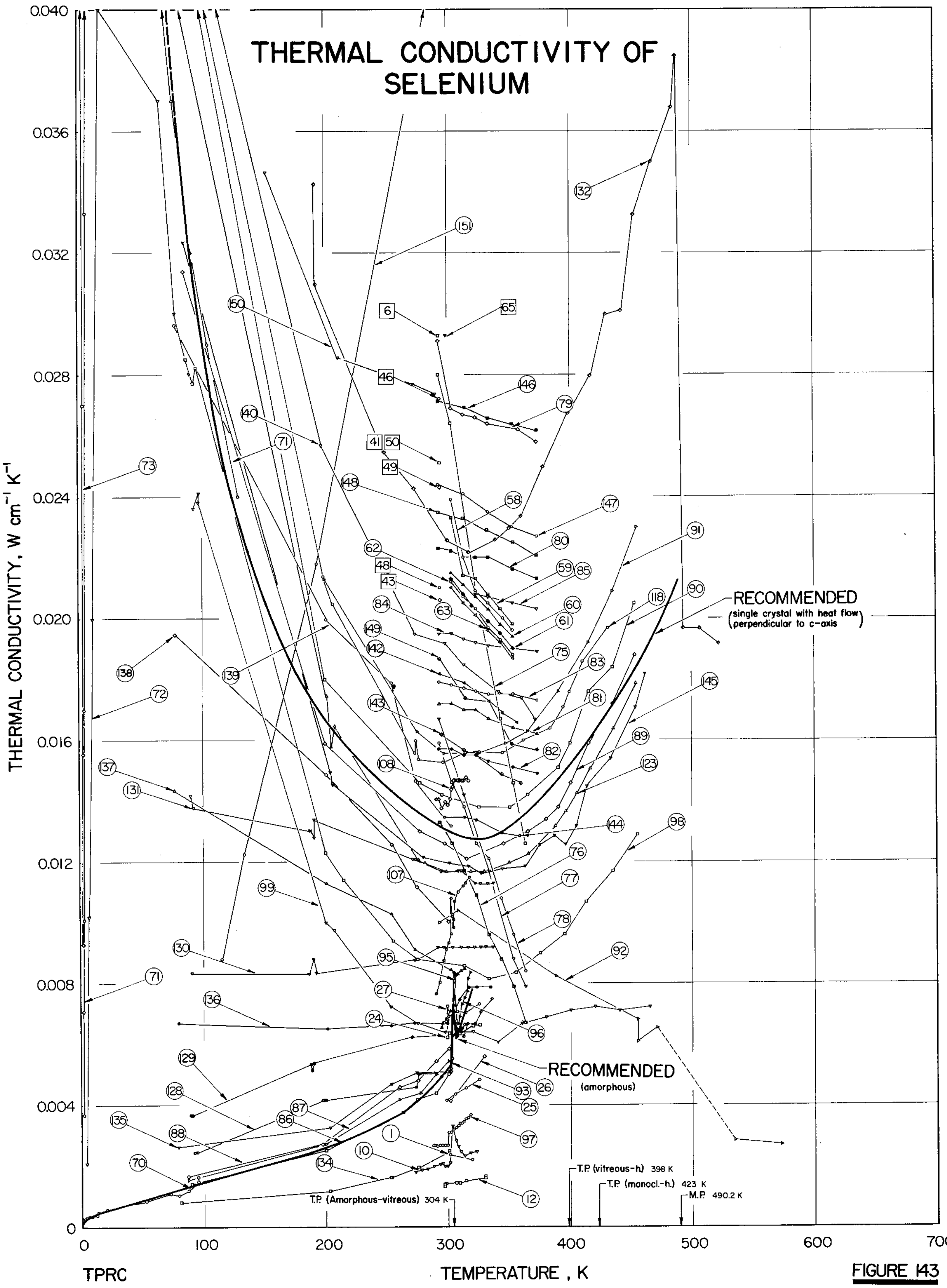

THERMAL CONDUCTIVITY OF SELENIUM
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE , K
RECOMMENDED
(single crystal with heat flow perpendicular to c-axis)
RECOMMENDED
(amorphous)
T.P. (vitreous-h) 398 K
T.P. (monocl.-h.) 423 K
M.P. 490.2 K
T.P. (Amorphous-vitreous) 304 K
TPRC

FIGURE 143

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	803	Kurtener, A. V. and Malyshev, E. K.	1943	L	301, 319		Pure.
2*	7, 118, 119	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	300.7		99.996 pure; vitreous and amorphous; specimen 20 mm in dia; polished.
3*	7, 118, 119	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	300.7		0.065 Br; same structure and dimensions as the above specimen; prepared by fusion in a molybdenum crucible, solidified and polished.
4*	7, 118, 119	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	300.7		0.13 Br; same structure, dimensions, and fabrication method as above.
5*	"	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	300.7		0.16 Br; same structure, dimensions, and fabrication method as above.
6	"	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	293.2		99.996 pure; hexagonal crystalline; specimen 18 mm in dia; polished.
7*	"	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	293.2		0.065 Br; same structure and dimensions as the above specimen; prepared by melting vitreous selenium containing bromine in a ceramic crucible, pouring into a molybdenum beaker, first crystallization at 130 C for 30 min, then second crystallization at 200 C for 25 min, polished.
8*	"	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	293.2		0.13 Br; same structure, dimensions and fabrication method as above.
9*	"	Abdullaev, G. B. and Bashshaliev, A. A.	1957	L	293.2		0.032 Br; same structure, dimensions, and fabrication method as above.
10	1054	Orthmann, H. J. and Ueberreiter, K.	1956	P	273-323		Pure selenium from Merck; thermal conductivity values calculated from measured data of thermal diffusivity, specific volume, and the specific heat data taken from Tammann, G. and Von Gronow, H. E. (Z. Anorg. Allg. Chemie, 192, 193, 1930).
11*	1253	Sayce, E. D.	1917	L	298.2	Disk-1	Vitreous selenium; 6.5 cm in dia and about 0.5 cm thick; cast in a hot iron mould, aged for 7 yrs.
12	1253	Sayce, E. D.	1917	L	297-331	Disk-2	Vitreous selenium; 6.5 cm dia x 0.7523 cm thick; cast in a hot iron mould, aged for 1 to 8 days.
13*	1253	Sayce, E. D.	1917	L	298.2	Disk-2	The above specimen re-tested after being aged for 1 yr.
14	1253	Sayce, E. D.	1917	L	298.2	Disk-3	Vitreous selenium; 6.5 cm dia x ~0.5 cm thick; cast in a hot iron mould, aged for 10 days.
15	1253	Sayce, E. D.	1917	L	298.2	Disk-3	The above specimen re-tested after being aged for 1 yr.
16*	1253	Sayce, E. D.	1917	L	298.2	Disk-4	Similar to above but prepared from highly purified selenium and aged for 10 days.
17	1253	Sayce, E. D.	1917	L	298.2	Disk-5	Similar to above but aged for 2 days.
18*	1253	Sayce, E. D.	1917	L	298.2	Disk A-I	Crystalline specimen 6.5 cm dia x ~0.5 cm thick; prepared by heating the vitreous disk in an oil oven to 160 C for 1 hr, cooled slowly, ground and polished; aged for 11 days.
19*	1253	Sayce, E. D.	1917	L	298.2	Disk A-II	The above specimen aged for 164 days.
20*	1253	Sayce, E. D.	1917	L	298.2	Disk A-III	The above specimen aged for 1 yr.
21*	1253	Sayce, E. D.	1917	L	298.2	Disk B-I	Similar to the above specimen but prepared by heating at 170 C and aged for 16 days.
22*	1253	Sayce, E. D.	1917	L	298.2	Disk B-II	The above specimen aged for 134 days.

* Not shown in figure.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
23*	1253	Sayce, E.D.	1917	L	298.2	Disk B-III	The above specimen aged for 1 yr.
24	1253	Sayce, E.D	1917	L	298-326	Disk C-I	Crystalline specimen; 6.5 cm dia x 0.5774 cm thick; prepared by heating at 180 C and aged for 38 days.
25	1253	Sayce, E.D.	1917	L	298-326	Disk C-II	The above specimen re-tested after being aged for 95 days.
26	1253	Sayce, E.D.	1917	L	298-330	Disk C-III	The above specimen re-tested after being aged for 1 yr.
27	1253	Sayce, E.D.	1917	L	298-325	Disk D-I	Similar to the above specimen but prepared by heating at 192 C and aged for 28 days.
28*	1253	Sayce, E.D.	1917	L	298.2	Disk D-II	The above specimen re-tested after being aged for 148 days.
29*	1253	Sayce, E.D.	1917	L	298.2	Disk D-III	The above specimen re-tested after being aged for 1 yr.
30*	1253	Sayce, E.D.	1917	L	298.2	Disk E-I	Similar to the above specimen but prepared by heating at 200 C and aged for 9 days.
31*	1253	Sayce, E.D.	1917	L	298.2	Disk E-II	The above specimen re-tested after 156 days.
32*	1253	Sayce, E.D.	1917	L	298.2	Disk E-III	The above specimen re-tested after 1 yr.
33*	1253	Sayce, E.D.	1917	L	298.2	Disk F-I	Similar to the above specimen but prepared by heating at 214 C and aged for 42 days.
34*	1253	Sayce, E.D.	1917	L	298.2	Disk F-III	The above specimen re-tested after being aged for 1 yr.
35*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	99.994 pure; amorphous; 20 mm dia cylindrical specimen.
36*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	0.0035 Cl; amorphous; 20 mm dia cylindrical specimen.
37*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	Similar to the above specimen but doped with 0.015 Cl.
38*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	Similar to the above specimen but doped with 0.03 Cl.
39*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	Similar to the above specimen but doped with 0.06 Cl.
40*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	1	Similar to the above specimen but doped with 0.125 Cl.
41	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	2	99.994 pure; crystalline; 20 mm dia cylindrical specimen; prepared from vitreous form by heating at 130 C for 40 min.
42*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	2	Similar to above but doped with 0.015 Cl.
43	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	2	Similar to above specimen but doped with 0.03 Cl.
44*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	2	Similar to above specimen but doped with 0.06 Cl.
45*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	2	Similar to above specimen but doped with 0.125 Cl.
46	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	3	99.994 pure; crystalline; 20 mm dia cylindrical specimen; prepared from vitreous form by heating at 200 C for 40 min.
47*	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	3	Similar to above specimen but doped with 0.015 C.
48	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	3	Similar to above specimen but doped with 0.03 C.
49	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	3	Similar to above specimen but doped with 0.06 C.
50	38	Aliev, G.M. and Abdullaev, G.B.	1957	L	294	3	Similar to above specimen but doped with 0.125 C.

* Not shown in figure.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
51*	37	Aliev, G. M.	1957	L	291.7	1	99.996 pure; amorphous.
52*	37	Aliev, G. M.	1957	L	291.7	2	Amorphous selenium doped with 0.0035 Cl.
53*	37	Aliev, G. M.	1957	L	291.7	3	Similar to the above specimen but doped with 0.007 Cl.
54*	37	Aliev, G. M.	1957	L	291.7	4	Similar to the above specimen but doped with 0.015 Cl.
55*	37	Aliev, G. M.	1957	L	291.7	5	Similar to the above specimen but doped with 0.03 Cl.
56*	37	Aliev, G. M.	1957	L	291.7	6	Similar to the above specimen but doped with 0.06 Cl.
57*	37	Aliev, G. M.	1957	L	291.7	7	Similar to the above specimen but doped with 0.125 Cl.
58	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	1	99.996 pure; crystalline.
59	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	2	Crystalline selenium doped with 0.0035 Cl.
60	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	3	Crystalline seleneium doped with 0.007 Cl.
61	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	4	Crystalline seleneium doped with 0.015 Cl.
62	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	5	Crystalline selenium doped with 0.06 Cl.
63	39	Aliev, G. M. and Abdullaev, G. B.	1958	L	303-353	6	Crystalline selenium doped with 0.03 Cl.
64*	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		99.994 pure; amorphous; 20 mm in dia and 5 to 9 mm thick.
65	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		The above specimen crystallized by subjecting to heat-treatment at 160 C for 1 hr and 214 C for 30 min.
66*	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		0.069 I; amorphous; 20 mm in dia and 5 to 9 mm thick; prepared from 99.994 pure Se by melting and casting.
67*	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		The above specimen crystallized by subjecting to heat-treatment at 160 C for 1 hr and at 214 C for 30 min.
68*	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		0.103 I; amorphous; 20 mm in dia and 5 to 9 mm thick; prepared from 99.994 pure Se by melting and casting.
69*	5, 40	Abdullaev, G. B. and Aliev, M. I.	1957	L	299.2		The above specimen crystallized by subjecting to heat-treatment at 160 C for 1 hr and at 214 C for 30 min.
70	1555	White, G. K., Woods, S. B., and Elford, M. T.	1958	L	1.9-95	Se 1	Glassy specimen ~3 cm long and 1 cm in dia; prepared by melting selenium powder (of probable 99.9^{+} purity) in a split brass mold at about 250 C and quenching rapidly in ice water.
71	1555	White, G. K., Woods, S. B., and Elford, M. T.	1958	L	2.2-130	Se 2	Polycrystalline; same dimensions and preparation method as above.
72	1555	White, G. K., et al.	1958	L	4.3-90	Se 3	Crystalline; 6 cm long, 1 cm in dia; supplied by Fairmount Chemical Co. (Newark, N. J.).

* Not shown in figure.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
73	1555	White, G.K., Woods, S.B., and Elford, M.T.	1958	L	2.7-92	Se 4	Polycrystalline specimen ~4 cm long and 4 mm in dia; average grain size ~20 μ; produced by melting 99.999 pure selenium powder (from Canadian Copper Refiners, Ltd) under vacuum in a glass tube, chilling rapidly to produce solid rod of glassy selenium, and annealing in vacuo at about 210 C for 50-60 hrs.
74	1555	White, G.K., et al.	1958	L	2.8-77	Se 5	Similar to the above specimen but having a regular triangular cross section of about 0.26 cm^2.
75	6, 42	Abdullaev, G.B., Aliev, M.I., and Akhundova, S.A.	1960	L	293-363		99.996 pure; polycrystalline; specimen about 10 mm thick and 16 mm in dia; annealed at 110 C and 210 C for 1 hr.
76	6, 42	Abdullaev, G.B., et al.	1960	L	293-363		0.05 Tl; polycrystalline selenium specimen of the same dimensions as above; prepared by melting together 99.996 pure selenium and Tl_2Se in a vacuum of 10^{-4} mm Hg; annealed at 110 C and 210 C for 1 hr.
77	6, 42	Abdullaev, G.B., et al.	1960	L	293-363		Similar to the above specimen but doped with 0.0125 Tl; electrical conductivity 0.014, 0.022, 0.040, 0.064, 0.105, 0.229, 0.759, 1.00, 1.29, and 2.26 x 10^{-8} ohm^{-1} cm^{-1} at 24.2, 40.4, 48.7, 59.5, 78.2, 98.1, 127.1, 136.5, 146.3, and 157.0 C, respectively.
78	6, 42	Abdullaev, G.B., et al.	1960	L	293-363		Similar to the above specimen but doped with 0.1 Tl; electrical conductivity 0.003, 0.011, 0.104, 0.217, 0.565, and 1.25 x 10^{-8} ohm^{-1} cm^{-1} at 24.9, 49.3, 98.4, 118.4, 137.4, and 156.8 C, respectively.
79	35	Aliev, B.D., Abdullaev, G.B., and Aliev, G.M.	1963	L	293-373	1	99.996 pure; crystalline; ~10 mm dia cylindrical specimen; heated at 215 C for 8 hrs.
80	35	Aliev, B.D., et al.	1963	L	293-373	2	Similar to the above specimen but doped with 0.01 Bi.
81	35	Aliev, B.D., et al.	1963	L	293-373	3	Similat to above but doped with 0.02 Bi.
82	35	Aliev, B.D., et al.	1963	L	293-373	4	Similar to above but doped with 0.04 Bi.
83	35	Aliev, B.D., et al.	1963	L	293-373	5	Similar to above but doped with 0.06 Bi.
84	35	Aliev, B.D., et al.	1963	L	293-373	6	Similar to above but doped with 0.08 Bi.
85	35	Aliev, B.D., et al.	1963	L	293-373	7	Similar to above but doped with 0.1 Bi.
86	3	Abdullaev, G.B., Aliev, G.M., and Barkinkhoev, Kh.G.	1963	L	90-300	V-3	Amorphous; about 10 mm in dia; prepared from the melt of 99.999 pure selenium by rapid cooling in vacuum.
87	3	Abdullaev, G.B., et al.	1963	L	87-300	V-4	Similar to above but prepared from 99.9999 pure Se.
88	3	Abdullaev, G.B., et al.	1963	L	87-300	V-5	Similar to above but prepared from 99.99999 pure Se.
89	3	Abdullaev, G.B., et al.	1963	L	85-453	V-3	Crystalline; about 10 mm in dia; prepared from the amorphous specimen V-3 for curve No. 86 by annealing in vacuum at 210 C for 50 hrs.
90	3	Abdullaev, G.B., et al.	1963	L	90-453	V-4	Similar to above but prepared from the amorphous specimen V-4 for curve No. 87.
91	3	Abdullaev, G.B., et al.	1963	L	85-455	V-5	Similar to above but prepared from the amorphous specimen V-5 for curve No. 88.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
92	979	Mogilevskiy, B. M. and Chudnovskiy, A. F.	1964	P	293-573		Data cover both solid and liquid states; measured by a nonsteady-probe method.
93	9	Abdullaev, G. B., Mekhtiyeva, S. I., Abdinov, D. Sh., and Aliev, G. M.	1966	L	294-313	1	Amorphous selenium; glass-formation temp ~31 C.
94*	9	Abdullaev, G. B., et al.	1966	L	294-313	3	Amorphous selenium irradiated by an electron beam with an energy of 5 MeV for 30 min.
95	9	Abdullaev, G. B., et al.	1966	L	294-313	2	Similar to above but irradiated for only 10 min.
96	9	Abdullaev, G. B., et al.	1966	L	288-318	1	Amorphous selenium.
97	9	Abdullaev, G. B., et al.	1966	L	294-313	3	0.197 P; amorphous.
98	8	Abdullaev, G. B., Dzhalilov, N. Z., and Aliev, G. M.	1966	L	87-455		Hexagonal single crystal grown out of a melt of grade V-5 selenium (99.99999 pure); each crystal 15 x 2 x 2 mm in size; specimen dimensions 7 x 6 x 4 mm; measurement carried out in darkness under a vacuum of 10^{-4} mm Hg; heat flow parallel to crystal axis.
99	8	Abdullaev, G. B., et al.	1966	L	93-465		Similar to above but measured perpendicular to crystal axis.
100	10, 293	Abdullaev, G. B., Mekhtieva, S. I., Abdinov, D. S., Aliev, G. M., and Alieva, S. G.	1966	L	293-315	B-5	99.99999 pure; amorphous; prepared from the melt by rapid cooling in vacuum; vitrification temp 31 C.
101*	10, 293	Abdullaev, G. B., et al.	1966	L	293-315		Doped with 0.05 Cd; prepared from the melt by rapid cooling in vacuum; vitrification temp 32.5 C.
102*, ‡	10, 293	Abdullaev, G. B., et al.	1966	L	89-341	B-4	99.9999 pure; amorphous; prepared from the melt by rapid cooling in vacuum.
103*, ‡	"	Abdullaev, G. B., et al.	1966	L	86-338	B-4	Similar to the above except annealed at 373 K for 0.5 hr.
104*, ‡	"	Abdullaev, G. B., et al.	1966	L	88-335	B-4	Similar to the above except annealed at 373 K for 2 hrs.
105*, ‡	"	Abdullaev, G. B., et al.	1966	L	86-338	B-4	Similar to above except annealed at 373 K for 10 hrs.
106*, ‡	"	Abdullaev, G. B., et al.	1966	L	89-533		Crystalline specimen prepared from the amorphous phase (specimen B-4) by annealing in vacuum at 210 C for 60 hrs. (Includes the liquid phase.)
107	10, 293	Abdullaev, G. B., et al.	1966	L	290-317		Doped with 0.05 Tl; amorphous specimen; prepared from the melt of 99.99999 pure selenium with admixture of thallium by rapid cooling in vacuum.
108	10, 293	Abdullaev, G. B., et al.	1966	L	291-317		Similar to the above specimen except doped with 0.125 Tl.
109	22	Adams, A. R., Baumann, F., and Stuke, J.	1967	L	1.8-94	A	Single crystal; specimen 1.46 mm^2 in cross section and 9.8 mm long; grown from the vapor phase; heat flow parallel to the c-axis; (additional information and data obtained from authors).
110	22	Adams, A. R., et al.	1967	L	1.9-112	B	Single crystal; specimen 0.973 mm^2 in cross section and 7.3 mm long; grown from the melt; heat flow parallel to the c-axis; (additional information and data obtained from authors).

* Not shown in figure.
‡ Curves 102 to 106 are probably for the same measurements as curves 128 to 132, respectively.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
111	22	Adams, A.R., Baumann, F., and Stuke, J.	1967	L	2.0-90	C	Cut from the same crystal as the above specimen, in the form of an almost circular platelet 12.1 mm in dia and 1.2 mm thick, with c-axis parallel to the flat faces; measured in the direction perpendicular to both the thickness and the c-axis, in the central portion of the platelet across a length of 2.5 mm with effective cross section 15 mm^2; (additional information and data obtained from authors).
112	22	Adams, A.R., et al.	1967	L	1.8-89	D	Cut from the same crystal as the above specimen, in the form of an almost circular platelet 12.1 mm in dia and 1.60 mm thick, with c-axis parallel to the flat faces; measured in the direction perpendicular to both the thickness and the c-axis, in the central portion of the platelet across a length of 3.66 mm with effective cross section 19.4 mm^2; (additional information and data obtained from authors).
113*	924	Mekhtieva, S.I., Abdinov, D.Sh., and Aliev, G.M.	1967		298.2		Density 4.63 g cm^{-3}.
114*	924	Mekhtieva, S.I., et al.	1967		298.2		0.04 Sb; density 4.44 g cm^{-3}.
115*	924	Mekhtieva, S.I., et al.	1967		298.2		0.09 Sb; density 4.37 g cm^{-3}.
116*	924	Mekhtieva, S.I., et al.	1967		298.2		0.13 Sb; density 4.30 g cm^{-3}.
117*	96	Askerov, Ch.M., Aliev, G.M., and Akhundova, E.G.	1964		298.2		99.99999 pure; crystalline; density 4.63 g cm^{-3}. (Measuring temp.assumed 25 C.)
118	96	Askerov, Ch.M., et al.	1964		79-431		The above specimen.
119*	96	Askerov, Ch.M., et al.	1964		298.2		99.99999 pure; amorphous selenium. (Measuring temp assumed 25 C.)
120*	96	Askerov, Ch.M., et al.	1964		298.2		0.025 S; crystalline; prepared from 99.99999 pure Se; density 4.46 g cm^{-3}. (Measuring temp assumed 25 C.)
121*	96	Askerov, Ch.M., et al.	1964		298.2		Similar to above but impurity 0.050 S and density 4.21 g cm^{-3}.
122*	96	Askerov, Ch.M., et al.	1964		298.2		0.075 S; prepared from 99.99999 pure Se.
123	96	Askerov, Ch.M., et al.	1964		80-454		The above specimen.
124*	96	Askerov, Ch.M., et al.	1964		298.2		Similar to above but impurity 0.1 S and density 4.53 g cm^{-3}. (Measuring temp assumed 25 C.)
125*	96	Askerov, Ch.M., et al.	1964		298.2		0.025 S; amorphous. (Measuring temp assumed 25 C.)
126	96	Askerov, Ch.M., et al.	1964		298.2		Similar to above but impurity 0.050 S.
127	96	Askerov, Ch.M., et al.	1964		298.2		Similar to above but impurity 0.1 S.
128	1	Abdinov, D.Sh. and Aliev, G.M.	1964		92-335		99.9999 pure; amorphous; glazing temp 30.7 C.
129	1	Abdinov, D.Sh. and Aliev, G.M.	1964		90-335		99.9999 pure; amorphous with 12 v/o crystalline selenium.
130	1	Abdinov, D.Sh. and Aliev, G.M.	1964		90-336		99.9999 pure; amorphous with 35 v/o crystalline selenium.

* Not shown in figure.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
131	1	Abdinov, D. Sh. and Aliev, G. M.	1964		90-337		99.9999 pure; amorphous with 54 v/o crystalline selenium.
132	1	Abdinov, D. Sh. and Aliev, G. M.	1964		93-522		99.9999 pure; crystalline; measured in both solid and liquid states.
133	923	Mekhtieva, S. I., Abdinov, D. Sh., and Aliev, G. M.	1966	L	293-315		Doped by 0.05 P; prepared from 99.99999 pure selenium melt by rapid cooling; vitrification temp ~30 C.
134	1482	Veliev, M. I., Kerimov, I. G., Aliev, G. M., and Aliev, M. I.	1963	L	81-301	1	99.9996 pure; amorphous; 0.64 cm^2 in cross-section and 0.7 cm long.
135	1482	Veliev, M. I., et al.	1963	L	78-301	2	The above specimen annealed at 100 C for 1 hr.
136	1482	Veliev, M. I., et al.	1963	L	79-299	3	The above specimen again annealed at 150 C for 1 hr.
137	1482	Veliev, M. I., et al.	1963	L	77-302	4	The above specimen again annealed at 200 C for 1 hr.
138	1482	Veliev, M. I., et al.	1963	L	78-300	5	The above specimen again annealed at 210 C for 1 hr.
139	1482	Veliev, M. I., et al.	1963	L	78-302	6	The above specimen again annealed at 215 C for 1 hr.
140	1482	Veliev, M. I., et al.	1963	L	80-371	7	The above specimen turned into crystalline after again annealed at 218 C for 1 hr.
141*	95	Askerov, Ch. M. and Aliev, G. M.	1962		294-360	1	Pure; original material crushed; melted in a vacuum of 10^{-4} mm Hg in a Pyrex tube, sealed ampule placed in a furnace at 300 C, cooled, crystallized by heating at 200 C for 10 hrs.
142	95	Askerov, Ch. M. and Aliev, G. M.	1962		294-357	3	Doped with 0.025 S; same preparation method as above.
143	95	Askerov, Ch. M. and Aliev, G. M.	1962		295-359	5	Similar to above but doped with 0.05 S.
144	95	Askerov, Ch. M. and Aliev, G. M.	1962		297-359	6	Similar to above but doped with 0.1 S.
145	2	Abdullaev, G. B., Aliev, G. M., and Barkinkhoev, Kh. G.	1963	L	86-461		99.999 pure; crystalline; 10 to 12 mm in dia and 10 to 13 mm thick.
146	36	Aliev, B. D. and Aliev, G. M.	1963	L	293-373		Pure; crystaline; 10 to 12 mm in dia and 8 to 10 mm thick; original powdered material sealed in ampule in a vacuum of 10^{-4} mm Hg, melted by heating to 400 C, cooled, crystallized by heating at 215 C for 8 hrs; electrical conductivity 0.427, 0.501, 0.562, 0.661, 0.741, 0.891, 0.977, 1.00, 1.00, 0.977, 0.891, 0.897, 0.912, 1.55, and 2.51 x 10^{-4} ohm^{-1} cm^{-1} at 292, 297, 301, 308, 315, 334, 351, 360, 366, 373, 385, 397, 403, 439, and 474 C, respectively.
147	36	Aliev, B. D. and Aliev, G. M.	1963	L	293-372		0.01 Cd-doped; same dimensions and fabrication method as the above specimen; electrical conductivity 0.195, 0.229, 0.309, 0.372, 0.427, 0.468, 0.501, 0.537, 0.589, 0.676, 0.776, 0.977, and 1.44 x 10^{-4} ohm^{-1} cm^{-1} at 292, 299, 315, 331, 346, 365, 385, 397, 410, 426, 435, 448, and 472 C, respectively.
148	36	Aliev, B. D. and Aliev, G. M.	1963	L	293-372		0.065 Cd-doped; same dimensions and fabrication method as the above specimen; electrical conductivity 0.148, 0.170, 0.190, 0.209, 0.263, 0.295, 0.309, 0.355, 0.398, 0.436, 0.513, 0.617, 0.759, and 1.02 x 10^{-4} ohm^{-1} cm^{-1}.
149	36	Aliev, B. D. and Aliev, G. M.	1963	L	293-372		0.125 Cd-doped; same dimensions and fabrication method as the above specimen; electrical conductivity 0.316, 0.295, 0.288, 0.288, 0.302, 0.331, 0.363, 0.407, 0.468, 0.562, 0.832, and 1.20 x 10^{-4} ohm^{-1} cm^{-1} at 294, 305, 312, 331, 341, 355, 375, 391, 405, 420, 448, and 476 C, respectively.

* Not shown in figure.

TABLE 143. THERMAL CONDUCTIVITY OF SELENIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
150	44	Aliev, M.I., Veliev, M.I., and Kerimov, I.G.	1961	L	93-290		99.996 pure; crystalline; 10 mm in dia and 8 to 10 mm long.
151	44	Aliev, M.I., et al.	1961	L	115-291		Amorphous; 10 mm in dia and 8 to 10 mm long.
152*	41	Aliev, M.I. and Akhundova, S.A.	1959	L	304-362	1	99.996 pure; crystalline; circular disk specimen 20 mm in dia.
153*	41	Aliev, M.I. and Akhundova, S.A.	1959	L	304-363	2	0.069 I; crystalline; prepared from 99.996 pure Se; disk specimen 20 mm in dia; heat-treated at 160 C for 1 hr and at 214 C for 30 min.
154*	41	Aliev, M.I. and Akhundova, S.A.	1959	L	303-363	3	Similar to above but 0.103 I doped.
155*	118, 119	Bashshliev, A.A.	1958	L	300.7		0.008 Br; amorphous; specimen 20 mm in dia; polished.
156*	118, 119	Bashshliev, A.A.	1958	L	300.7		0.032 Br; similar to above.
157*	118, 119	Bashshliev, A.A.	1958	L	300.7		0.008 Br; crystalline; specimen 18 mm in dia; prepared by melting vitreous selenium and bromine in a ceramic crucible; crystallized in a molybdenum beaker by heating at 130 C for 30 min and at 200 C for 25 min.
158*	118, 119	Bashshliev, A.A.	1958	L	300.7		0.016 Br; similar to above.
159*	925, 926	Mekhtieva, S.I., Adbinov, D.Sh., and Aliev, G.M.	1968	L	373.2		99.99999 pure; amorphous specimens partially crystallized; measured after different duration of heat-treatment at 100 C ranging from 0.25 to 25 hrs.
160*	925, 926	Mekhtieva, S.I., et al.	1968	L	383.2		Similar to above but heat-treated at 110 C.
161*	925, 926	Mekhtieva, S.I., et al.	1968	L	403.2		Similar to above but heat-treated at 130 C.
162*	925, 926	Mekhtieva, S.I., et al.	1968	L	453.2		Similar to above but heat-treated at 180 C.
163*	925, 926	Mekhtieva, S.I., et al.	1968	L	483.2		Similar to above but heat-treated at 210 C.

* Not shown in figure.

Silicon

At low temperatures many thermal conductivity measurements have been reported, of which the majority have been directed toward determining the differences in thermal conductivity between samples characterized as either *n*- or *p*-type and determining the effects of various impurities on the lattice thermal conductivity of silicon.

The highest value at the maximum of a thermal conductivity curve so far reported, 52 W cm^{-1} K^{-1} at 22 K, is by Holland for both an *n*-type single crystal doped with phosphorus [621] (curve 24) and a *p*-type single crystal with boron as major impurity [624] (curve 102). It has been observed that for many of the *n*-type samples, although the effect of the impurities on the thermal conductivity results in a large decrease of the thermal conductivity over the entire temperature range (with larger decreases due to higher impurity concentrations), the temperature at which the maximum thermal conductivity occurs remains almost the same (in the small range of about 18 to 28 K), i.e., the decrease in the thermal conductivity curve is symmetric with respect to the peak. On the other hand, for many *p*-type samples, the effect of impurities produces a large asymmetric decrease in the thermal conductivity curve, i.e., as the thermal conductivity curve decreases, the temperature of the thermal conductivity maximum shifts to higher temperature.

The likely curve for the thermal conductivity of pure silicon at low temperatures has been based on the highest thermal conductivity data (curve 102) of Holland. Below his lowest temperature the curve has been extrapolated to 1 K and in this range the thermal conductivity varies approximately as $T^{2.7}$.

The same curve of Holland's has been followed above the maximum, although above about 45 K it lies below some of the data having lower maxima. Around 120 K, the curve merges into one due to Glassbrenner and Slack [497] (curve 31) and follows this curve to about 250 K, above which it drops to a slightly lower position intermediate between the values of Glassbrenner and Slack (curve 32) and the later determinations of Fulkerson, Moore, Williams, Graves, and McElroy [468] (curve 82). These two sets of workers have made careful determinations on silicon to temperatures of 1570 and 1350 K, respectively, using a radial heat flow method, and for most of this higher range, 700 K and above, the values all agree to within 4 percent, those of Fulkerson, et al. being consistently lower.

The proposed curve has been drawn to 1350 K in an intermediate position between these two sets of data, and has been continued smoothly through the higher temperature data of Glassbrenner and Slack and on to the melting point.

For the solid in the region of the melting point it is interesting to note that Glassbrenner and Slack deduced that 63 percent of the heat conduction was by phonons, 32 percent by an electronic bipolar contribution, and only 5 percent by the electronic polar contribution which would correspond to the usual electronic component that predominates in the case of a metal.

The thermal conductivity of molten silicon near the melting point has been reported by Mil'vidskii and Eremeev [974] as 2.09 W cm^{-1} K^{-1} (curve 92) and by Shashkov and Grishin [1300] as 0.699 W cm^{-1} K^{-1} (curve 90). Since these two values differ by a factor of 3, no proposal is made at present. Furthermore, in view of the small proportion of the electronic contribution for the near-melting solid, any estimation of the thermal conductivity of molten silicon from the electrical resistivity would seem to present unusual difficulties.

The proposed curve is for high-purity silicon. The values at and above room temperature are recommended values, and those below room temperature are merely typical values. The recommended values are thought to be accurate to within ±5 percent at temperatures from 300 to 1000 K, the uncertainty increasing to ±10 percent near the melting point.

TABLE 144. Recommended thermal conductivity of silicon†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	250	1.91
1	0.0693*	273.2	1.68
2	0.454	298.2	1.49
3	1.38	300	1.48
4	2.97	323.2	1.33
5	5.27	350	1.19
6	8.23	373.2	1.08
7	11.7	400	0.989
8	15.5	473.2	0.814
9	19.5	500	0.762
10	23.3	573.2	0.651
11	27.0	600	0.619
12	30.9	673.2	0.536
13	34.8	700	0.508
14	38.4	773.2	0.442
15	41.6	800	0.422
16	44.1	873.2	0.374
18	47.7	900	0.359
20	49.8	973.2	0.323
25	51.3	1000	0.312
30	48.1	1073.2	0.286
35	41.3	1100	0.279
40	35.3	1173.2	0.262
45	30.6	1200	0.257
50	26.8	1273.2	0.247
60	21.1	1300	0.244
70	16.8	1373.2	0.237
80	13.4	1400	0.235
90	10.8	1473.2	0.229
100	8.84	1500	0.227
123.2	5.99	1573.2	0.223
150	4.09	1600	0.221
173.2	3.30	1673.2	0.220
200	2.64	1685	0.220
223.2	2.25		

†The values are for well-annealed high-purity silicon, and those below room temperature are merely typical values.
*Extrapolated.

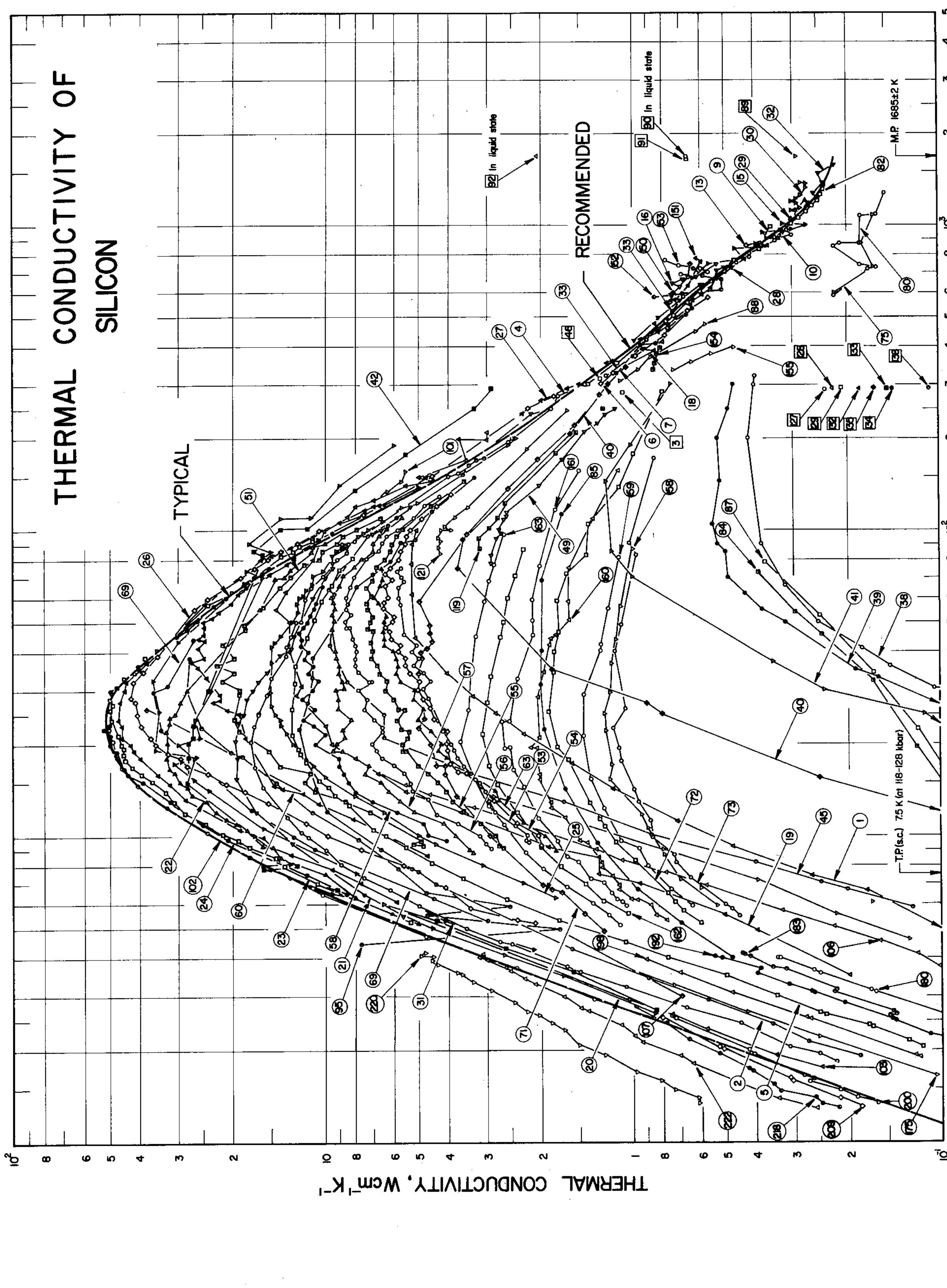

THERMAL CONDUCTIVITY OF SILICON
RECOMMENDED
TYPICAL
M.P. 1685±2 K
T.P.(s.c.) 7.5 K (at 118–128 kbar)
In liquid state
TEMPERATURE, K
THERMAL CONDUCTIVITY, $W cm^{-1} K^{-1}$
TPRC

FIGURE 144

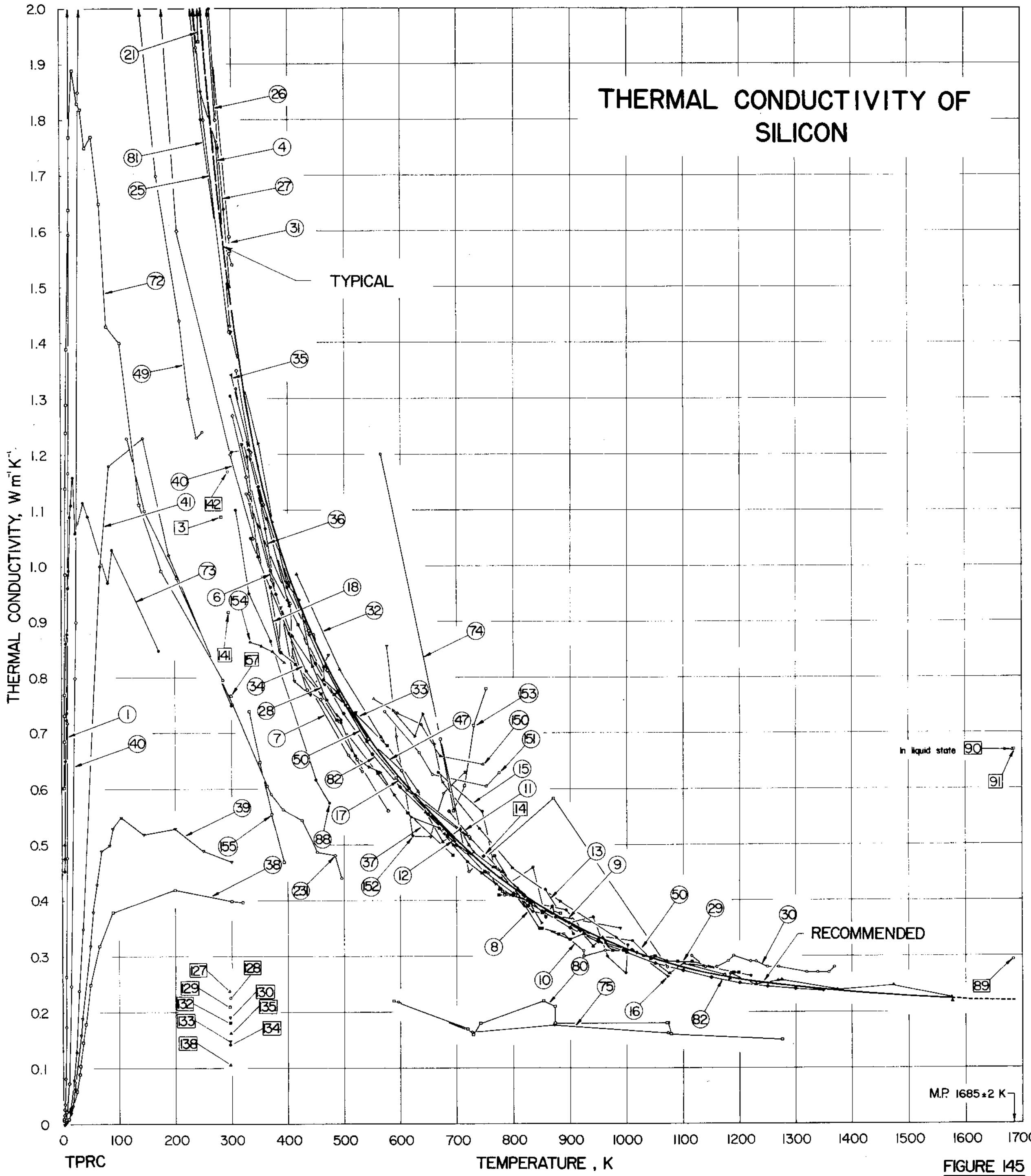

THERMAL CONDUCTIVITY OF SILICON
THERMAL CONDUCTIVITY, W m⁻¹ K⁻¹
TEMPERATURE, K
TYPICAL
RECOMMENDED
In liquid state
M.P. 1685±2 K
TPRC

FIGURE 145

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1218	Rosenberg, H. M.	1954	L	1.7–100	Si 1	High purity; polycrystalline, composed of fairly large crystallites about 0.2 mm in size; specimen 1 cm long, 1.5 mm^2 cross section; supplied by Messrs. Johnson, Matthey Co.; nickel plated to solder thermal contacts, excess nickel dissolved with acid.
2	1544	White, G.K. and Woods, S.B.	1956	L	1.9–149	Si 1	Pure single crystal; n-type; specimen cross-sectional area 1.75 x 1.5 mm^2; electrical resistivity 6.7 ohm cm at 295 K.
3	658	Ioffe, A.V. and Ioffe, A.F.	1954		283		Pure crystal.
4	241	Carruthers, J.A., Geballe, T.H., Rosenberg, H.M., and Ziman, J.M.	1957	L	1.8–300	Si 2	Pure single crystal; n-type; axis of specimen along [100] direction; 5 x 0.215 x 0.198 cm; carrier concentration 5 x 10^{14} cm^{-3}; electrical resistivity 15–25 ohm cm at room temp.
5	241	Carruthers, J.A., et al.	1957	L	2.1–80	Si 3	Gold-doped single crystal; p-type; axis of specimen along [100] direction; 5 x 0.236 x 0.221 cm; carrier concentration 10^{15} cm^{-3}; electrical resistivity 18–26 ohm cm at room temp.
6	1373	Stuckes, A.D.	1960	C	303–579		Pure single crystal; p-type; electrical resistivity 3 ohm cm at room temp; FH stainless steel used as comparative material.
7	1373	Stuckes, A.D.	1960	C	328–533		Pure single crystal; n-type; electrical resistivity 3 ohm cm at room temp; FH stainless steel used as comparative material.
8	887, 888, 994	Martin, J.J.	1962	C	767, 846	KA-1 (Knapic)	p-type single crystal; 23 mm dia x 8 mm thick; specimen axis in (111) orientation; supplied by Knapic Electro-Physics; carrier concentration 10^{18} cm^{-3}; Armco iron used as comparative material.
9	887, 888, 994	Martin, J.J.	1962	C	769–989	KA-1 (Knapic)	Second run of the above specimen.
10	887, 888, 994	Martin, J.J.	1962	C	756–997	KA-1 (Knapic)	Third run of the above specimen.
11	887, 888, 994	Martin, J.J.	1962	C	687, 826	KA-1 (Knapic)	Fourth run of the above specimen.
12	887, 888, 994	Martin, J.J.	1962	C	679, 778	KB-1 (Knapic)	n-type single crystal; 23 mm dia x 8 mm thick; specimen axis in (111) orientation; supplied by Knapic Electro-Physics; carrier concentration 5 x 10^{16} cm^{-3}; Armco iron used as comparative material.
13	887, 888, 994	Martin, J.J.	1962	C	857, 906	KB-2 (Knapic)	Similar to above.
14	887, 888, 994	Martin, J.J.	1962	C	748	KB-2 (Knapic)	Second run of above specimen.
15	887, 888, 994	Martin, J.J.	1962	C	669–1002	KB-2 (Knapic)	Third run of above specimen.
16	172	Bobone, R., Kendall, L.F., and Vought, R.H.	1962	E	588–1073		p-type single crystal; 0.25 in. dia x 1.5 in. long; data corrected for isothermal conditions and shield.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur.	Ref.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17	172	Bobone, R., Kendall, L. F., and Vought, R. H.	1962	E	593-883		The above specimen held for some time at 1073 K; measured in the cooling-down period.
18	172	Bobone, R., et al.	1962	E	334-473		The above specimen measured with the length of the thermocouple wire between junctions and shield increased by a factor of approx two to three.
19	1408	Thompson, J. C. and Younglove, B. A.	1961	L	3.5-210	Q-20	p-type single crystal; boron doped (1×10^{15} atoms cm^{-3}); O concentration, 2×10^{17} atoms cm^{-3}; dimensions 3 x 3 x 20 mm; supplied by H. L. Taylor, Texas Instruments, Inc.; electrical resistivity reported as 7.2 ohm cm at 0 C.
20	1408	Thompson, J. C. and Younglove, B. A.	1961	L	2.6-190	M-1	p-type single crystal; boron doped (2×10^{12} atoms cm^{-3}); oxygen concentration, $<10^{17}$ cm^{-3}; dimensions 3 x 3 x 20 mm; supplied by F. J. Bourassa, Electronics Chemical Div., Merck and Co., Inc.; electrical resistivity reported as 2000 ohm cm at 0 C.
21	621	Holland, M. G.	1961	L	5.5-246	K4	n-type single crystal; oxygen concentration, 1.4×10^{18} cm^{-3}; specimen cross-section 0.625 x 0.627 cm; carrier concentration 3.5×10^{14} cm^{-3}; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 12 ohm cm at room temp.
22	621	Holland, M. G.	1961	L	5.2-208	K5	n-type single crystal; oxygen concentration, 6×10^{17} cm^{-3}; specimen cross-section 0.622 x 0.622 cm; carrier concentration 3.5×10^{13} cm^{-3}; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 110 ohm cm at room temp.
23	621	Holland, M. G.	1961	L	5.3-200	M6	n-type single crystal; phosphorus doped; oxygen concentration, $<10^{16}$ cm^{-3}; carrier concentration 1.1×10^{15} cm^{-3}; specimen cross-section, 0.634 x 0.640 cm; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 5 ohm cm at room temp.
24	621	Holland, M. G.	1961	L	6-120	M4	n-type single crystal; phosphorus doped; oxygen concentration $<10^{16}$ cm^{-3}; carrier concentration 4×10^{13} cm^{-3}; cross-section 0.637 x 0.629 cm; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 260 ohm cm at room temp.
25	621	Holland, M. G.	1961	L	6.3-298	SA-1	p-type single crystal; boron doped; oxygen concentration 7×10^{17} cm^{-3}; cross-section 0.616 x 0.623 cm; carrier concentration 4.8×10^{15} cm^{-3}; electrical resistivity reported as 3.0 ohm cm at room temp.
26	621	Holland, M. G.	1961	L	5.2-275	M3	p-type single crystal; boron doped; oxygen concentration $<10^{16}$ cm^{-3}; specimen cross-section 0.635 x 0.632 cm; carrier concentration 4.0×10^{15} cm^{-3}; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 4.5 ohm cm at room temp.
27	621	Holland, M. G.	1961	L	5.9-300	M2	p-type single crystal; boron doped; oxygen concentration $<10^{16}$ cm^{-3}; specimen cross-section 0.630 x 0.640 cm; carrier concentration 4.0×10^{14} cm^{-3}; dislocation density of the order of 10^4 cm^{-2}; electrical resistivity reported as 45.5 ohm cm at room temp.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
28	765, 1297	Shanks, H.R., Maycock, P.D., Sidles, P.H., and Danielson, G.C.	1963	P	300-850	4A	p-type single crystal; specimen axis in [111] orientation; 0.9 cm in dia, 6 cm long; electrical resistivity reported as 107 ohm cm at 300 K; thermal conductivity values calculated from measured data of thermal diffusivity using the specific heat data taken from Dennison, D.H. (Institute for Atomic Research, Ames, Iowa) and density (determined by Smakula, A. and Sils, V.) 2.32902 ±3 x 10^{-5} g cm^{-3} at 298 K.
29	765, 1297	Shanks, H.R., et al.	1963	P	775-1200	1F	n-type single crystal; 0.9 cm in dia, 6 cm long; specimen axis in [111] orientation; electrical resistivity reported as 33.0, 50.0, 58.0, 42.0, 6.2, and 0.1 ohm cm at 300, 400, 460, 500, 650, and 1000 K, respectively; thermal conductivity values calculated by the same method as above.
30	765, 1297	Shanks, H.R., et al.	1963	P	1115-1370	3C	n-type single crystal; 0.9 cm in dia, 6 cm long; specimen axis in [100] orientation; electrical resistivity reported as 1010, 2000, 1700, 125, 6.2, and 0.1 ohm cm at 300, 375, 400, 500, 650, and 1000 K, respectively; thermal conductivity values calculated by the same method as above.
31	497	Glassbrenner, C.J. and Slack, G.A.	1964	L	4.3-304		High purity; p-type single crystal; specimen axis in [111] orientation; 2 cm long and average dia 0.44 cm; vacancy clusters $<1\ \mu$ in dia; electrical resistivity reported as ~2000 ohm cm at room temp; measured in helium atmosphere.
32	497	Glassbrenner, C.J. and Slack, G.A.	1964	R	418-1577		n-type single crystal; 2.6 cm dia x ~13 cm long; axis of cylinder in [111] direction; produced by floating zone process in argon atmosphere; dislocation density of the order of 10^5 cm^{-2}; carrier concentration, 1.27 x 10^{13} cm^{-3}; electrical resistivity reported as 440 ohm cm at room temp; measured in helium atmosphere; after the measurement, room temp resistivity dropped to 177 ohm cm, carrier concentration rose to 2.46 x 10^{13} cm^{-3}.
33	647, 993	Hust, J.G.	1961	C	320-578	S-B-1	Single crystal; p-type; impurity concentration 2 x 10^{15} atoms cm^{-3}; supplied by Battelle Memorial Institute; ground to a dia of 11.8 mm and sliced to 7 mm thick; measured in a vacuum of 10^{-5} mm Hg; Armco iron (99.9$^+$ Fe) used as comparative material.
34	647, 993	Hust, J.G.	1961	C	300-495	S-B-1	Second run of the above specimen.
35	647, 993	Hust, J.G.	1961	C	404, 307	S-B-1	Third run of the above specimen.
36	647, 993	Hust, J.G.	1961	C	302-467	S-B-2	Similar to above except impurity concentration 6 x 10^{14} atoms cm^{-3}.
37	647, 993	Hust, J.G.	1961	C	336-694	S-B-2	Second run of the above specimen.
38	1320	Slack, G.A.	1964	L	10-320	R-3	Polycrystalline, p-type; major impurity boron, 5 x 10^{20} atoms cm^{-3}; 1.24 cm effective dia, 3.2 cm long; electrical conductivity reported as 3.8 x 10^3 ohm^{-1} cm^{-1} at 300 K.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
39	1320	Slack, G.A.	1964	L	2.1-300	R-5	Synthetic single crystal, p-type; major impurity boron, 3×10^{20} atoms cm^{-3}; 0.56 cm effective dia, 2.6 cm long; electrical conductivity reported as 2.2×10^3 ohm^{-1} cm^{-1} at 300 K.
40	1320	Slack, G.A.	1964	L	3.2-340	R-6	Synthetic single crystal, n-type; major impurity phosphorus, 2.0×10^{19} atoms cm^{-3}; 1.20 cm effective dia, 3.2 cm long; electrical conductivity reported as 3.6×10^2 ohm^{-1} cm^{-1} at 300 K.
41	1320	Slack, G.A.	1964	L	3.8-300	R-55	Synthetic single crysal, n-type; major impurity phosphorus, 1.7×10^{20} atoms cm^{-3}; 0.55 cm effective dia, 1.7 cm long; electrical conductivity reported as 1.5×10^3 ohm^{-1} cm^{-1} at 300 K.
42	1589	Younglove, B.A.	1961	L	2.7-290	Si-1	High purity; 0.2 x 0.4 x 2 cm; supplied by Texas Instruments Inc.; electrical resistivity 2000 ohm cm at 0 C.
43*	1589	Younglove, B.A.	1961	L	3.1-106	Si-2	Similar to the above specimen but with more impurities; electrical resistivity 18 ohm cm at 0 C.
44*	1589	Younglove, B.A.	1961	L	3.6-290	Si-3	Similar to the above specimen but with more impurities; electrical resistivity 7.2 ohm cm at 0 C.
45	1589	Younglove, B.A.	1961	L	5.8-210	Si-4	Similar to the above specimen but with more impurities; electrical resistivity 0.57 ohm cm at 0 C.
46	1374	Stuckes, A.D. and Chasmar, R.P.	1956	C	313	Si	p-type; electrical resistivity 2 to 3 ohm cm at 293 K; Firth Brown F.H. steel used as comparative material. (Preliminary result.)
47	15	Abeles, B., Cody, G.D., Dismukes, J.P., Hockings, E.F., Lindenblad, N.E., Richman, D., and Rosi, F.D.	1961	P	311-1018	Si-142	Crystal specimen; electrical resistivity 100 ohm cm at room temperature; measured in vacuo; thermal conductivity values calculated from measured data of thermal diffusivity using specific heat data taken from Amer. Inst. Physics Handbook (McGraw Hill Book Co., New York, p. 4-42, 1957).
48*	1031	Nguyen, V.D., Vandevyver, M., and Pham, N.T.	1963		84-285		Virgin specimen.
49	1031	Nguyen, V.D., et al.	1963		78-250		Similar to the above specimen except irradiated with 1.2×10^{18} fast neutrons cm^{-2}.
50	125	Beers, D.S., Cody, G.D., and Abeles, B.	1962	P	310-1220	Si-1142	Pure; intrinsic; single crystal; thermal conductivity values calculated from measured data of thermal diffusivity using specific heat data taken from Amer. Inst. Physics Handbook (McGraw Hill Book Co., New York, 1957).
51	1492	Vook, F.L.	1965	L	9.3-299	1	Prepared from high-purity vacuum-floating-zone single crystal p-type (residual boron) material obtained from Merck and Co.; 0.152 cm wide x 0.046 cm thick; 1.0 cm long dimension in the <111> direction; electrical resistivity 5000 ohm cm, carrier concentration $\sim 3 \times 10^{12}$ cm^{-3}.
52*	1492	Vook, F.L.	1965	L	47-59	1	The above specimen irradiated at 47 K in <110>direction with a total time-integrated flux of 8.0×10^{18} 2-Mev e cm^{-} on a length of 1.0 cm; annealed at 60 K for 15 min.
53	1492	Vook, F.L.	1965	L	9.5-76	1	The above specimen annealed again for 15 min at 77 K.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54	1492	Vook, F. L.	1965	L	9.3–132	1	The above specimen annealed again for 15 min at 135 K.
55	1492	Vook, F. L.	1965	L	9.1–146	1	The above specimen annealed again for 15 min at 150 K.
56	1492	Vook, F. L.	1965	L	9.1–176	1	The above specimen annealed again for 15 min at 180 K.
57	1492	Vook, F. L.	1965	L	8.8–227	1	The above specimen annealed again for 15 min at 230 K.
58	1492	Vook, F. L.	1965	L	9.7–172	1	The above specimen annealed again for 15 min at 280 K.
59*	1492	Vook, F. L.	1965	L	9.4–300	1	The above specimen annealed again for 15 min at 410 K.
60	1492	Vook, F. L.	1965	L	8.6–303	2	Prepared from high-purity vacuum-floating-zone single crystal p-type (residual boron) material obtained from Merck and Co.; 0.153 cm wide x 0.048 cm thick; 1.0 cm long dimension in the <111> direction; electrical resistivity 5000 ohm cm; carrier concentration ~3 x 10^{12} cm^{-3}.
61*	1492	Vook, F. L.	1965	L	47–59	2	The above specimen irradiated at 47 K in <110> direction with a total time-integrated flux of 8.0 x 10^{18} 2-Mev e cm^{-2} on a length of 1.0 cm; annealed at 60 K for 15 min.
62*	1492	Vook, F. L.	1965	L	8.9–76	2	The above specimen annealed again for 15 min at 77 K.
63	1492	Vook, F. L.	1965	L	8.9–132	2	The above specimen annealed again for 15 min at 135 K.
64*	1492	Vook, F. L.	1965	L	8.8–146	2	The above specimen annealed again for 15 min at 150 K.
65*	1492	Vook, F. L.	1965	L	8.7–176	2	The above specimen annealed again for 15 min at 180 K.
66*	1492	Vook, F. L.	1965	L	8.4–226	2	The above specimen annealed again for 15 min at 230 K.
67*	1492	Vook, F. L.	1965	L	8.5–81	2	The above specimen annealed again for 15 min at 280 K.
68*	1492	Vook, F. L.	1965	L	8.9–301	2	The above specimen annealed again for 15 min at 410 K.
69	32, 1459, 1460	Vandevyver, M. and Albany, H. J.	1965	L	5.4–285		Phosphorus-doped n-type single crystal; 15 x 4 x 2 mm; long dimension in the <111> direction; obtained by floating zone technique; electrical resistivity 0.35 ohm cm.
70*	32, 1459, 1460, 1462	Vandevyver, M. and Albany, H. J.	1965	L	5.5–288		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux 1.1 x 10^{17} n cm^{-2}.
71	32, 1459, 1460	Vandevyver, M. and Albany, H. J.	1965	L	4.9–277		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux 2.5 x 10^{17} n cm^{-2}.
72	32, 1459	Albany, H. J. and Vandevyver, M.	1965	L	5.5–173		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux 1.7 x 10^{18} n cm^{-2}.
73	32, 1459	Albany, H. J. and Vandevyver, M.	1965	L	5.2–286		Similar to the above specimen; irradiated at 30 C with a fast-neutron integrated flux 3.4 x 10^{20} n cm^{-2}.
74	991	Morris, R. G.	1965	C	567–1072	S-1	n-type single crystal; carrier concentration N_D = 5 x 10^{15} cm^{-3}; high purity silicon used as comparative material.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
75	991	Morris, R.G.	1965	C	596-1073	S-2	n-type single crystal; N_D 5 x 10^{15} cm^{-3}; Armco iron used as comparative material.
76*	991	Morris, R.G.	1965	C	98		n-type single crystal; supplied by Knapic Electro-Physics; 23 mm dia x 8 mm thick; circular cross-section perpendicular to <111> direction; N_D ~5 x 10^{15} cm^{-3}; Armco iron used as comparative material.
77*	991	Morris, R.G.	1965	C	179-256		2nd run of the above specimen.
78*	991	Morris, R.G.	1965	C	143,217		3rd run of the above specimen.
79*	627	Holyer, R.J.	1965	C	98-255		n-type single crystal; supplied by Knapic Electro-Physics; 23 mm dia x 8 mm thick; circular cross-section perpendicular to <111> direction; N_D ~5 x 10^{15} cm^{-3}; Armco iron used as comparative material.
80	129	Benbow, R. L.	1967	C	588-1276	Si-E4	0.1 P-doped; n-type single crystal; measured in a vacuum of 5 x 10^{-5} to 10^{-6} torr; Armco iron used as comparative material.
81	468	Fulkerson, W., Moore, J.P., Williams, R.K., Graves, R.S., and McElroy, D.L.	1968	L	100-300		99.9973$^+$ Si, 0.0014 O, 0.0005 N, 0.0003 H, <0.0001 Mg, <0.0001 Th, <0.0001 Ti, <0.0007 Ta, <0.00003 P, ~0.000022 Na, 0.000015 U, <0.00001 Cr, <0.00001 Fe, <0.00001 K, <0.000005 Mn, <0.000004 Ag, ~ 0.0000038 W, <0.000003 Nb, ~0.0000026 Cu, 0.000002 Ca, and <0.0000005 B; single crystal; square cross section approx 0.150 in. x 0.150 in. and 2 in. long; procured from Semi-elements, Inc.; density 2.327 g cm^{-3}; measured after the electrical resistivity measurements to 1273 K had been completed.
82	468	Fulkerson, W., et al.	1968	R	300-1350		Two single-crystal disks and seven polycrystalline disks were used for radial heat flow thermal conductivity measurements; the composition of the single-crystal disks is the same as that of the above specimen which was machined from a slice cut from a single-crystal disk; composition of the polycrystalline disks: 99.9945$^+$ Si, 0.0024 O, 0.0012 P, 0.0005 N, 0.0004 H, <0.0004 Fe, <0.0001 Be, <0.0001 Mg, <0.00007 Ag, <0.00007 Ta, ~0.000068 Na, 0.00003 Cr, <0.00003 Nb, <0.00003 Th, <0.00003 Ti, <0.00002 Ca, <0.00002 Mn, ~0.0000117 Cu, <0.00001 K, 0.0000086 W, <0.000007 B, and 0.0000054 U; disks 2 in. in dia and 1 in. thick; all procured from Semi-elements Inc.; polycrystalline disks density 2.326 g cm^{-3}.
83*	1291	Seyfert, P.	1967		4.3-152		P-doped n-type single crystal; oxygen concentration ~10^{18} cm^{-3}; phosphor concentration ~10^{14} cm^{-3}; cross section 3 x 3 mm; prepared by the Czochralski method; electrical resistivity 11 ohm cm.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
84	1291	Seyfert, P.	1967		2.8-73		The above specimen irradiated at 80 K by a fast neutron (1 MeV) flux of 4.3 x 10^{17} cm^{-2}.
85	1291	Seyfert, P.	1967		4.0-112		The above specimen annealed at 20 C for 2 hrs.
86*	1291	Seyfert, P.	1967		4.3-105		B-doped p-type single crystal; oxygen concentration ~10^{18} cm^{-3}; boron concentration ~10^{14} cm^{-3}; cross section 3 x 3 mm; prepared by the Czochralski method; electrical resistivity 150 μohm cm.
87	1291	Seyfert, P.	1967		2.7-79		The above specimen irradiated at 80 K for a fast neutron (1 MeV) flux of 4.3 x 10^{17} cm^{-2}.
88	992	Morris, R. G. and Delinger, W. G.	1965	C	308-473		p-type single crystal; impurity concentration 2 x 10^{15} atoms cm^{-3}; supplied by Battelle Memorial Institute; specimen about 8 mm thick by 12 mm in dia; Armco iron used as comparative material.
89	1300	Shashkov, Yu. M. and Grishin, V. P.	1966	→	<1684		Thermal conductivity of the solid near the melting point determined from heat balance at crystallization front in Czochralski method; melting point 1411 ± 1 C.
90	1300	Shashkov, Yu. M. and Grishin, V. P.	1966	→	>1684		The above specimen and method used for determination in liquid state.
91	974	Mil'vidskii, M. G. and Eremeev, V. V.	1964	→	1685		Thermal conductivity determined based on utilization of the equation of heat balance at phase separation boundary; measuring temp assumed 1412 C as the melting point taken by TPRC.
92*	974	Mil'vidskii, M. G. and Eremeev, V. V.	1964	→	1685		The above specimen in liquid state.
93*	1004	Moyer, D. F.	1962	L	2.1-3.8		Single crystal; obtained from P. R. Mallory and Co., Inc.; form factor ℓ/A = 54.7 cm^{-1}; electrical resistivity 700 ohm cm at room temp.
94*	1246	Sawin, F.	1962	L	2.6-5.0	20	Form factor 41.43 cm^{-1}; nickel-plated; measured in a vacuum of 5 x 10^{-5} mm Hg.
95	1246	Sawin, F.	1962	L	4.5-51	1015	In-doped; obtained from Texas Instrument, Inc.; form factor 29.1 cm^{-1}; nickel-plated; carrier concentration 10^{15} cm^{-3}; measured in a vacuum of 5 x 10^{-5} mm Hg; run 18.
96*	1246	Sawin, F.	1962	L	80-222	1015	The above specimen; run 19.
97*	1246	Sawin, F.	1962	L	2.4-4.4	1015	The above specimen; run 20.
98*	1246	Sawin, F.	1962	L	5.2-29	2822	B-doped; obtained from Texas Instrument, Inc.; form factor 20.3 cm^{-1}; nickel-plated; electrical resistivity 145 ohm cm; measured in a vacuum of 5 x 10^{-5} mm Hg; run 15.
99*	1246	Sawin, F.	1962	L	68-211	2822	The above specimen; run 16.
100*	1246	Sawin, F.	1962	L	74-223	2822	The above specimen; run 17.
101	1246	Sawin, F.	1962	L	4.7-156	4100	Hyperpure; obtained from DuPont; form factor 26.4 cm^{-1}; electrical resistivity 4100 ohm cm; measured in a vacuum of 5 x 10^{-5} mm Hg.
102	624	Holland, M. G. and Neuringer, L. J.	1962	L	2.0-265	1 M	Impurities: 1.0 x 10^{13} cm^{-3} B and 3.7 x 10^{11} cm^{-3} P; single crystal; 1.25 x 0.248 x 0.239 in.
103	624	Holland, M. G. and Neuringer, L. J.	1962	L	1.8-74	2 M	Impurities: 4.2 x 10^{14} cm^{-3} B and 1.6 x 10^{13} cm^{-3} P; single crystal; 1.25 x 0.249 x 0.243 in.
104*	624	Holland, M. G. and Neuringer, L. J.	1962	L	1.7-287	3 M	Impurities: 4.0 x 10^{15} cm^{-3} B and 4.3 x 10^{13} cm^{-3} P; single crystal; 1.25 x 0.231 x 0.231 in.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
105*	624	Holland, M. G. and Neuringer, L. J.	1962	L	1.7-249	9 M	Impurities: 1.0 x 10^{15} cm^{-3} B and 3.9 x 10^{14} cm^{-3} P; single crystal; 1.25 x 0.249 x 0.244 in.
106	624	Holland, M. G. and Neuringer, L. J.	1962	L	2.2-282	12 M	Impurities: 4.0 x 10^{16} cm^{-3} B and <1.0 x 10^{15} cm^{-3} P; single crystal; 1.25 x 0.247 x 0.246 in.
107	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 26	2 M-s	Impurities: 4.2 x 10^{14} cm^{-3} B and 1.6 x 10^{13} cm^{-3} P; single crystal; 1.25 x 0.138 x 0.136 in.
108*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	RA47	Impurities: 1.1 x 10^{18} cm^{-3} O, 9.7 x 10^{14} cm^{-3} B, and 3 x 10^{14} cm^{-3} As or P; single crystal; 1.25 x 0.242 x 0.238 in.
109*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 31	T 1	Impurities: 4 x 10^{15} cm^{-3} Al and ~10^{14} cm^{-3} B; single crystal; 1.25 x 0.256 x 0.250 in.
110*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 29	T 2	Impurities: 3 x 10^{15} cm^{-3} Ga and ~10^{14} cm^{-3} B; single crystal; 1.25 x 0.253 x 0.250 in.
111*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 37	T 4	Impurities: 3.5 x 10^{15} cm^{-3} In, ~4 x 10^{14} cm^{-3} B, 4 x 10^{14} cm^{-3} P, and ~2 x 10^{14} cm^{-3} Ga; single crystal; 1.25 x 0.253 x 0.247 in.
112*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	C-Si-337	Impurities: 9 x 10^{17} cm^{-3} O, ~1 x 10^{14} cm^{-3} Mn, 1 x 10^{14} cm^{-3} As or P, and some B; single crystal; 1.25 x 0.111 x 0.110 in.
113*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	4 M	Impurities: 3.8 x 10^{13} cm^{-3} P and 2.3 x 10^{13} cm^{-3} B; single crystal; 1.25 x 0.249 x 0.246 in.
114*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	6 M	Impurities: 1.1 x 10^{15} cm^{-3} P and 1.7 x 10^{13} cm^{-3} B; single crystal; 1.25 x 0.252 x 0.250 in.
115*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	18 M	Impurities: 2.5 x 10^{15} cm^{-3} As and ~1 x 10^{13} cm^{-3} B; single crystal; 1.25 x 0.252 x 0.248 in.
116*	624	Holland, M. G. and Neuringer, L. J.	1962	L	3, 22	T 3	Impurities: 1.9 x 10^{15} cm^{-3} Sb and 6.8 x 10^{14} cm^{-3} As or B; single crystal; 1.25 x 0.252 x 0.250 in.
117*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	85-241		n-type; cross-section 6 mm^2; iron used as comparative material.
118*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	83-241		The above specimen irradiated by fast neutron with a dose of 1.2 x 10^{18} n cm^{-2} at 70 C for 15 hrs.
119	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	87-247		The above specimen annealed at 133 C for 1 hr.
120*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	80-288		The above specimen again annealed at 166 C for 1 hr.
121	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	84-246		The above specimen again annealed at 200 C for 1 hr.
122*	29, 31	Albany, H. J. and Vandevyver, M	1963	C	82-256		The above specimen again annealed at 233 C for 1 hr.
123*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	88-241		The above specimen again annealed at 266 C for 1 hr.
124*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	84-185		The above specimen again annealed at 300 C for 1 hr.
125*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	83-116		The above specimen again annealed at 333 C for 1 hr.
126*	29, 31	Albany, H. J. and Vandevyver, M.	1963	C	82-100		The above specimen again annealed at 366 C for 1 hr and at 400 C for 1 hr.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
127	1011	Nakamura, T.	1965	L	293.2		1.2 x 1 x 1 cm; prepared from 99.99 pure commercial silicon powder of grain size 44 μ by pressing under 0.5~20 ton cm^{-2}, sintered in a vacuum of 10^{-5} mm Hg at 1250 C for 4 hrs, cooled rapidly, polished; porosity 30.8%; electrical conductivity 3.69 x 10^{-4} ohm^{-1} cm^{-1}.
128	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 32.2% and electrical conductivity 2.62 x 10^{-4} ohm^{-1} cm^{-1}.
129	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 33.0% and electrical conductivity 2.76 x 10^{-4} ohm^{-1} cm^{-1}.
130	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 34.7% and electrical conductivity 1.16 x 10^{-4} ohm^{-1} cm^{-1}.
131*	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 35.6% and electrical conductivity 2.07 x 10^{-4} ohm^{-1} cm^{-1}.
132	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 36.6% and electrical conductivity 2.85 x 10^{-4} ohm^{-1} cm^{-1}.
133	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 37.6% and electrical conductivity 1.25 x 10^{-4} ohm^{-1} cm^{-1}.
134	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 38.6% and electrical conductivity 1.48 x 10^{-4} ohm^{-1} cm^{-1}.
135	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 38.7% and electrical conductivity 3.92 x 10^{-4} ohm^{-1} cm^{-1}.
136*	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 40.6% and electrical conductivity 1.37 x 10^{-4} ohm^{-1} cm^{-1}.
137*	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 42.8% and electrical conductivity 2.36 x 10^{-4} ohm^{-1} cm^{-1}.
138	1011	Nakamura, T.	1965	L	293.2		Similar to above but porosity 43.6% and electrical conductivity 2.92 x 10^{-4} ohm^{-1} cm^{-1}.
139*	1459, 1461	Vandevyver, M. and Albany, H. J.	1967	L	5.1-280		P-doped single crystal; rod specimen of cross-section 4 x 2 mm with specimen axis along the <111> direction; electrical resistivity 0.35 ohm cm at room temp.
140*	"	Vandevyver, M. and Albany, H. J.	1967	L	7.4-70		The above specimen irradiated at ~40 C with a dose of 1 x 10^{18} electrons cm^{-2}.
141	564	Gulevskaya, A. S., Lipatova, V. A., and Gel'd, P. V.	1961	L	293.2	KR-0	Commercial silicon, as used to produce p-type β-lebeauite; 2.5 to 3.5 mm dia and 26 to 30 mm long.
142	564	Gulevskaya, A. S., et al.	1961	L	293.2	KM-1	Pure silicon, as used to produce n-type β-lebeauite; 2.5 to 3.5 mm dia and 26 to 30 mm long.
143*	620	Holland, M. G.	1960	L	9.0-247	B 3	n-type single crystal; 6.20 x 6.11 mm in cross-section; oxygen concentration 1.3 x 10^{18} cm^{-3}; room temp carrier concentration 7.8 x 10^{14}; electrical resistivity 5.5 ohm cm at room temp.
144*	620	Holland, M. G.	1960	L	12-197	B 3-HT 1	n-type single crystal; 6.20 x 6.13 mm in cross-section; heat-treated at 1000 C for 40 hrs; oxygen concentration 3 x 10^{17} cm^{-3}; room temp carrier concentration 7.8 x 10^{14}; electrical resistivity 5.5 ohm cm at room temp.
145*	620	Holland, M. G.	1960	L	5.8-155	S 1 - HT 1	p-type single crystal; 6.12 x 6.10 mm in cross-section; heat-treated at 1000 C for 40 hrs; room temp carrier concentration 4.8 x 10^{15} cm^{-3}; oxygen concentration 7 x 10^{17} cm^{-3}; electrical resistivity 3.0 ohm cm at room temp.
146*	620	Holland, M. G.	1960	L	16-233	X 1 HT 2	p-type single crystal; 6.05 x 5.88 mm in cross-section; heat-treated at 1000 C for 200 hrs; room temp carrier concentration 4.8 x 10^{15} cm^{-3}; oxygen concentration 3.5 x 10^{17} cm^{-3}; electrical resistivity 3.0 ohm cm at room temp.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
147*	620	Holland, M. G.	1960	L	12-266	S 1-HT 3	p-type single crystal; 5.73 x 5.65 mm in cross-section; heat-treated at 1350 C for 0.5 hr; room temp carrier concentration 4.8 x 10^{15} cm^{-3}; oxygen concentration 6 x 10^{17} cm^{-3}; electrical resistivity 3.0 ohm cm at room temp.
148*	620	Holland, M. G.	1960	L	12-189	R-17	p-type single crystal; 6.35 x 6.23 mm in cross-section; room temp carrier concentration 1.1 x 10^{15} cm^{-3}; oxygen concentration 1.1 x 10^{18} cm^{-3}; electrical resistivity 15 ohm cm at room temp.
149*	1080	Perron, J. C.	1961	P	300		3 cm long; measured by Angström's method.
150	945	Mette, H., Gärtner, W. W., and Loscoe, C.	1960	→	552-746		p-type; electrical resistivity 81 ohm cm; thermal conductivity values calculated from measured Nernst coefficient and Ettingshausen coefficient using the Bridgman relation; measured in a magnetic field of 9000 gauss.
151	945	Mette, H., et al.	1960	→	551-775		Similar to above but electrical resistivity 22 ohm cm.
152	945	Mette, H., et al.	1960	→	575-714		Similar to above but electrical resistivity 0.96 ohm cm.
153	945	Mette, H., et al.	1960	→	671-752		Similar to above but electrical resistivity 0.22 ohm cm.
154	123	Bean, K. E., Hentzschel, H. P., and Colman, D.	1969	C	333-393	Sample A	p-type; polycrystalline; apparent carrier concentration 2.8 x 10^{11} cm^{-3}; electrical resistivity 5.2 x 10^{4} ohm cm at 24 C; heat flow measured parallel to grain.
155	123	Bean, K. E., et al.	1969	C	333-393	Sample B	p-type; polycrystalline; apparent carrier concentration 5.8 x 10^{11} cm^{-3}; electrical resistivity 3.2 x 10^{5} ohm cm at 24 C; heat flow measured perpendicular to grain.
156*	123	Bean, K. E., et al.	1969	C	333-393	Sample C	Similar to the above specimen except apparent carrier concentration 2.1 x 10^{11} cm^{-3} and electrical resistivity 5.9 x 10^{5} ohm cm at 24 C.
157	364	Dismukes, J. P., Ekstrom, L., Steigmeier, E. F., Kudman, I., and Beers, D. S.	1964	L	300		1 cm cubic specimen; carrier concentration ≤2 x 10^{18} cm^{-3}.
158	1459	Vandevyver, M.	1968	L	5.9-87		The specimen for curve No. 72 annealed at 100 C for 1 hr.
159	1459	Vandevyver, M.	1968	L	6.0-82		The above specimen annealed again at 130 C for 1 hr.
160	1459	Vandevyver, M.	1968	L	5.4-158		The above specimen annealed again at 160 C for 1 hr.
161	1459	Vandevyver, M.	1968	L	5.9-156		The above specimen annealed again at 190 C for 1 hr.
162	1459	Vandevyver, M.	1968	L	5.6-86		The above specimen annealed again at 220 C for 1 hr.
163	1459	Vandevyver, M.	1968	L	5.1-96		The above specimen annealed again at 250 C for 1 hr.
164*	1459	Vandevyver, M.	1968	L	5.5-88		The above specimen annealed again at 280 C for 1 hr.
165*	1459	Vandevyver, M.	1968	L	5.4-79		The above specimen annealed again at 310 C for 1 hr.
166*	1459	Vandevyver, M.	1968	L	5.2-72		The above specimen annealed again at 340 C for 1 hr.
167*	1459	Vandevyver, M.	1968	L	5.0-82		The above specimen annealed again at 370 C for 1 hr.
168*	1459	Vandevyver, M.	1968	L	5.2-80		The above specimen annealed again at 400 C for 1 hr.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
169*	1459	Vandevyver, M.	1968	L	5.1–74		The above specimen annealed again at 430 C for 1 hr.
170*	1459	Vandevyver, M.	1968	L	5.2–69		The above specimen annealed again at 490 C for 1 hr.
171*	1459	Vandevyver, M.	1968	L	5.3–67		The above specimen annealed again at 550 C for 1 hr.
172*	1459	Vandevyver, M.	1968	L	5.2–68		The above specimen annealed again at 580 C for 1 hr.
173*	1459	Vandevyver, M.	1968	L	5.4–98		The above specimen annealed again at 640 C for 1 hr.
174*	1459	Vandevyver, M.	1968	L	5.5–56		Similar to the above specimen with all the heat-treatment but never irradiated.
175	645	Hurst, W. S.	1968	L	1.7–4.5	Sample 1-1A; run 20	p-type; specimen 2.17 x 2.17 x 21 mm; manufactured by Knapic Electro-Physics Corp; cut from ingot A with the rod axis in (111) direction exposed two (110) and two $(11\bar{2})$ rod faces; lapped surfaces prepared with 10 μ Al_2O_3; electrical resistivity 195 ohm cm at room temp; dislocation density 750 pits cm^{-2}.
176*	645	Hurst, W. S.	1968	L	2.3–4.5	Sample 1-1A; run 21	The above specimen, different run.
177*	645	Hurst, W. S.	1968	L	2.5–3.8	Sample 1-17A; run 41	Cut in the same way from the same ingot A as the above specimen; 2.81 x 0.729 x 30.0 mm; same surface treatment as above.
178*	645	Hurst, W. S.	1968	L	2.0–3.6	Sample 1-17A; run 42	The above specimen, different run.
179*	645	Hurst, W. S.	1968	L	1.3–3.6	Sample 1-5A; run 43	Similar to the above specimen but dimensions 0.996 x 0.996 x 32.0 mm.
180	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 1-6A; run 44	Similar to the above specimen but dimensions 0.508 x 0.544 x 36.8 mm.
181*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 1-5B; run 45	Similar to the above specimen but dimensions 0.876 x 0.826 x 32.0 mm and lapped surfaces prepared with 1 μ diamond polishing compound, then 60 sec CP4-A etch.
182*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 1-7A; run 47	Similar to the above specimen except dimensions 0.523 x 0.577 x 25.0 mm and lapped surfaces prepared with 10 μ Al_2O_3.
183	645	Hurst, W. S.	1968	L	1.4–4.1	Sample 1-8A; run 48	Similar to the above specimen except dimensions 0.650 x 0.62 x 42.3 mm.
184*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 1-9A; run 49	Similar to the above specimen except dimensions 0.528 x 0.546 x 27.3 mm and lapped surfaces prepared with 1 μ diamond polishing compound, then Lustrox on Politex Pix for 90 sec, followed by 30 sec CP4-A etch.
185*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 1-9B; run 50	Similar to the above specimen except dimensions 0.508 x 0.490 x 27.3 mm and lapped surfaces prepared by 30 sec CP4-A etch.
186*	645	Hurst, W. S.	1968	L	1.4–4.2	Sample 1-10A; run 51	Similar to the above specimen except dimensions 3.015 x 2.733 x 4.22 mm and lapped surfaces prepared with 5 μ Al_2O_3.
187*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 1-11A;	Similar to the above specimen except dimensions 0.541 x 0.584 x 21.6 mm and lapped surfaces prepared with 1 μ diamond polishing compound, 2 min Lustrox on Pellon.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
188*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 1-11C; run 54	Similar to the above specimen except dimensions 0.503 x 0.549 x 21.6 mm and lapped surfaces prepared by 30 sec CP4-A etch.
189*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 1-12A; run 67	Similar to the above specimen except dimensions 1.02 x 0.861 x 42.5 mm and lapped surfaces prepared with 1 μ diamond polishing compound.
190*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 1-12B; run 68	60 sec Lustrox 1200 on Politex Supreme of No. 1-12A.
191*	645	Hurst, W. S.	1968	L	1.3–4.2	Sample 1-13A; run 83	Cut from the same ingot A as the above specimen; all exposed faces with (110); hexagonal cross section with dia of inscribed circle = 2.11 mm and 42.2 mm long; lapped surfaces prepared with 5 μ Al_2O_3.
192	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 1-17A; run 86	Cut from the same ingot A as the above specimen with exposed (110) on wide face and $(11\bar{2})$ on narrow face; 0.457 x 2.99 x 42.5 mm; lapped surfaces prepared with 10 μ Al_2O_3.
193*	645	Hurst, W. S.	1968	L	1.4–4.1	Sample 1-14A; run 93	Similar to the above specimen except dimensions 0.389 x 3.57 x 42.5 mm and lapped. surfaces prepared with 20 μ Al_2O_3.
194*	645	Hurst, W. S.	1968	L	1.4–4.1	Sample 1-14A; run 99	The above specimen, different run.
195*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 1-15A; run 98	Similar to the above specimen except dimensions 0.544 x 3.96 x 42.0 mm.
196*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 1-16A; run 97	Cut from the same ingot As as the above specimen exposed two (110) and two $(11\bar{2})$ rod faces; 0.902 x 0.838 x 39.0 mm.
197*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 2-1A; run 55	n-type; 0.874 x 0.843 x 46.7 mm; manufactured by Futurecraft Corp; cut from ingot B with the rod axis in (100) direction and all exposed faces (100); lapped surfaces prepared with 1 μ diamond polishing compound; electrical resistivity 500 ohm cm at room temp.
198	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 2-2A; run 57	Cut in the same way from the same ingot B as the above specimen; 0.823 x 0.810 x 38.0 mm; lapped surfaces prepared with 10 μ Al_2O_3.
199*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 2-1C; run 58	Similar to the above specimen except dimensions 0.874 x 0.843 x 42.8 mm and lapped surfaces prepared by 30 sec CP4-A etch.
200	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 3-1A; run 59	Cut from the same ingot B as the above specimen; 0.894 x 0.856 x 41.5 mm; all exposed faces (110); lapped surfaces prepared with 1 μ diamond polishing compound.
201*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 2-1D; run 60	Cut from the same ingot B as the above specimen; 0.833 x 0.866 x 41.3 mm; all exposed faces (100); lapped surfaces prepared with 1 μ diamond polishing compound then 3 min Lustrox 1200 on Politex Supreme.
202*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 3-1B; run 61	Cut from the same ingot B as the above specimen; 0.894 x 0.856 x 41.5 mm; all exposed faces (110); lapped surfaces prepared by 3 min Lustrox 1200 on Politex Supreme.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
203*	645	Hurst, W. S.	1968	L	1.4–4.0	Sample 2-1E; run 62	30 sec CP4-A etch of sample No. 2-1D.
204*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 3-3A; run 63	Cut from the same ingot B as the above specimen; 0.902 x 0.853 x 42.5 mm; all exposed faces (110); lapped surfaces prepared with 1 μ diamond polishing compound then 60 sec Lustrox on Politex Pix.
205*	645	Hurst, W. S.	1968	L	1.5–4.0	Sample 2-3A; run 69	Cut from the same ingot B as the above specimen; 0.843 x 0.859 x 46.6 mm; all exposed faces (100); lapped surfaces prepared with 1 μ diamond polishing compound, then 30 sec of Lustrox 1000 and 30 sec Lustrox 1200 on Politex Pix.
206*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 3-4A; run 70	Similar to the above specimen except dimensions 0.844 x 0.851 x 45.5 mm and lapped surfaces prepared with 1 μ diamond polishing compound, then 0.1 μ Gamal on Fisher polisher, then 60 sec Lustrox 1000 on Politex Pix.
207*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 3-5A; run 76	Cut from the same ingot B as the above specimen; 0.826 x 0.815 x 41.5 mm; all exposed faces (110); lapped surfaces prepared with 5 μ Al_2O_3.
208*	645	Hurst, W. S.	1968	L	1.3–3.9	Sample 3-5B; run 84	Similar to the above specimen except dimensions 0.704 x 0.676 x 42.0 mm and lapped surfaces prepared with 9 μ SiC.
209	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 4-1A; run 64	n-type; 0.749 x 0.927 x 44.5 mm; manufactured by Semi-Elements, Inc.; cut from ingot C with the rod axis in (100) direction and all exposed faces with (100); lapped surfaces prepared with 1 μ diamond polishing compound; electrical resistivity 3000 ohm cm at room temp.
210*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 4-1B; run 66	45 sec Lustrox 1200 on Politex Supreme of sample No. 4-1A.
211*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 4-2A; run 71	Similar to the above specimen except dimensions 0.929 x 0.752 x 44.5 mm and lapped surfaces prepared same as run 70.
212*	645	Hurst, W. S.	1968	L	1.4–4.2	Sample 4-3A; run 72	Similar to the above specimen except dimensions 0.696 x 0.732 x 44.5 mm and lapped surfaces prepared with 5 μ Al_2O_3.
213*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 5-1A; run 73	Cut from the same ingot B as the above specimen; 0.826 x 0.841 x 42.5 mm; all exposed faces with (110); lapped surfaces prepared same as run 70.
214*	645	Hurst, W. S.	1968	L	1.3–4.0	Sample 5-2A; run 74	Similar to the above specimen except dimensions 0.818 x 0.767 x 39.5 mm and lapped surfaces prepared with 1 μ diamond polishing compound, then 60 sec Lustrox on Politex Pix.
215*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 5-3A; run 75	Similar to the above specimen except dimensions 0.709 x 0.721 x 33.9 mm and lapped surfaces prepared with 5 μ Al_2O_3.
216*	645	Hurst, W. S.	1968	L	1.4–4.1	Sample 5-4A; run 77	Similar to the above specimen except dimensions 0.475 x 0.470 x 39.7 mm and lapped surfaces prepared same as run 74 except all polishing done with motion along length of rod only.
217*	645	Hurst, W. S.	1968	L	1.3–4.1	Sample 5-5A; run 78	Similar to the above specimen except dimensions 1.98 x 1.93 x 40.5 mm and lapped surfaces prepared with 5 μ Al_2O_3.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
218	645	Hurst, W.S.	1968	L	1.3-4.0	Sample 5-4B; run 79	Similar to the above specimen except dimensions 0.467 x 0.467 x 39.7 mm and surfaces prepared with mechanical polish of 5-4A to 1 μ, then 30 sec Lustrox 1000 using rotary polishing motion.
219*	645	Hurst, W.S.	1968	L	1.3-4.1	Sample 5-7A; run 81	Similar to the above specimen except dimensions 0.218 x 0.823 x 27.5 mm and lapped surfaces prepared with 1 μ diamond polishing compound, then 30 sec Lustrox on Politex Pix.
220	645	Hurst, W.S.	1968	L	1.4-4.2	Sample 5-5B; run 82	Similar to the above specimen except dimensions 1.66 x 1.96 x 40.5 mm and lapped surfaces prepared same as run 81.
221*	645	Hurst, W.S.	1968	L	1.4-4.2	Sample 6-1A; run 85	Cut from the same ingot C as the above specimen; 0.960 x 0.935 x 24.0 mm; rod axis cut in (111) direction exposed two (110) and two $(11\bar{2})$ rod faces; lapped surfaces prepared with 9 μ SiC lap.
222	645	Hurst, W.S.	1968	L	1.3-4.1	Sample 5-1B; run 87	Cut from the same ingot C as the above specimen; 0.826 x 0.841 x 34.1 mm; rod axis cut in (100) direction and all exposed faces with (110); lapped surfaces prepared same as run 73.
223*	645	Hurst, W.S.	1968	L	1.3-4.1	Sample 5-1C; run 88	Similar to the above specimen except dimensions 0.826 x 0.841 x 28.8 mm.
224*	645	Hurst, W.S.	1968	L	1.3-4.2	Sample 5-1D; run 89	Similar to the above specimen except dimensions 0.826 x 0.841 x 21.3 mm.
225*	645	Hurst, W.S.	1968	L	1.4-3.6	Sample 5-3C; run 94	Similar to the above specimen except dimensions 0.709 x 0.721 x 25.5 mm and lapped surfaces prepared with 10 μ Al_2O_3, then annealed in N_2 atm.
226*	645	Hurst, W.S.	1968	L	1.4-4.0	Sample 5-2B; run 95	Specimen No. 5-2A (see curve No. 214) ion-bombarded at surfaces.
227*	645	Hurst, W.S.	1968	L	1.4-4.1	Sample 5-2C; run 96	Specimen No. 5-2B (see curve No. 226) annealed in vacuum.
228*	645	Hurst, W.S.	1968	L	1.4-4.1	Sample 7-1A; run 90	Cut from the same ingot C as the above specimen; 0.894 x 0.843 x 19.0 mm; rod axis cut in (110) direction exposed two (110) and two (100) rod faces; lapped surfaces prepared with 10 μ Al_2O_3.
229*	645	Hurst, W.S.	1968	L	1.4-4.0	Sample 7-2A; run 91	Similar to the above specimen except dimensions 0.889 x 0.864 x 19.3 mm.
230*	87	Arasly, D.G. and Aliev, M.I.	1966		144-485		As-doped; carrier concentration 1×10^{16} cm^{-3}.
231	87	Arasly, D.G. and Aliev, M.I.	1966		117-494		As-doped; carrier concentration 8×10^{19} cm^{-3}.
232*	87	Arasly, D.G. and Aliev, M.I.	1966		213-501		Sb-doped; carrier concentration 1.1×10^{18} cm^{-3}.
233*	87	Arasly, D.G. and Aliev, M.I.	1966		140		As-doped; thermal conductivity data reported as a function versus the carrier concentration.

* Not shown in figure.

TABLE 145. THERMAL CONDUCTIVITY OF SILICON - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
234*	87	Arasly, D.G. and Aliev, M.I.	1966		300		P-doped; thermal conductivity data reported as a function versus the carrier concentration.
235*	87	Arasly, D.G. and Aliev, M.I.	1966		480		Sb-doped; thermal conductivity data reported as a function versus the carrier concentration.

* Not shown in figure.

Silver

At low temperatures the recommended curve for a sample having residual electrical resistivity $\rho_0 = 0.000621$ $\mu\Omega$ cm is based on the data of White [1537] (curve 14). The values below about 1.5 T_m are calculated to fit the experimental data by using equation (7) and using the constants m, n, and α'' as listed in table 1 and the parameter $\beta = 0.0254$. The curve has been extended to follow White's data to about 50 K.

Seven determinations have been made of the thermal conductivity of silver at temperatures above 373 K. Bailey [106] (curve 5) extended the measurements on Lee's specimen to higher temperatures, but this sample was clearly not of the highest purity. The minimum value obtained at 660 K is very questionable. Evans [413] (curve 83) and Mikryukov [964] (curve 49) obtained values which decreased steadily with increase in temperature at comparable rates. Whereas the purity of the sample studied by Evans was stated to be only 99.4 percent, that of Mikryukov was 99.99 percent. Moreover, the latter worker included electrical resistivity data which agree with the values for high purity silver. From room temperature to 373 K other workers, including Lees [830] (curve 10) and Jaeger and Diesselhorst [664] (curve 4) have obtained Lorenz functions for silver in the range 2.31×10^{-8} to 2.39×10^{-8} whereas Mikryukov's value at 338 K is 2.45×10^{-8} V^2 K^{-2}. This is why the earlier recommended curve, which was derived in 1965 and published in [1126] had been drawn below that of Mikryukov in this region. The earlier recommended curve also agrees reasonably well with the data of other named workers after allowance has been made for the electrical conductivities of their samples being less than that of pure silver. The recent measurements of Laubitz [818] (curve 81) agree well with the earlier recommendations and his data lie less than 2 percent above the earlier recommended curve over the whole range of his measurement temperatures up to 1072 K. The earlier recommended curve above room temperature has now been slightly modified to be 1 to 2 percent higher, so as to pass through Laubitz's recent data, and becomes the present recommended curve.

The uncertainty of the recommended values is about ±2 percent near room temperature and increases to about ±5 percent below 100 K and above 1000 K. The values below 150 K are applicable only to silver having $\rho_0 =$ 0.000621 $\mu\Omega$ cm.

No experimental data are available for the thermal conductivity of molten silver. The provisional values are based on the estimation up to the critical point by Grosse [546] (curve 85) from derived values for the electrical conductivity and assuming the theoretical Lorenz number to hold throughout the range. These values are probably good to ±20 percent from the melting point to 2000 K.

TABLE 146. Recommended thermal conductivity of silver†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid				Liquid			
T	*k*	*T*	*k*	*T*	*k*	*T*	*k*
0	0	123.2	4.36	1235.08	1.75*	3273	1.85*
1	39.4	150	4.32	1273.2	1.77*	3400	1.82*
2	78.3	173.2	4.31	1300	1.78*	3473	1.79*
3	115	200	4.30	1373.2	1.82*	3600	1.76*
4	147	223.2	4.30	1400	1.83*	3673	1.74*
5	172	250	4.29	1473.2	1.86*	3800	1.70*
6	187	273.2	4.29	1500	1.87*	3873	1.68*
7	193	298.2	4.29	1573.2	1.89*	4000	1.63*
8	190	300	4.29	1600	1.90*	4073	1.61*
9	181	323.2	4.28	1673.2	1.92*	4273	1.54*
10	168	350	4.27	1700	1.93*	4500	1.45*
11	154	373.2	4.26	1773.2	1.94*	4773	1.33*
12	139	400	4.25	1800	1.95*	5000	1.23*
13	124	473.2	4.20	1873.2	1.96*	5273	1.11*
14	109	500	4.19	1900	1.96*	5500	1.01*
15	96	573.2	4.14	1973.2	1.97*	5773	0.875*
16	85	600	4.12	2000	1.97*	6000	0.764*
18	66	673.2	4.07	2073.2	1.98*	6273	0.628*
20	51	700	4.04	2173.2	1.98*	6500	0.514*
25	29.5	773.2	3.99	2200	1.98*	6773	0.373*
30	19.3	800	3.96	2273.2	1.99*	7000	0.251*
35	13.7	873.2	3.90	2400	1.98*	7273	0.104*
40	10.5	900	3.88	2473.2	1.98*		
45	8.4	973.2	3.82	2600	1.97*		
50	7.0	1000	3.79	2673.2	1.96*		
60	5.30	1073.2	3.73*	2800	1.95*		
70	4.82	1100	3.70*	2873.2	1.94*		
80	4.64	1173.2	3.63*	3000	1.91*		
90	4.51	1200	3.61*	3073	1.90*		
100	4.44	1235.08	3.58*	3200	1.87*		

†The values are for well-annealed high-purity silver, and those below 150 K are applicable only to a specimen having residual electrical resistivity of 0.000621 μΩ cm. The values for molten silver are provisional.

*Extrapolated or estimated.

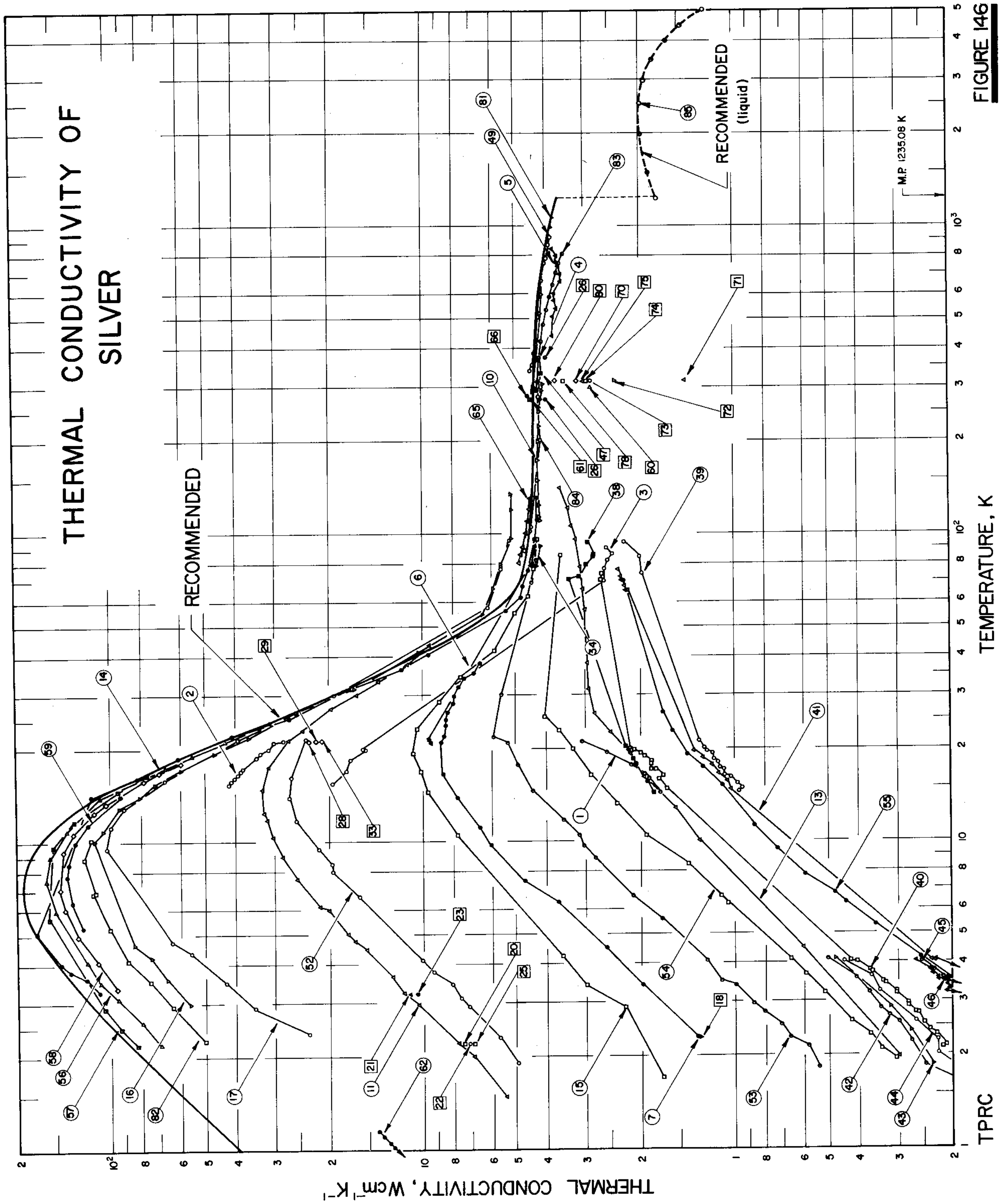

THERMAL CONDUCTIVITY OF SILVER
RECOMMENDED
RECOMMENDED (liquid)
M.P. 1235.08 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 146

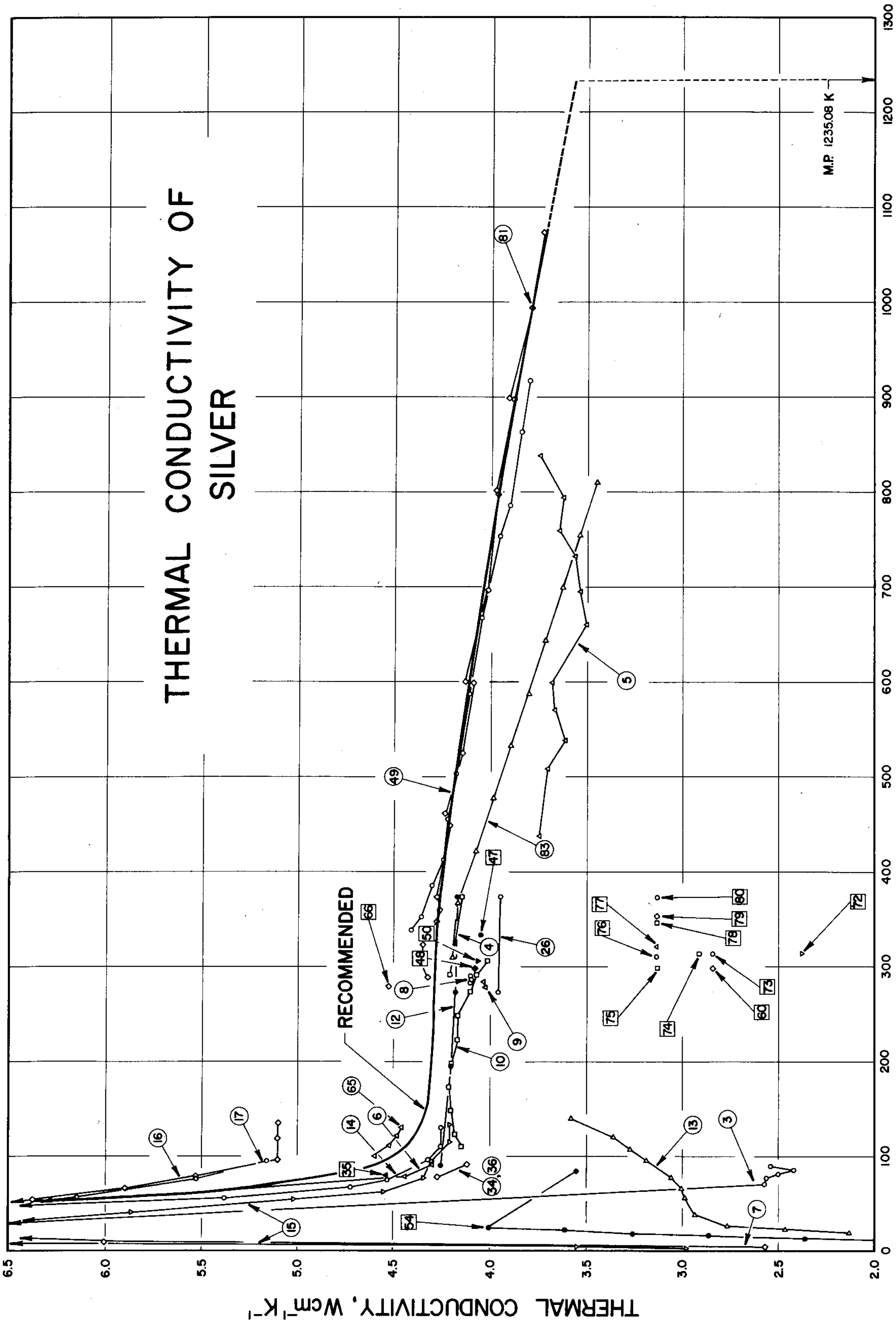

THERMAL CONDUCTIVITY OF SILVER
RECOMMENDED
M.P. 1235.08 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 147

TABLE 147. THERMAL CONDUCTIVITY OF SILVER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	487	Gerritsen, A. N. and Linde, J. O.	1956	L	14-21	Ag 2	Commercially pure; supplied by Nordiska Affiveriet, Hälsingborg; cold-worked; electrical resistivity ratio $\rho(273K)/\rho_0$ = 38.4.
2	487	Gerritsen, A. N. and Linde, J. O.	1956	L	15-21	Ag 2t	The above specimen etched and annealed at 740 K; electrical resistivity reported as 0.00447, 0.00519, 0.00619, 0.00743, 0.238, 0.297, 0.359, and 1.47 μohm cm at 14, 16, 18, 20, 70, 80, 90, and 273 K, respectively; electrical resistivity ratio $\rho(273K)/\rho_0$ = 417.
3	487	Gerritsen, A. N. and Linde, J. O.	1956	L	16-90	Ag 4t	Similar to the above specimen but annealed at 750 K; electrical resistivity reported as 0.00694, 0.00758, 0.00852, 0.00983, 0.235, 0.299, 0.363, and 1.48 μohm cm at 14, 16, 18, 20, 70, 80, 90, and 273 K, respectively; electrical resistivity ratio $\rho(273K)/\rho_0$ = 250.
4	664	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373		99.98 pure; 1.1086 cm dia x 25.2 cm long; density 10.53 g cm^{-3} at 18 C; electrical conductivity reported as 61.4 and 46.9 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
5	106	Bailey, L. C.	1931	L	437-838		99.9 pure; 0.585 cm dia x 7-8 cm long; melting point 961 C; same specimen as used by Lees (curve 10).
6	561	Grüneisen, E. and Reddemann, H.	1934	L	21-91	Ag 1	Pure; cold-worked and annealed at 350 C for 2 hrs.
7	937, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-38	JM 1722; Ag 1	99.99 pure; polycrystalline wire; 1.22 mm dia x 2.85 cm long; supplied by Johnson, Matthey and Co., Ltd.; $\rho(293K)/\rho(20K)$ = 30.9.
8	702	Kannuluik, W. G.	1931	E	283-291	Ag 1	Commercially pure electrolytic silver; 0.05286 cm dia x 8.82 cm long; electrical conductivity 64.6 x 10^4 ohm^{-1} cm^{-1} at 273 K; Lorenz function 2.32 x 10^{-8} V^2 K^{-2} at 273 K.
9	702	Kannuluik, W. G.	1931	E	278-284	Ag II	Spectroscopically pure; 0.05059 cm dia x 8.74 cm long; electrical conductivity 61.2 x 10^4 ohm^{-1} cm^{-1} at 273 K; Lorenz function 2.41 x 10^{-8} V^2 K^{-2} at 273 K.
10	830	Lees, C. H.	1908	L	110-306		99.9 pure; 0.585 cm dia x 7-8 cm long; density 10.47 g cm^{-3} at 21 C; electrical resistivity reported as 0.460, 0.470, 0.456, 0.609, 0.660, 0.693, 0.880, 0.923, 0.942, 1.236, 1.239, 1.245, 1.468, 1.471, 1.675, and 1.684 μohm cm at -178.3, -177.7, -176.1, -151.2, -144.9, -139.2, -109.0, -102.5, -98.6, -54.9, -52.8, -50.6, -13.0, -12.0, 21.0, and 21.3 C, respectively.
11	1220	Rosenberg, H. M.	1955	L	1.5-44	JM 3351; Ag 2	99.99⁺ pure; polycrystalline; 1.33 mm dia x 2.8 cm long; supplied by Johnson, Matthey; prepared from a 5 mm rod by rolling and drawing; annealed in vacuo at 750 C for several hrs.
12	707	Kannuluik, W. G.	1933	E	90-373		Traces of Bi, Cd, Cu, Pb, Mg, Si, and Na; 0.06095 cm dia x 9.770 cm long; drawn from a rod of H. S. brand silver supplied by A. Hilger, Ltd.; annealed at 500 C; electrical resistivity reported as 0.341, 1.035, 1.510, 2.123, and 2.863 μohm cm at -183.00, -78.50, 0, 100, and 217.96 C, respectively; measured in a vacuum of 10^{-4} mm Hg.
13	1537	White, G. K.	1953	L	2.0-140	JM 4606; Ag 1	99.999⁺ pure; polycrystalline; 2 mm dia rod supplied by Johnson, Matthey and Co., Ltd.
14	1537	White, G. K.	1953	L	3.3-131	JM 4606; Ag 2	The above specimen annealed at 650 C; grain size ~0.1 mm.

TABLE 147. THERMAL CONDUCTIVITY OF SILVER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
15	1537	White, G. K.	1953	L	1.7-134	JM 4606; Ag 3	1.16 mm dia rod drawn from the above specimen.
16	1537	White, G. K.	1953	L	3.0-135	JM 4606; Ag 4	The above specimen annealed at 650 C.
17	1537	White, G. K.	1953	L	2.4-95	JM 4606; Ag 5	The above specimen, Ag 4, after being removed and replaced in cryostat.
18	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.3	Ag 1	99.99 pure; polycrystal; annealed; measured in a transverse magnetic field of 4.2 kilooersteds.
19*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.2	Ag 2	99.999 pure; polycrystal; annealed; measured in a transverse magnetic field of 1.09 kilooersteds.
20	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.2	Ag 2	The above specimen measured in a transverse magnetic field of 1.75 kilooersteds.
21	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.2	Ag 2	The above specimen measured in a transverse magnetic field of 1.97 kilooersteds.
22	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.2	Ag 2	The above specimen measured in a transverse magnetic field of 2.7 kilooersteds.
23	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.2	Ag 2	The above specimen measured in a transverse magnetic field of 3.6 kilooersteds.
24*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.2	Ag 2	The above specimen measured in a longitudinal magnetic field of 3.6 kilooersteds.
25	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.2	Ag 2	The above specimen measured in a transverse magnetic field of 3.7 kilooersteds.
26	1282	Sedstrom, E.	1919	T	273, 373		1 mm dia wire; rolled and drawn; heated 0.5 hr at temp close to melting point; electrical conductivity reported as 57.0 and 41.3 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively.
27*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Ag 37	Single crystal.
28	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.24	Ag 37	The above specimen measured at H (the transverse magnetic field strength) = 8810 oersteds and at θ (the angle of rotation of the magnetic field in a plane perpendicular to the specimen axis) = +1° at which the dependence of k on H is maximum.
29	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.26	Ag 37	The preceding specimen measured at H = 10850 oersteds and at θ = +1°.
30*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Ag 37	The above specimen measured without magnetic field.
31*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.20	Ag 37	The above specimen measured at H = 4580 oersteds and at θ = +45° at which the dependence of k on H is minimum.
32*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.26	Ag 37	The above specimen measured at H = 8810 oersteds and at θ = +45°.
33	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.27	Ag 37	The above specimen measured at H = 10850 oersteds and at θ = +45°.
34	555	Grüneisen, E. and Reddemann, H.	1938	L	79, 91	Ag e_4	Pure; single crystal; deformed; electrical resistivity 1.50 μohm cm at 0 C.
35	555	Grüneisen, E. and Reddemann, H.	1938	L	80	Ag e_4	The above specimen annealed for 2 hrs at 350 C; electrical resistivity 1.49 μohm cm at 0 C.

* Not shown in figure.

TABLE 147. THERMAL CONDUCTIVITY OF SILVER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
36	555	Grüneisen, E. and Reddemann, H.	1934	L	80, 91	Ag e_5	Pure; single crystal.
37*	1065	Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L.	1961	P	295.2		Pure; 1.9 x 1.9 x 0.322 cm; thermal conductivity value calculated from measured value of thermal diffusivity using specific heat and density values taken from Smithsonian Physical Tables (9th ed., 1954).
38	487	Gerritsen, A. N. and Linde, J. O.	1956	L	14–94	Ag-Mn 3	0.14 at. % Mn; polycrystal; rectangular rod specimen of square cross section 2.5 x 2.5 mm; annealed at 720 K for several hrs in vacuo; electrical resistivity reported as 0.233, 0.234, 0.235, 0.237, 0.473, 0.534, 0.595, and 1.69 μohm cm at 14, 16, 18, 20, 70, 80, 90, and 273 K, respectively; electrical resistivity ratio $\rho(273K)/\rho_0$ = 7.26.
39	487	Gerritsen, A. N. and Linde, J. O.	1956	L	15–94	Ag-Mn 2	0.32 at. % Mn; polycrystal; rectangular rod specimen of square cross section 2.5 x 2.5 mm; annealed at 720 K for several hrs in vacuo; electrical resistivity reported as 0.523, 0.521, 0.523, 0.526, 0.772, 0.830, 0.881, and 1.98 μohm cm at 14, 16, 18, 20, 70, 80, 90, and 273 K, respectively; electrical resistivity ratio $\rho(273K)/\rho_0$ = 3.77.
40	258	Chari, M. S. R. and de Nobel, J.	1959	L	1.6–74		0.14 at. % Mn; polycrystal; prepared from pure silver and from manganese of 99.995^+ pure; melted, rolled, and cut into rods of cross-sectional area ~2.5 mm^2; residual electrical resistivity 0.27 μohm cm.
41	258	Chari, M. S. R. and de Nobel, J.	1959	L	1.5–76		0.32 at. % Mn; polycrystal with fine grains; same fabrication method as above; residual electrical resistivity 0.54 μohm cm.
42	346	de Nobel, J.	1956	L	1.5–4.1		0.14 at. % Mn; measured in a magnetic field of 25.5 kilooersteds.
43	346	de Nobel, J.	1956	L	1.9–4.1		0.14 at. % Mn; measured in a magnetic field of 19 kilooersteds.
44	346	de Nobel, J.	1956	L	1.4–4.0		0.14 at. % Mn; measured in a magnetic field of 12 kilooersteds.
45	346	de Nobel, J.	1956	L	3.0–4.0		0.32 at. % Mn; measured in a magnetic field of 19 kilooersteds.
46	346	de Nobel, J.	1956	L	1.5–4.0		0.32 at. % Mn; measured in a magnetic field of 25.5 kilooersteds.
47	1327	Smith, A. W.	1925	L	333		99.9 pure; electrical conductivity 58.8 x 10^4 ohm^{-1} cm^{-1} at 25 C.
48	1280	Schulze, F. A.	1911	E	298		Impurities <0.03; electrical conductivity 57.35 x 10^4 ohm^{-1} cm^{-1} at 25 C.
49	964	Mikryukov, V. E.	1957	E	338–917		99.99 pure; polycrystal; electrical resistivity reported as 1.89, 2.21, 2.97, 4.62, and 5.91 μohm cm at 338.2, 385.2, 503.2, 753.2, and 917.2 K, respectively; Lorenz function reported as 2.45, 2.46, 2.45, 2.42, and 2.44 x 10^{-8} V^2 K^{-2} at the above temps, respectively.
50	794	Kudryavtsev, Ye, V. and Chakalev, K. N.	1960	E	306		99.99 pure.
51*	939	Mendelssohn, K, Sharma, J. K. N., and Yoshida, I.	1965	L	0.43–0.93		Pure silver wire.
52	877	Malm, H. L. and Woods, S. B.	1966	L	1.9–22	69 grade	0.005 at. % Mn; prepared from 99.9999 pure silver supplied by Cominco and 99.95 pure manganese supplied by Johnson, Matthey and Mallory; melted in argon; chill cast, rolled to 1 mm thick rolled to 1 mm thick ingot from which rectangular wire was cut; annealed at 750 C for 4 hrs in a vacuum of <2 x 10^{-4} torr; a sample of the 69 grade silver when given the same treatement had a ratio $\rho(293K)/\rho(4K)$ = 1030.

* Not shown in figure.

TABLE 147. THERMAL CONDUCTIVITY OF SILVER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
53	877	Malm, H. L. and Woods, S. B.	1966	L	1.8-82	59 grade	0.067 at. % Mn added to 99.999 Ag; same sources of materials and fabrication method as above.
54	877	Malm, H. L. and Woods, S. B.	1966	L	2.0-85	59 grade	0.11 at. % Mn added to 99.999 Ag; same sources of materials and fabrication method as above.
55	877	Malm, H. L. and Woods, S. B.	1966	L	1.8-86	59 grade	0.31 at. % Mn added to 99.999 Ag; same sources of materials and fabrication method as above.
56	425	Fenton, E. W., Rogers, J. S., and Woods, S. B.	1963	L	2.2-30	1	Pure; specimen 3 mm in dia and about 6 cm long; supplied by Engelhard Industries in Toronto; rolled and drawn, etched with nitric acid; annealed at 850 C in vacuo for 3 hrs; residual electrical resistivity 0.000799 μohm cm; measured in a vacuum of $<5 \times 10^{-6}$ mm Hg.
57	425	Fenton, E. W., Rogers, J. S., and Woods, S. B.	1963	L	2.2-17	2	Similar to the above specimen except residual electrical resistivity 0.000670 μohm cm.
58	1454	van Baarle, C., Roest, G. J., Roest-Young, Mrs. M. K., and Gorter, F. W.	1966	L	3.4-29	HPM 735;1	99.9999 Ag, 0.00001 Fe, 0.00001 Si, <0.00001 Ca, and <0.00001 Mg; fine grain polycrystalline; obtained from the Consolidated Mining and Smelting Co.; re-melted and outgassed, annealed at 550 C for 24 hrs; residual electrical resistivity 0.00081 μohm cm.
59	1454	van Baarle, C., et al.	1966	L	5.3-14	HPM 735; 2	Similar to the above specimen except annealed at 530 C for 24 hrs and residual electrical resistivity 0.00088 μohm cm.
60	807	LaMarre, D. A., Simpson, G. R., and Thorburn, M. R.	1962	C	298.2		0.05 In; cast; copper used as comparative material.
61	216	Brown, H. M.	1927	E	273.2		99.9 pure; 0.125 in. dia x 10 cm long; obtained from Baker and Co.; electrical resistivity 1.491 μohm cm at 0 C.
62	64	Anderson, A. C., Peterson, R. E., and Robichaux, J. E.	1968	L	0.38-1.2		99.999 pure; rectangular specimen 0.000161 cm^2 in cross section and 1.185 cm long; obtained from Cominco American; annealed in vacuum; strained during mounting; electrical resistivity 0.00203 μohm cm below 4 K; electrical resistivity ratio $\rho(300K)/\rho_0 = 740$; Lorenz number 2.53×10^{-8} W ohm K^{-2}.
63*	1299	Sharma, J. K. N.	1967	L	0.42-0.89		99.999 pure; polycrystalline wire specimen; supplied by Johnson, Matthey and Co., Ltd. (Lab. No. 24757); form factor $(\ell/a) = 1.10 \times 10^4$ cm^{-1}; electrical resistivity 0.167 μohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 115$; anomalous peak occurred at 0.65 K; run No. 14.
64*	1299	Sharma, J. K. N.	1967	L	0.40-0.93		The above specimen run No. 15.
65	1467	van Witzenburg, W. and Laubitz, M. J.	1968	L	80-130		99.9999 pure; 1.6 mm dia wire supplied by Cominco; oxidized in pure oxygen at 950 K for 69 hrs, then annealed in a vacuum of 10^{-6} mm Hg at 770 K for 17 hrs; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 1650$; residual electrical resistivity 0.0009 μohm cm; reported thermal conductivity values calculated from the measurements of the two (electrical and thermal) magneto resistances and the two normal resistances.
66	217	Brown, H. M.	1928	E	279.9		10 cm x 0.0783 cm^2; electrical resistivity 1.492 μohm cm at 6.75 C; no changes in thermal conductivity and electrical resistivity observed during the application of magnetic fields of 10,000 gauss in longitudinal, and 4000 and 8000 gauss in transverse direction.

* Not shown in figure.

TABLE 147. THERMAL CONDUCTIVITY OF SILVER - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
67*,‡	966	Mikryukov, V. Ye.	1968	E	311-873		Electrical resistivity 1.76, 2.83, 4.00, and 4.86 μohm cm at 120, 287, 485, and 628 C, respectively (read from smooth curve).
68*,‡	966	Mikryukov, V. Ye.	1968	E	325-769		The above specimen; 2nd run.
69*	120	Batalov, V.S. and Peletskii, V.E.	1968	P	331.7		Specimen 10 cm long; measured in a vacuum of $\sim 10^{-3}$ torr; thermal conductivity value calculated from the measurement of thermal diffusivity.
70	17	Abrosimov, V.N., Egorov, B.N., Lidorenko, N.S., and Rubashov, I.B.	1969	C	313.2	Silver film	Silver film specimen 190 Å thick deposited on a plate of a substrate (a thermally stable polypyromellitimide film 25-30 μ thick) in 10^{-6} mm Hg vacuum at 50 C; polypyromellitimide film used as comparative material (k = 0.00814 W cm^{-1} K^{-1} at 40 C).
71	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 150 Å thick.
72	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 690 Å thick.
73	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 860 Å thick.
74	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 1570 Å thick.
75	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 2000 Å thick.
76	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 3170 Å thick.
77	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 4130 Å thick.
78	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 5460 Å thick.
79	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 7050 Å thick.
80	17	Abrosimov, V.N., et al.	1969	C	313.2	Silver film	Similar to above except specimen 9110 Å thick.
81	818	Laubitz, M.J.	1969	L	289-1072		<0.0001 each of Ca, Cu, Mg, and Si, and 0.00003-0.0002 Fe; obtained from Cominco; annealed in oxygen at 900 K for 4 wks; density 10.512 g cm^{-3} at 20 C; electrical resistivity ratio $\rho(273K)/\rho_0$ = 600-4000; electrical resistivity 1.6285, 2.2356, 2.8623, 3.5085, 4.2497, 4.8597, 5.5646, 6.2891, and 7.0332 μohm cm at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K, respectively; data obtained in tabular form from the author in a private communication.
82	424	Fenton, E.W.	1962	L	2.3-10.3	Specimen No. 5	Similar to the specimen No. 1 reported in curve No. 56 except (ℓ/a) = 1470; electrical resistivity reported as 1.077, 1.084, 1.084, 1.084, 1.094, 1.084, 1.094, 1.178, and 1.296 x 10^{-3} μohm cm at 2.23, 2.74, 3.22, 3.79, 4.14, 5.53, 6.85, 8.96, and 10.76 K, respectively.
83	413	Evans, J.E., Jr.	1951	C	310-810		99.4 pure; National Bureau of Standards melting-point standard lead used as reference standard.
84	101	Bäcklund, N.G. and Langemar, K.T.	1967	L	86-375		Material obtained from Johnson and Matthey Co.; melted, rolled to a bar 10 cm long and about 13 mm^2 in cross section; annealed in vacuum at 560 C for 11 hrs; density 10.51 g cm^{-3}; electrical resistivity 1.626 μohm cm at 297.1 K.
85	546 548	Grosse, A. V.	1965		1234-7460		Estimated from derived values for the electrical conductivity and assuming the theoretical Lorenz number to hold over the entire liquid range from M. P. to C. T.

* Not shown in figure.
‡ Thermal conductivity data are apparently in error and are not shown intentionally.

Sodium

Determinations of the thermal conductivity of sodium for the solid and liquid phases cover the continuous temperature range of 2 to 1173 K and appear at first sight to present a reasonably consistent series of results. There is, however, a definite need for further measurements of both thermal and electrical conductivity for the solid phase from about 30 to the melting point of 371 K.

Existing measurements for the solid phase near the melting point yield a thermal conductivity that decreases with increase in temperature. A negative temperature coefficient is also derived from the recent electrical resistivity measurements of Tepper, et al. [1401] for the range 302 to 370 K, unless the assumed Lorenz function increases over this range of temperature by more than 6 percent. Use of a Lorenz function of 2.2×10^{-8} V^2 K^{-2} yields values that conform quite well with the earlier measurements of Hornbeck [635] (curve 3), Bidwell [157] (curve 5), and Hall [581] (curve 4). The value of 1.32 W cm^{-1} K^{-1} so obtained at 302 K is of the same order as the values of Berman and MacDonald [144] (curves 6 and 7) at 80 K, for the two samples which they had studied over the approximate range of 5 to 98 K. Above 80 K they had found one curve to be relatively flat whilst the other turned up. On the basis of these results, the curve of conductivity against temperature should have a maximum between 100 and 300 K. The only measurements in this range are those of Bidwell and these give some support in that after falling steadily to 223 K the next value at 273 K is some 20 percent greater, above which a decrease with increase in temperature again occurs.

Sodium is clearly another metal for which further measurements in this subnormal temperature range would be of considerable interest, and, indeed, these relatively simple thermal conductivity determinations are really essential before any firm recommendations can be made.

At present, the recommended curve at low temperatures is based on the measurements (curve 8) of MacDonald, White, and Woods [873] and is only for a sample having $\rho_0 = 0.00147$ $\mu\Omega$ cm. The recommended values at temperatures below 1.5 T_m have been calculated to fit their data by using equation (7) and using the constants m, n, and α'' as listed in table 1 and the parameter $\beta = 0.0600$. This curve continues to follow their data to 12 K where it merges into the upper curve due to Berman and MacDonald, following this to about 80 K where it begins to increase to a gentle maximum before following the lower set (curve 60) of the recent data of Fritsch and Lüscher [463] to the melting point.

For the liquid phase a lot of information is available and only above 1100 K, about the limit so far reached experimentally, do further measurements seem necessary. At least seven sets of experimental values below 1100 K agree to within some 7 percent, as do many calculated values derived from electrical resistivity data. The curve (curve 22) so derived by Tepper, Zelenak, Roehlich, and May [1401] lies a little above the main group. These workers assumed a Lorenz function of 2.45×10^{-8} V^2 K^{-2}, and it seems clear that, at least for the range so far examined experimentally, a lower value would be more appropriate. The values derived by Grosse [546] (curve 64), who gave preference to the electrical resistivity data of Kapelner and Bratton [712], are of the order of 5 percent lower in this range since his semi-empirical equation gave a good fit to the electrical resistivity data and he chose to assume a Lorenz function of 2.33×10^{-8} V^2 K^{-2}. As with other metals, Grosse, on the assumption that this equation and Lorenz function held good to the critical point, extended the derivations of thermal conductivity to his assumed value for the critical temperature, 2800 K.

The recommended curve for liquid sodium follows a mean position through the group of experimental and estimated values from the melting point to 1100 K. Here it lies midway between the predicted curves of Tepper, et al. and Grosse, and has been smoothly continued a little above the latter curve to the value of 0.0013 W cm^{-1} K^{-1} as estimated by Grosse for sodium vapor at the critical point.

It is of interest to note that recommendations by Golden and Tokar [511] for the range 371 to 1643 K, which have come to our notice after the above recommendations had been reported [608], agree to within 1 percent near the melting point, are lower by not more than 2.5 percent over the range 400 to 1450 K, and greater by up to a maximum of 3.5 percent at 1643 K. Golden and Tokar mainly based their recommendations on the works of Evangelisti and Isacchini [410, 411] (curve 15) and of Tepper, et al. (curve 22) but made no mention of the estimated values of Grosse.

The recommended values are thought to be accurate to within ±6 percent of the true values at temperatures below 60 K, ±10 percent from 60 K to the melting point, ±5 percent for the liquid state below 1000 K, and ±10 percent from 1000 to 1600 K. The values above 1600 K are provisional. Below 80 K the values are, of course, applicable only to a specimen having $\rho_0 = 0.00147$ $\mu\Omega$ cm.

TABLE 148. Recommended thermal conductivity of sodium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Liquid	
T	k	T	k
0	0	371	0.883
1	16.6*	373.2	0.882
2	31.8*	400	0.868
3	43.2	473.2	0.827
4	48.5	500	0.815
5	48.2	573.2	0.778
6	44.2	600	0.764
7	38.4	673.2	0.728
8	31.7	700	0.715
9	26.3	773.2	0.681
10	22.0	800	0.668
11	18.8	873.2	0.638
12	16.1	900	0.625
13	14.0	973.2	0.596
14	12.2	1000	0.583
15	10.7	1073.2	0.553
16	9.40	1100	0.543
18	7.48	1173.2	0.513
20	6.09	1200	0.503
25	3.94	1273.2	0.476
30	2.83	1300	0.465
35	2.22	1373.2	0.438
40	1.89	1400	0.428*
45	1.71	1473.2	0.402*
50	1.58	1500	0.393*
60	1.45	1573.2	0.367*
70	1.38	1600	0.358*
80	1.35	1673.2	0.334*
90	1.36	1700	0.325*
100	1.36	1773.2	0.301*
123.2	1.38	1800	0.292*
150	1.40	1873.2	0.269*
173.2	1.41	1900	0.260*
200	1.42	1973.2	0.238*
223.2	1.42	2000	0.229*
250	1.43	2073.2	0.207*
273.2	1.42	2173.2	0.177*
298.2	1.42	2200	0.170*
300	1.41	2273.2	0.148*
323.2	1.39	2400	0.112*
350	1.35	2473.2	0.087*
371	1.32	2600	0.056*
		2673.2	0.033*
		2800	0.0013*

†The values are for high-purity sodium, and those below 80 K are applicable only to a specimen having $\rho_0 = 0.00147$ $\mu\Omega$ cm. The values above 1600 K are provisional.

*Extrapolated or estimated.

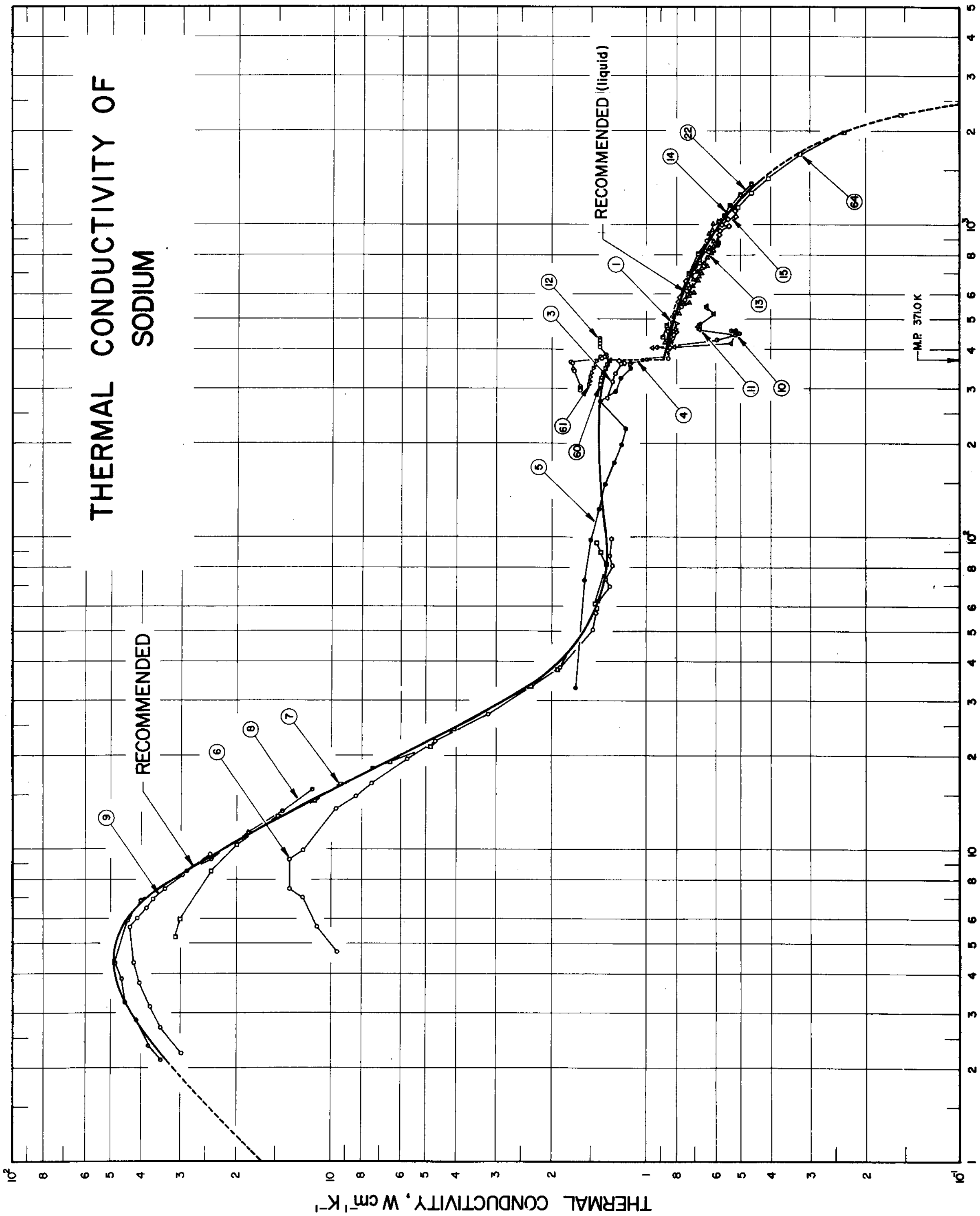
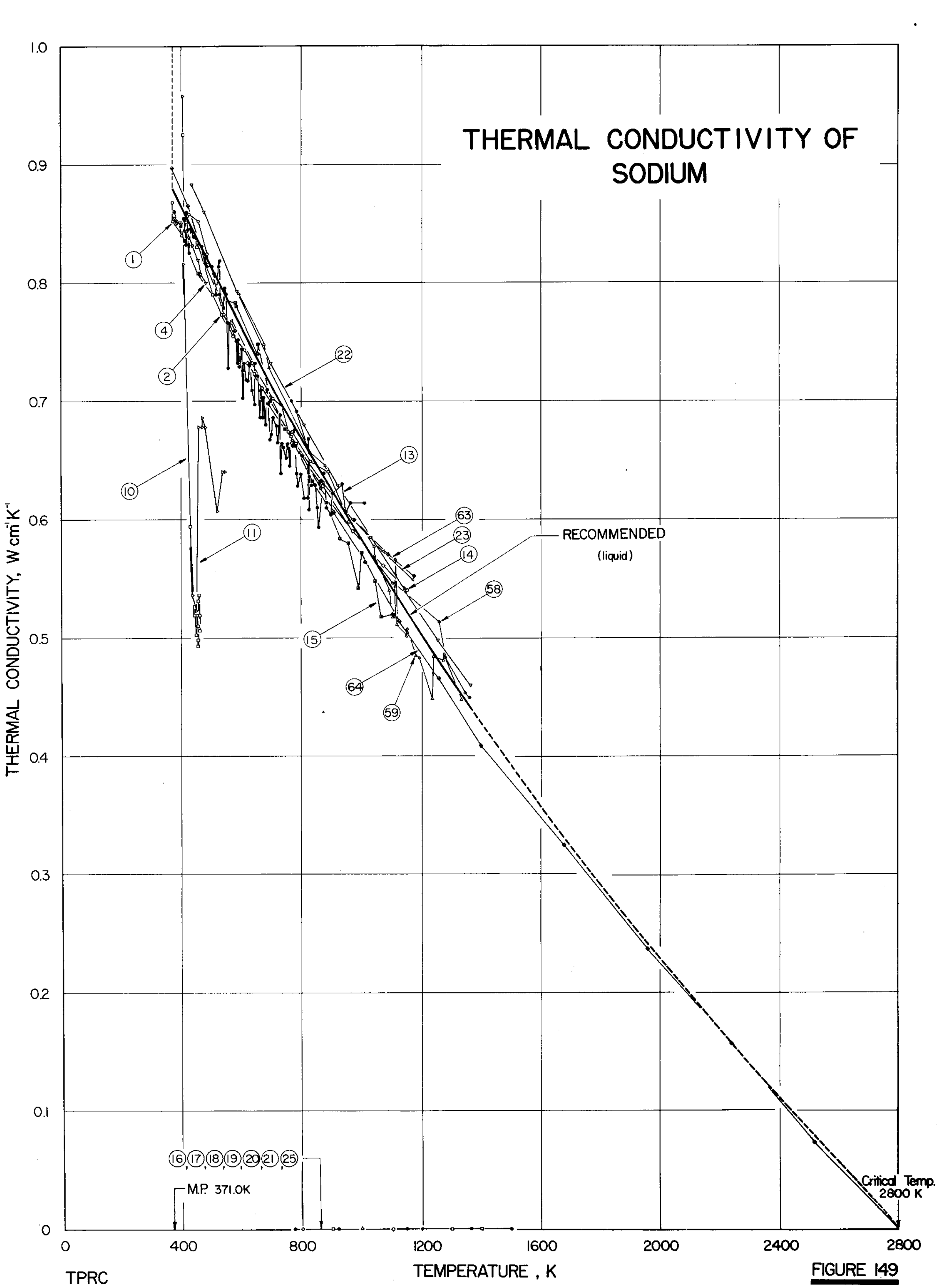

THERMAL CONDUCTIVITY OF SODIUM
RECOMMENDED
RECOMMENDED (liquid)
M.P. 371.0 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 148



TPRC

FIGURE 149

TABLE 149. THERMAL CONDUCTIVITY OF SODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1044	Novikov, I.I., Solovyev, A.N., Khabakhpasheva, E.M., Gruzdev, V.A., Pridantsev, A.I., and Vasenina, M.Ya.	1956	P	374-961		Pure; thermal conductivity values calculated from measured (in argon) thermal diffusivity data using specific heat data of Ginnings, D.C., et al. (J. Res., NBS, 45, 1950) and density data of Miller, R.R. (Liquid Metals Handbook, 2nd ed., 1952).
2	405, 414	Ewing, C.T. and Grand, J.A.	1951	L	455-786		Impurities: 0.0001 to 0.001 Ag, <0.00001 K, <0.001 O, and negligible amounts of Li, Si, Be, Cs, Rb, Ca, Al, Mg, Fe, Cr, Ni, Sn, and Pb; distilled.
3	635	Hornbeck, J.W.	1913	E	279-361		Pure, supplied by Eimer and Amend; electrical resistivity reported as 4.66, 5.06, 5.63, 6.04, and 6.63 μohm cm at 5.7, 21.5, 42.1, 61.4, and 88.1 C, respectively.
4	581	Hall, W.C.	1938	L	358-485		Pure; measured above and below melting point (97.5 C); electrical conductivity 1.02 and 0.73 x 10^5 ohm^{-1} cm^{-1} at 100 and 200 C, respectively; extrapolation of the thermal conductivity data for the solid and the liquid state to the melting point gives the ratio 1.33.
5	157	Bidwell, C.C.	1926	F	33-348		Pure; 1.10 cm in dia, 25 cm long; extruded; electrical resistivity 4.26 μohm cm at 0 C.
6	144	Berman, R. and MacDonald, D.K.C.	1951	L	4.7-99	Na I	Approx 0.01 to 0.1 Ca and Al; supplied by British-Thomson-Houston Research Lab.; cast under vacuum in soft glass tubes; electrical conductivity ranging from 106 to 3.15 x 10^6 ohm^{-1} cm^{-1} at 2 to 46.7 K.
7	144	Berman, R. and MacDonald, D.K.C.	1951	L	5.3-96	Na II	Trace of Ag; supplied by Messrs. Philips Ltd., Mitcham; cast under vacuum in soft glass tubes; electrical conductivity ranging from 756 to 1.0 x 10^6 ohm^{-1} cm^{-1} at 2 to 90 K.
8	873	MacDonald, D.K.C., White, G.K., and Woods, S.B.	1956	L	2.1-16	Na 2	High purity; 0.5 mm in dia; electrical resistivity ratio $\rho(295K)/\rho(0K)$ = 3420 (using Hackspill's value $\rho(295K)$ = 4.75 μohm cm).
9	873	MacDonald, D.K.C., et al.	1956	L	2.2-9.6	Na 3	High purity; 0.13 mm in dia; electrical resistivity ratio $\rho(295K)/\rho(0K)$ = 2860 (using Hackspill's value $\rho(295K)$ = 4.75 μohm cm).
10	1583	Yaggee, F.L. and Untermyer, S.	1950	L	407-462		Commercial grade (high purity); supplied by Mine Safety Appliance Co.; 0.684 in. dia; M.P. 97.9 C; specimen in liquid state; apparatus in open air.
11	1583	Yaggee, F.L. and Untermyer, S.	1950	L	403-549		The above specimen; apparatus in heated oven.
12	755	Khalileev, P.A.	1940	L	296-433		Distilled; measured above and below melting point (approx 97 C).
13	1036	Nikol'skii, N.A., Kalakutskaya, N.A., Pchelkin, I.M., Klassen, T.B., and Vel'tishcheva, V.A.	1959	L	402-1011		M.P. 97.5 C; specimen in liquid state; measured in vacuum of approx 4 x 10^{-4} mm Hg.
14	1232	Rudnev, I.I., Lyashenko, V.S., and Abramovich, M.D.	1961	P	623-1153		Impurities (after test): 0.049 Cr, 0.041 K, 0.016 Fe, 0.016 O, 0.014 Ni, <0.002 Pb, 0.0017 Mn, 0.0011 Ti, <0.001 Al, 0.00045 Cu, 0.0003 Ca, 0.00027 Mg, and 0.0002 Ag; distilled; 8.4 mm dia, approx 230 mm long; in liquid state; measured in vacuum; data calculated from an empirical equation derived from experimental data.
15	410, 411	Evangelisti, R. and Isacchini, F.	1965	C	363-1103		Melting point 97.81 C; specimen in liquid state; AISI 304 stainless steel used as comparative material.

TABLE 149. THERMAL CONDUCTIVITY OF SODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	1362	Stefanov, B.I., Timrot, D.L., Totskii, E.E., and Chu, W.H.	1966		900-1500		Vapor; measured in the 1 mm gap between concentric cylinders 900 mm long; vapor pressure = 0.01 kg cm^{-2}.
17	1362	Stefanov, B.I., et al.	1966		1000-1500		Similar to above except vapor pressure = 0.05 kg cm^{-2}.
18	1362	Stefanov, B.I., et al.	1966		1000-1500		Similar to above except vapor pressure = 0.1 kg cm^{-2}.
19	1362	Stefanov, B.I., et al.	1966		1100-1500		Similar to above except vapor pressure = 0.5 kg cm^{-2}.
20	1362	Stefanov, B.I., et al.	1966		1200-1500		Similar to above except vapor pressure = 1.0 kg cm^{-2}.
21	1362	Stefanov, B.I., et al.	1966		800-1200		Similar to above except measured on saturation curve.
22	1211, 1212, 1401	Tepper, F., Zelenak, J., Roehlich, F., and May, V.	1965	→	437-1366		Density reported as 0.8977, 0.8255, 0.8119, 0.7881, 0.7640, 0.7381, and 0.6967 g cm^{-3} at 483.8, 804.1, 873.1, 972.7, 1085, 1189, and 1384 K, respectively; electrical resistivity reported as 5.23, 5.72, 6.54, 6.70, 6.82, 11.04, 11.10, 11.99, 12.42, 14.54, 15.61, 16.25, 18.01, 20.09, 21.86, 24.76, 28.01, 31.54, 35.31, 37.35, 41.76, 46.44, 48.94, 54.16, 60.10, 66.17, 69.59, and 72.48 μohm cm at 302, 324, 356, 365, 370, 406, 413, 431, 444, 501, 525, 542, 554, 630, 668, 726, 790, 850, 913, 945, 1009, 1079, 1108, 1171, 1238, 1300, 1334, and 1360 K, respectively; thermal conductivity values calculated from measured electrical resistivity data using Lorenz function of 2.45 x 10^{-8} V^2 K^{-2}.
23	280, 712	Kapelner, S.M. and Bratton, W.D.	1962	→	473-1173		Composition (pretest): <0.0375 Cs, <0.0375 K, <0.0150 Li, 0.0066 Fe, 0.0048 N, 0.0032 O, 0.0022 Ni, and <0.0010 Cr; composition (posttest): <0.0375 Cs, <0.0375 K, 0.0215 C, <0.0150 Li, 0.0055 O, 0.0049 N, 0.0045 Fe, <0.0010 Cr, and <0.0009 Ni; purchased from U.S. Industrial Chemicals Co.; purified by melting and forcing the molten liquid through a 20 micron stainless steel filter under purified argon; electrical resistivity reported as 9.64, 11.44, 13.78, 17.98, 23.16, 28.68, 34.91, 41.86, 46.40, and 51.00 μohm cm at 371.2, 424.5, 482.5, 585.7, 693.9, 804.4, 908.7, 1012.8, 1072.8, and 1126.0 K, respectively; thermal conductivity values calculated from electrical resistivity data using Lorenz function of 2.31, 2.31, 2.33, 2.33, 2.36, 2.41, 2.48, and 2.52 x 10^{-8} V^2 K^{-2} at 473, 573, 673, 773, 873, 973, 1073, and 1123 K, respectively; the first four values being derived from the thermal conductivity measurements of Ewing, C.T. and Grand, J.A. (NRL Rept. 3835, 1951) and the authors' own electrical resistivity data.
24*	781	Kozlan, F.A. and Antonov, I.N.	1965	L	328		0.13 Na_2O.

* Not shown in figure.

TABLE 149. THERMAL CONDUCTIVITY OF SODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
25	1414	Timrot, D. L. and Totskii, E. E.	1967	→	886-1202		Vapor state; contained in the annulus between two concentric thin-walled hollow cylinders; measuring method based on thermal expansion of the coaxial cylinders; measured at a sodium vapor pressure of 0.034 kg cm^{-2}.
26*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1033-1245		Similar to above but sodium vapor pressure 0.077 kg cm^{-2}.
27*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1054-1268		Similar to above but sodium vapor pressure 0.24 kg cm^{-2}.
28*	1414	Timrot, D. L. and Totskii, E. E.	1967	→	1154, 1188		Similar to above but sodium vapor pressure 0.69 kg cm^{-2}.
29*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1007		99.8 pure; in vapor state; contained in the annulus between two coaxial hollow cylinders of 200 mm height with 12.92 mm I. D. and 14.08 mm O. D.; measured at a sodium vapor pressure of 0.008 atm.
30*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	957.2		Similar to above but sodium vapor pressure 0.013 atm.
31*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1165		Similar to above but sodium vapor pressure 0.017 atm.
32*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1166		Similar to above but sodium vapor pressure 0.03 atm.
33*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	969-1006		Similar to above but sodium vapor pressure 0.044 atm.
34*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1166		Similar to above but sodium vapor pressure 0.054 atm.
35*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1053		Similar to above but sodium vapor pressure 0.058 atm.
36*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	945.8		Similar to above but sodium vapor pressure 0.07 atm.
37*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1039		Similar to above but sodium vapor pressure 0.078 atm.
38*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	969.6, 970.0		Similar to above but sodium vapor pressure 0.084 atm.
39*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1005		Similar to above but sodium vapor pressure 0.10 atm.
40*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1052		Similar to above but sodium vapor pressure 0.13 atm.
41*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1050-1052		Similar to above but sodium vapor pressure 0.127 atm.
42*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1003, 1107		Similar to above but sodium vapor pressure 0.144 atm.
43*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1167		Similar to above but sodium vapor pressure 0.154 atm.
44*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1107		Similar to above but sodium vapor pressure 0.162 atm.
45*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1057, 1058		Similar to above but sodium vapor pressure 0.176 atm.
46*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1059		Similar to above but sodium vapor pressure 0.18 atm.
47*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1050		Similar to above but sodium vapor pressure 0.23 atm.
48*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1155		Similar to above but sodium vapor pressure 0.261 atm.
49*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1163.8, 1164.2		Similar to above but sodium vapor pressure 0.276 atm.
50*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1159		Similar to above but sodium vapor pressure 0.386 atm.
51*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1155		Similar to above but sodium vapor pressure 0.49 atm.

* Not shown in figure.

TABLE 149. THERMAL CONDUCTIVITY OF SODIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
52*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1155, 1157		Similar to above but sodium vapor pressure 0.62 atm.
53*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1155		Similar to above but sodium vapor pressure 0.684 atm.
54*	1476	Vargaftik, N. B. and Voshchinin, A. A.	1967	R	1165		Similar to above but sodium vapor pressure 0.82 atm.
55*	412	Evangelisti, R. and Isacchini, F.	1965	L	363-1105		Cylindrical specimen; in both solid and liquid states; measured in a vacuum of 10^{-5} mm Hg.
56*	1043	Novikov, I. I., Gruzdev, V. A., Kraev, O. A., Odintzov, A. A., and Roshchunkin, V. V.	1969	L	522-1103		99.8 Na; before test: 0.015 O, 0.014 Fe, >0.001 Ca, >0.001 Si, 0.001 Li, and 0.001 Ni; after test: 0.013 Si, >0.002 Fe, and >0.001 Ni; liquid specimen contained in a steel cell about 20 mm in dia, 170-200 mm long, and 0.5 mm in wall thickness; density 0.927 g cm^{-3} at 100 C.
57*	1043	Novikov, I. I., et al.	1969	L	554-982		Similar to above.
58	1043	Novikov, I. I., et al.	1969	L	770-1361		Similar to above.
59	19	Achener, P. Y. and Jouthas, J. T.	1969	C	553-1332	Reactor grade sodium	0.0315 K, 0.0044 C, 0.0021 O, 0.0009 Cl, 0.0006 Au, 0.0003 Ca, <0.0002 B, <0.0002 S, <0.0001 each of Cd, In, and Ag, and 0.00004 Li; in liquid state; supplied by duPont Corp; contained in a cylindrical chamber 1.375 in. I. D. and 2 in. long; Ta-8W-2Hf used as comparative material (data taken from Hedge, J. C., et al., ASD-TDR-63-597, 1-128, 1963).
60	463	Fritsch, G. and Lüscher, E.	1969	L	308-371		99.99 Na, <0.0100 K, <0.0020 Mg, <0.0005 Ca, and <0.0005 Fe; cylindrical shell specimen 6 mm in dia, 12 cm long, and 0.1 mm in wall thickness; measured in an argon atm; data standardized by the average literature value of 0.86 W cm^{-1} K^{-1} after melting.
61	463	Fritsch, G. and Lüscher, E.	1969	L	308-371		The above measurement standardized by the value of 0.923 W cm^{-1} K^{-1} (from Ewing, C. T., et al., J. Am. Chem. Soc., 74, 11, 1952) after melting.
62*	1509	Weatherford, W. D., Jr., Tyler, J. C., and Ku, P. M.	1961		767-1514		Saturated vapor; recommended values calculated from the frozen specific heat and viscosity of saturated vapor assuming a constant Prandtl No. of 0.73.
63	1509	Weatherford, W. D., Jr., et al.	1961		800-1158		Liquid state; recommended values based upon information from Liquid Metals Handbook, Sodium (NaK) Supplement, third edition, 1955.
64	546	Grosse, A. V.	1964	→	371-2800		Liquid state; thermal conductivity values calculated from electrical resistivity values derived partly from the measurements of Kapelner and Bratton (USAEC Rept. PWAC-376, 1962) and partly from semiempirical correlation and the Lorenz function assumed to be 2.33 x 10^{-8} V^2 K^{-2}.

* Not shown in figure.

Strontium

No values appear to have been reported for the thermal conductivity of strontium, so the best that can be done is to derive provisional values from electrical resistivity data.

Meaden [912] has listed values for the electrical resistivity of strontium over the range 4 to 295 K and Rinck [1202] has published values from about 325 to 970 K. These two sets of data appear to be reasonably consistent but to apply to rather impure strontium, since Meaden indicates the residual resistivity to be 2.0 $\mu\Omega$ cm. In order to yield eletcrical resistivity values that are more appropriate to pure strontium, this quantity, ρ_0, has been subtracted from each measured value, ρ, and the thermal conductivity has been calculated by means of the expression $2.443 \times 10^{-8}\ T/(\rho-\rho_0)$. The resultant curve is shown by the short-dashed line in the figure.

These provisional values are probably good to ±20 percent at temperatures below 450 K. The uncertainty increases above 450 K due to the effect of the phase transformations.

TABLE 150. Provisional thermal conductivity of strontium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	488	0.281*
150	0.446*	500	0.280*
173.2	0.424*	573.2	0.277*
200	0.405*	600	0.276*
223.2	0.390*	673.2	0.277*
250	0.375*	700	0.278*
273.2	0.364*	773.2	0.282*
298.2	0.354*	800	0.284*
300	0.353*	873.2	0.289*
323.2	0.344*	878	0.290*
350	0.333*	878	0.248*
373.2	0.325*	900	0.250*
400	0.317*	973.2	0.257*
473.2	0.304*	1000	0.260*
488	0.300*		

†For high-purity strontium.
*Estimated.

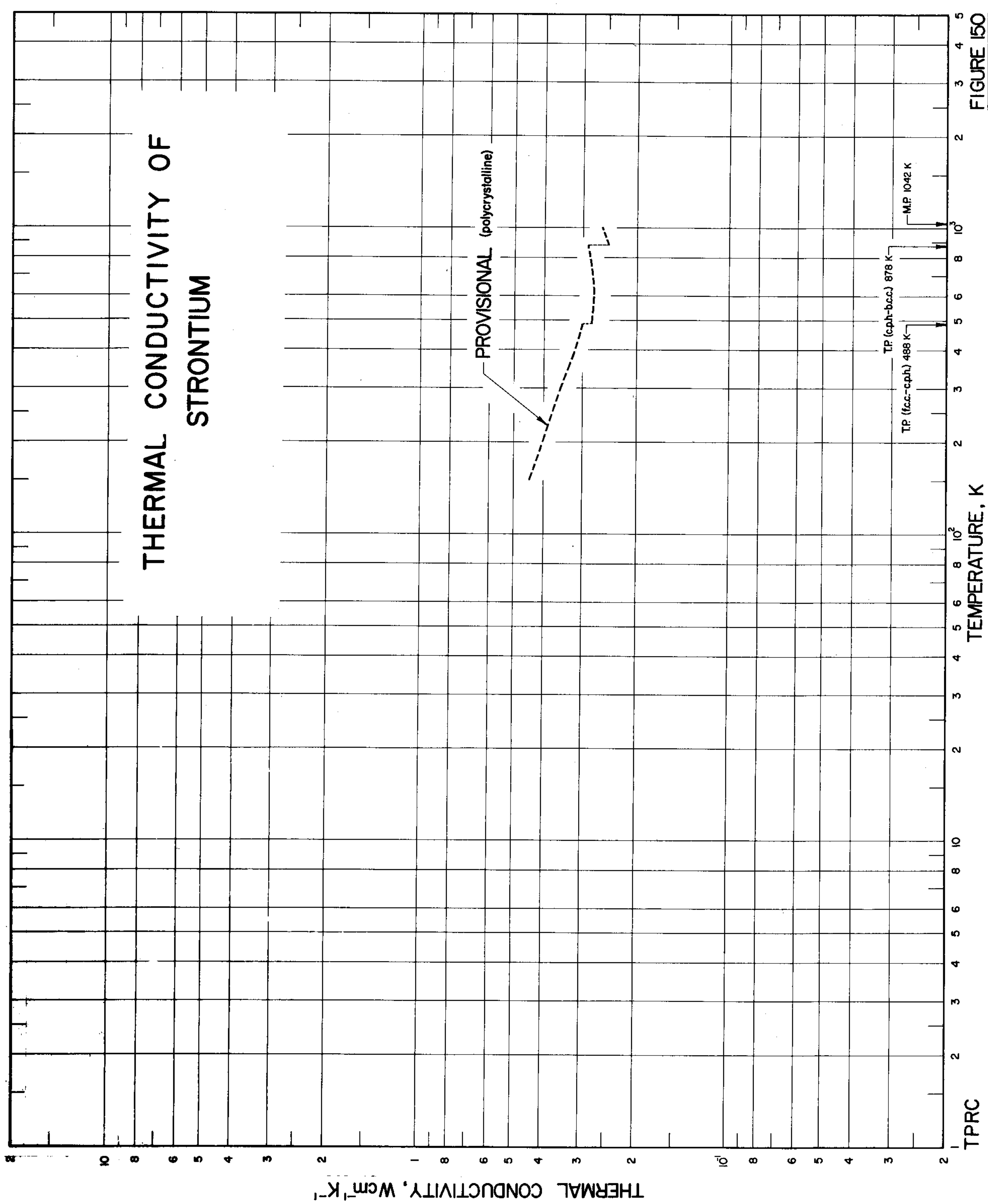


FIGURE 150
THERMAL CONDUCTIVITY OF
STRONTIUM
PROVISIONAL (polycrystalline)
M.P. 1042 K
T.P. (c.p.h.-b.c.c.) 878 K
T.P. (f.c.c.-c.p.h.) 488 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm^{-1}K^{-1}
TPRC

Sulfur

The only thermal conductivity measurements reported for sulfur at cryogenic temperatures are those of Slack [1321] (curves 6, 7). These relate to two single crystals of sulfur regarded as exceeding 99 percent purity, each a rod-shaped sample about 0.7 cm long and 0.2 cm diameter that had been cut from a crystal of the stable orthorhombic form to give the heat flow perpendicular to the *c*-axis in one and parallel to it in the other. Over the approximate range 12 to 90 K the thermal conductivity curves for these two samples agree to within about 10 percent, and cross at 25 K. These differences could reflect the experimental uncertainty, but at lower temperatures quite different maxima are indicated and the thermal conductivity differences increase to over 300 percent, that for the direction parallel to the *c*-axis being the greater. However, Slack did not regard the observed differences as due to true crystal anisotropy, but thought them to result from differences in crystal perfection and crystallite size. Slack had found no marked thermal conductivity anisotropy to be revealed by tests made at room temperature on several samples by means of a method of the de Sénarmont type. He found all values of the thermal conductivity to agree to within 20 percent.

For the time being, the thermal conductivity at low temperatures is represented by a smooth curve fitted to the higher set of Slack's values (curve 7) and passing through Eucken's [400] 83 K point for a crystalline sample (curve 4). Slack's data do not extend above 92 K, and, since no measurements have been reported for sulfur between 92 and 273 K, the curve has been continued smoothly to pass a little below Eucken's other point at 273 K. This brings the curve in fair agreement with the measurements of Kaye and Higgins [721] (curve 1) and with those reported some thirty years later by Yoshizawa, Sugawara, and Yamada [1587, 1375] (curves 8, 9). Each of these groups of workers included measurements for both crystal forms and for molten sulfur. Their data agree well, except as regards the sign of the temperature coefficient for the short temperature range of the monoclinic form.

Continuing from 273 K, a mean curve has been drawn through these two sets of values. It indicates a drop of about 30 percent at the $\alpha \rightarrow \beta$ phase transformation, a falling value for the monoclinic form, and another drop of about 17 percent on passing into the liquid phase. The thermal conductivity of molten sulfur is shown to have a small positive temperature coefficient.

The foregoing treatment has so far ignored the two points at 300 K (curves 20, 21) due to A. V. Ioffe and A. F. Ioffe [657]. These values, which are for two single crystals having the direction of the heat flow in mutually perpendicular planes, are respectively about 70 and 116 percent greater than the recommended values. Moreover they indicate an anisotropy of 27 percent.

Considerable changes in the recommended values would be necessary should these measurements prove to be reliable. Whilst the latest careful measurements by Sugawara [1375] on polycrystalline samples would appear to make this seem unlikely, the Ioffes at the same time reported a determination (curve 19) on a sample of amorphous sulfur, and for this form their value was only about 4 percent greater than a value due to Eucken [400] (curve 5). Thus the possbility of single crystals of sulfur having considerably higher values than those now proposed cannot entirely be ruled out.

For amorphous sulfur Eucken [400] made measurements at 83 and 273 K (curve 5). A curve representing the thermal conductivity of amorphous sulfur has been drawn from Eucken's value at 83 K to a mean of the Eucken and Ioffe values at 286.5 K. The thermal conductivity of amorphous sulfur is much lower and the temperature coefficient is of opposite sign than that of the crystalline form.

The proposed values are for high-purity sulfur. Those for crystalline solids above 70 K are recommended values for high-purity polycrystalline sulfur and are considered accurate to within ±10 percent of the true values from 70 K to room temperature and ±5 percent from room temperature to the melting point. Those below 70 are merely typical values for high-purity sulfur. The recommended values for amorphous sulfur are probably good to ±15 percent. Those recommended for liquid sulfur are considered accurate to within ±5 percent.

TABLE 151. Recommended thermal conductivity of sulfur†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
Polycrystalline				Amorphous	
T	k	T	k	T	k
0	0	60	0.00799	90	0.00163
1	0.00662*	70	0.00717	100	0.00165
2	0.0320*	80	0.00654	123.2	0.00169
3	0.0694	90	0.00602	150	0.00175
4	0.106	100	0.00562	173.2	0.00180
5	0.124	123.2	0.00490	200	0.00185
6	0.128	150	0.00430	223.2	0.00190
7	0.123	173.2	0.00389	250	0.00195
8	0.112	200	0.00355	273.2	0.00200
9	0.0970	223.2	0.00330	298.2	0.00205
10	0.0817	250	0.00305	300	0.00206
11	0.0688	273.2	0.00287	323.2	0.00210*
12	0.0581	298.2	0.00270	350	0.00216*
13	0.0499	300	0.00269		
14	0.0435	323.2	0.00256	Liquid	
15	0.0384	350	0.00242		
16	0.0343	368.6	0.00233		
18	0.0280	368.6	0.00154	T	k
20	0.0235	373.2	0.00154		
25	0.0169	392.2	0.00150		
				392.2	0.00129
30	0.0140			400	0.00132
35	0.0122			473.2	0.00153
40	0.0109			500	0.00160
45	0.00993			573.2	0.00169
50	0.00917				
				600	0.00170*

†The values are for high-purity sulfur, and those below 70 K are merely typical values.

*Extrapolated.

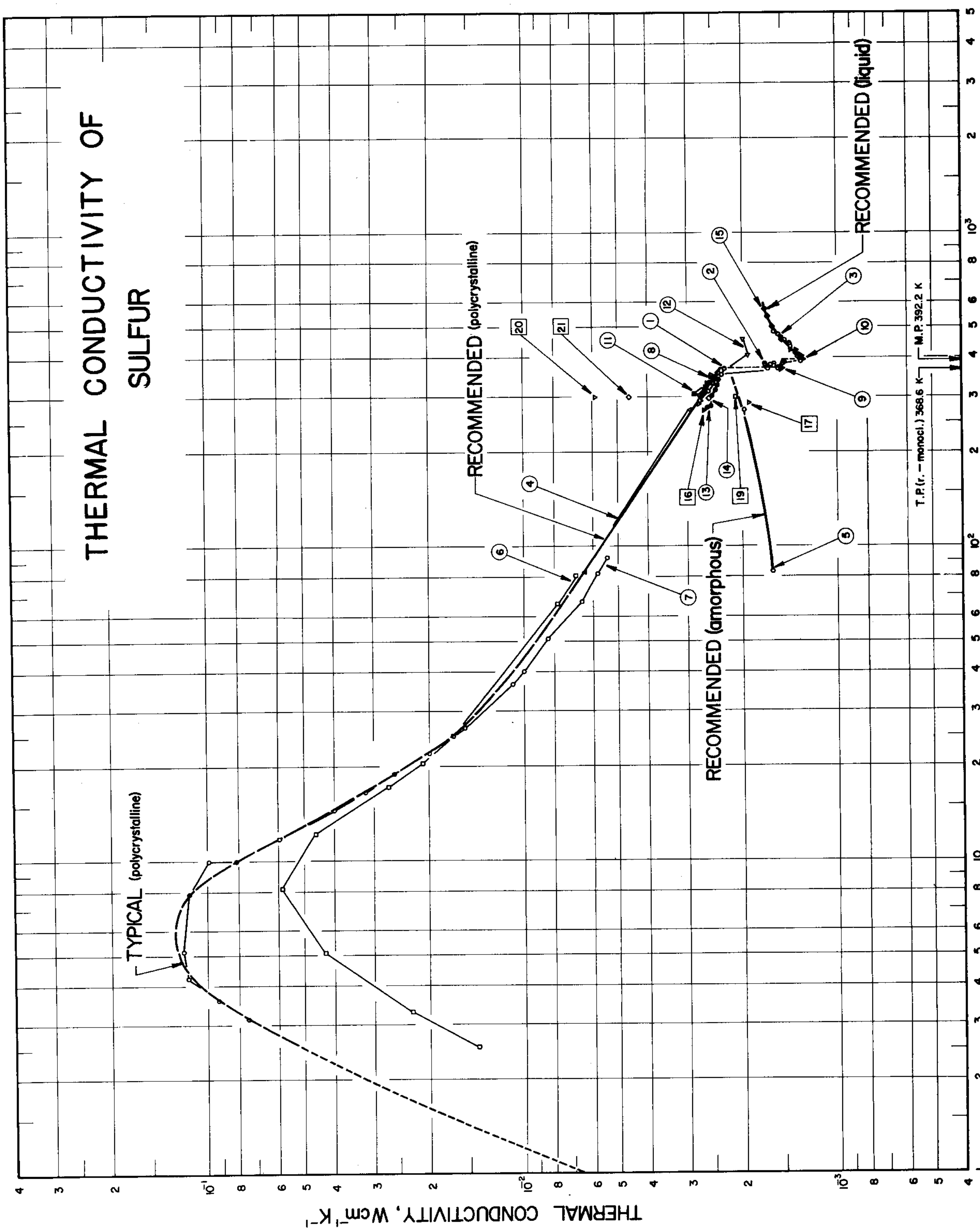

THERMAL CONDUCTIVITY OF SULFUR
RECOMMENDED (polycrystalline)
RECOMMENDED (amorphous)
RECOMMENDED (liquid)
TYPICAL (polycrystalline)
T.P. (r. – monocl.) 368.6 K
M.P. 392.2 K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 151

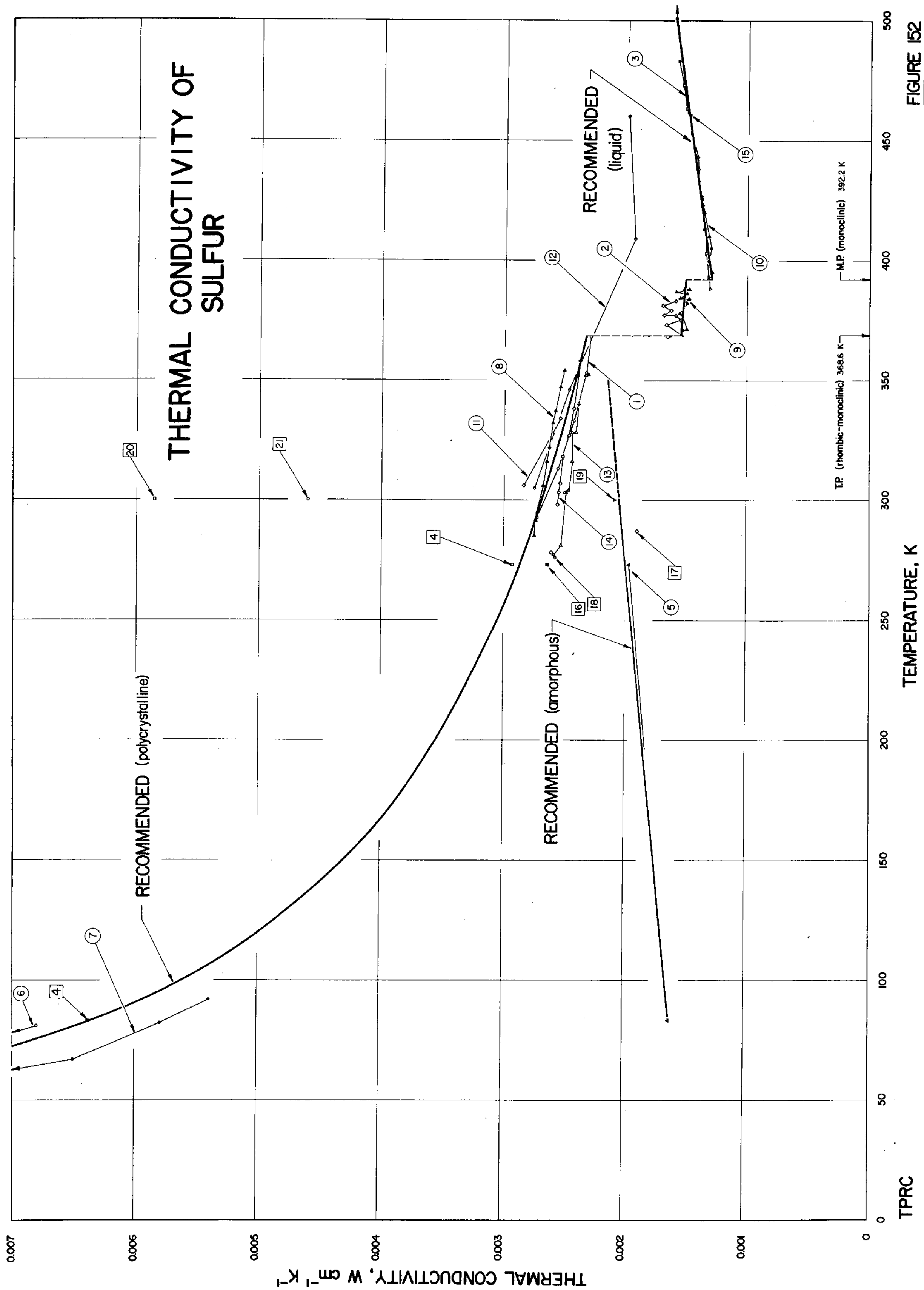

THERMAL CONDUCTIVITY OF SULFUR
RECOMMENDED (liquid)
RECOMMENDED (polycrystalline)
RECOMMENDED (amorphous)
T.P. (rhombic-monoclinic) 368.6 K
M.P. (monoclinic) 392.2 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

FIGURE 152

TABLE 152. THERMAL CONDUCTIVITY OF SULFUR - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	721	Kaye, G.W.C. and Higgins, W.F.	1929	L	293-368		Commercial purity; crystalline variety of rhombic aggregate state; specimen prepared at temperature not exceeding 160 C.
2	721	Kaye, G.W.C. and Higgins, W.F.	1929	L	368-383		The above specimen in monoclinic aggregate state.
3	721	Kaye, G.W.C. and Higgins, W.F.	1929	L	388-483		Commercial purity; in liquid state.
4	400	Eucken, A.	1911	L	83,273		Rhombic crystalline sulfur.
5	400	Eucken, A.	1911	L	83,273		Amorphous; made by casting boiling sulfur.
6	1321	Slack, G.A.	1965	L	2.6-81	R 124	Single crystal of the stable orthorhombic modification slowly grown from a CS_2 solution at room temperature in one week; sulfur starting material > 99 pure; rod-shaped sample about 0.2 cm in diameter and 0.7 cm long; transparent with a yellow color; a few small internal growth flaws visible in the sample; heat flow perpendicular to the c-axis.
7	1321	Slack, G.A.	1965	L	3.2-92	R 127	Similar to the above specimen but heat flow parallel to the c-axis.
8	1587	Yoshizawa, Y., Sugawara, A., and Yamada, E.	1964 1965	C	285-354		99.98 pure; α (rhombic) sulfur; polycrystalline; crown glass plate used as comparative material, the thermal conductivity of which is given as k = 0.803 + 0.00054 t with k in k cal $m^{-1} hr^{-1} C^{-1}$ and t in C.
9	1375	Sugawara, A.	1965	C	370-389		99.98 pure; β (monoclinic) sulfur; polycrystalline; same comparative material used as above.
10	1375	Sugawara, A.	1965	C	395-428		99.98 pure; liquid sulfur; same comparative material used as above.
11	829	Lees, C.H.	1898	L	306,334		Specimen 4 cm in dia and 0.193 cm thick.
12	979	Mogilevskii, B.M. and Chudnovskii, A.F.	1964	P	305-460		Data cover both solid and liquid states; measured by a nonsteady probe method.
13	526	Green, S.E.	1932	R	277-353		Rhombic crystal; spherical shell specimen with O.D. 10.200 cm and I.D. 5.514 cm; prepared by melting sulfur flowers at 170 C, cast in a brass mould, cooling to complete solidification in about 1.5 hrs, lowering the temperature to about 60 C for 30 min, then allowing to cool in the lagging; density 1.90 g cm^{-3}.
14	526	Green, S.E.	1932	R	280-358		Rhombic crystal; spherical shell specimen with O.D. 10.208 cm and I.D. 5.508 cm; prepared by melting sulfur flowers at 127 C, poured into a brass mould, heated to 135 C; cooled to the melting point in about 5 hrs, completely solidified after another 40 min; density 1.94 g cm^{-3}.
15	1433	Turnbull, A.G.	1959	P	460-574		Chemically pure; molten specimen contained in a cell made from two thick-walled silver tubes, the liquid annulus has outer dimensions of 28.5 mm dia x 100 mm long and a width of 8 mm; held for 24 hrs at each temperature during measurements.
16	596	Hecht, H.	1904	P	373.2		10.8 cm cubic specimen; density 2.03 g cm^{-3}; thermal conductivity value calculated from measured thermal diffusivity and the specific heat value of 0.187 cal $g^{-1} C^{-1}$.
17	828	Lees, C.H.	1892	C	287.4		Irregular shaped plate specimen 0.0584 cm in thickness; prepared by pressing between two microscope slides having plane surfaces; brass used as comparative material.
18	1039	Niven, C. and Geddes, A.E.M.	1912	L	298.2		Thin plate specimen. (Measuring temp assumed 25 C.)
19	657	Ioffe, A.V. and Ioffe, A.F.	1952	L	300		Amorphous sulfur.

TABLE 152. THERMAL CONDUCTIVITY OF SULFUR - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20	657	Ioffe, A.V. and Ioffe, A.F.	1952	L	300		Single crystal; heat flow along one crystal axis.
21	657	Ioffe, A.V. and Ioffe, A.F.	1952	L	300		Single crystal; heat flow along another crystal axis perpendicular to the above.
22*	96	Askerov, Ch. M., Aliev, G. M., and Akhundova, E. G.	1964		298.2		Crystalline; density 1.93 g cm^{-3}. (Measuring temp assumed 25 C.)
23*	96	Askerov, Ch. M., et al.	1964		298.2		Amorphous. (Measuring temp assumed 25 C.)

* Not shown in figure.

Tantalum

At low temperatures the recommended thermal conductivity values for a sample in the normal state having $\rho_0 = 0.213$ $\mu\Omega$ cm are based on the measurements of White and Woods [1554] (curve 18) for a 99.9 percent tantalum that had been annealed at 2500 C. The value of $\beta = 8.70$ derived from these measurements has been used to give calculated values up to about 30 K. White and Woods' experimental curve has been followed up to about 65 K. From here to about 300 K is a region of uncertainty and lacking in experimental evidence.

Rosenberg [1220] (curve 7) had obtained considerably lower values for a purer but unannealed sample, and had indicated a minimum in the region of 65 K but this occurred towards the upper limit of his method and appears unlikely. In the temperature range from 323 to 400 K, however, thermal conductivity values due to Deverall [353] (curve 10), Tye [1437] (curve 25), and Denman [343] (curve 53) agree to within ±4 percent and all have small positive temperature coefficients. Hence, from about 65 K, the recommended curve has been smoothly extrapolated to give a shallow minimum at about 250 K and then to pass through a point at 373 K which is the mean value obtained from these three sets of data. This curve has been continued through the upper portion of Denman's curve approximately linearly to about 1300 K and then with gradually decreasing slope as the melting point is approached. In this upper temperature range the proposed curve lies some 9 percent above the mean values of Rasor and McClelland [1178] (curves 57 and 58) and of Peletskii and Voskresenskii [1076] (curve 55), and from 5 to 10 percent below the values derived by Wheeler [1533] (curve 27) from his thermal diffusivity determinations. There are, however, uncertainties associated with the density and specific heat data required for deriving thermal conductivity values from thermal diffusivity measurements, and other available values of density and specific heat could bring Wheeler's data into close agreement at the highest temperature. For similar reasons, it seems possible that the thermal diffusivity determinations of Kraev and Stel'makh [782] (curve 54) could yield thermal conductivities having a negative temperature coefficient at these high temperatures. This would support some of the measurements of Jun and Hoch [699] (curves 30 and 31), but, these seem low, since, if the recent electrical resistivity value of Peletskii and Voskresenskii [1076] of 108.8 $\mu\Omega$ cm at 2900 K represents the value for pure tantalum, any thermal conductivity at this temperature that is lower than the recommended value by more than 2 percent would bring the Lorenz function below the theoretical value.

It is of interest to note that the 1914 measurements of Worthing [1579] (curve 3) which must have been the first reported thermal conductivity measurements for temperatures of the order of 2000 K are only from 16 to 29 percent above the proposed curve.

The uncertainty of the proposed curve is probably of the order of ±5 percent at moderate temperatures and ±10 percent at low and high temperatures. The values at temperatures below 100 K are, of course, only applicable to a sample in normal state having $\rho_0 = 0.213$ $\mu\Omega$ cm.

TABLE 153. Recommended thermal conductivity of tantalum†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	k	T	k	T	k
0	0	123.2	0.586*	1300	0.614
1	0.115	150	0.580*	1373.2	0.617
2	0.230	173.2	0.578*	1400	0.618
3	0.344	200	0.575*	1473.2	0.622
4	0.458	223.2	0.574*	1500	0.622
5	0.569	250	0.574*	1573.2	0.625
6	0.678	273.2	0.574	1600	0.626
7	0.784	298.2	0.575	1673.2	0.629
8	0.884	300	0.575	1700	0.630
9	0.979	323.2	0.576	1773.2	0.633
10	1.07	350	0.576	1800	0.634
11	1.15	373.2	0.577	1873.2	0.637
12	1.22	400	0.578	1900	0.638
13	1.28	473.2	0.582	1973.2	0.640
14	1.33	500	0.582	2000	0.641
15	1.37	573.2	0.585	2073.2	0.644
16	1.40	600	0.586	2173.2	0.647
18	1.43	673.2	0.588	2200	0.648
20	1.42	700	0.590	2273.2	0.650
25	1.30	773.2	0.593	2400	0.654
30	1.15	800	0.594	2473.2	0.656
35	0.99	873.2	0.597	2600	0.659
40	0.87	900	0.598	2673.2	0.661
45	0.78	973.2	0.602	2800	0.664
50	0.72	1000	0.602	2873.2	0.665
60	0.651	1073.2	0.605	3000	0.666
70	0.616	1100	0.606	3073	0.666
80	0.603	1173.2	0.609	3200	0.666
90	0.596	1200	0.610		
100	0.592	1273.2	0.613		

†The recommended values are for well-annealed high-purit tantalum, and those below 100 K are applicable only to a specimen having $\rho_0 = 0.214$ $\mu\Omega$ cm.

*Interpolated.

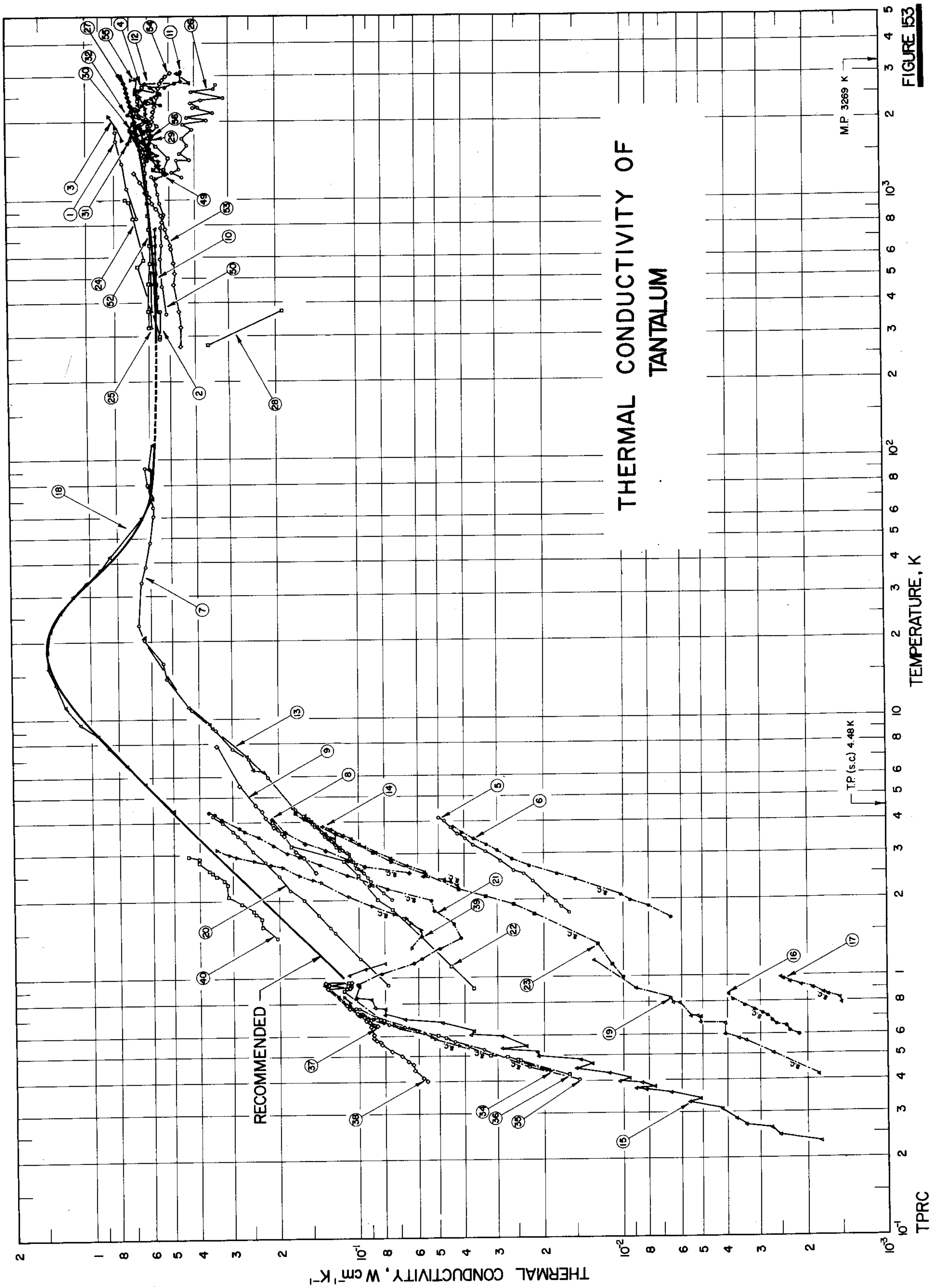


FIGURE 153
THERMAL CONDUCTIVITY OF
TANTALUM
M.P. 3269 K
T.P. (s.c) 4.48 K
RECOMMENDED
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

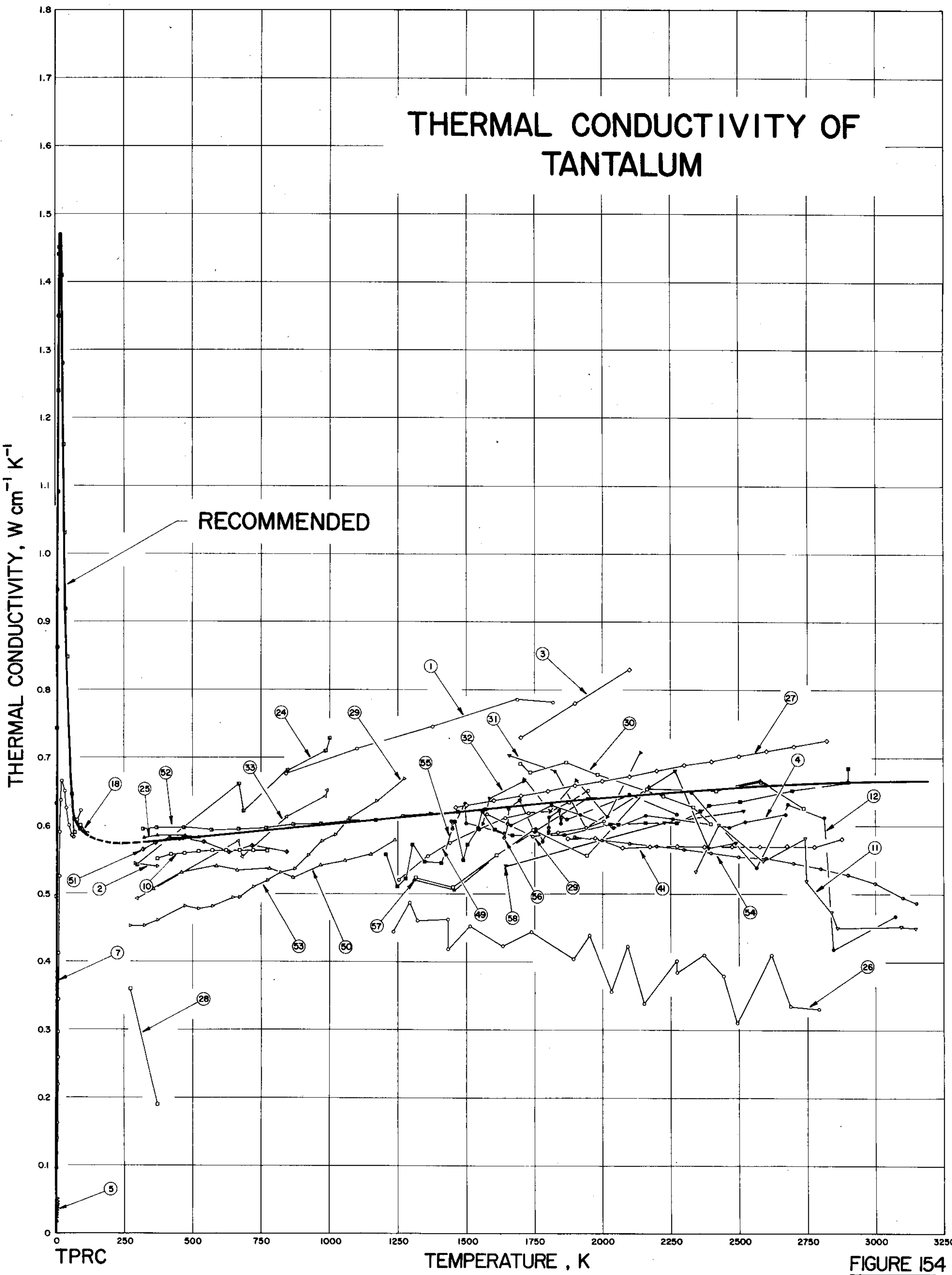

THERMAL CONDUCTIVITY OF
TANTALUM
RECOMMENDED
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE , K
TPRC

FIGURE 154

TABLE 154. THERMAL CONDUCTIVITY OF TANTALUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	430	Fieldhouse, I. B., Hedge, J. C., and Waterman, T. E.	1956	L	842-1820		Impurities (pre-test): 0.052 N, traces of Ca, Cu, and Mg; impurities (after test): 0.12 O, 0.044 N, 0.0061 H, traces of Al, Ca, Cu, Fe, and Mg; sintered; density 16.48 g cm^{-3}.
2	116	Barratt, T.	1914	F	290, 373		Pure; 0.0475 cm dia x 28.14 cm long; specific gravity 16.67; electrical resistivity reported as 14.452 and 19.178 μohm cm at 0 and 100 C, respectively.
3	1579	Worthing, A. G.	1914	E	1700-2100		Pure; filament.
4	699	Jun, C. K. and Hoch, M.	1966	→	1665-2671	No. 5	0.0036 O, 0.0018 N, 0.00009 H, and 0.00005 C; 1.9062 cm dia x 0.2273 cm thick; machined from a 1 in. rod supplied by Fansteel Metallurgical Corp; average grain size 1.86 mm; density 16.60 g cm^{-3}; thermal conductivity derived from the temp distribution on the flat surface of the cylindrical disc heated in vacuum by induction.
5	642	Hulm, J. K.	1950	L	1.7-4.2	Hilger 8017, Ta 1	99.9 pure; polycrystalline; superconducting transition point 4.38 K; measured in a magnetic field; in normal state.
6	642	Hulm, J. K.	1950	L	1.7-3.9	Hilger 8017, Ta 1	The above specimen in superconducting state.
7	1220	Rosenberg, H. M.	1955	L	2.0-92	JM 3804; Ta 1	99.98 pure; polycrystalline; specimen 0.225 cm in dia, 3 cm long; Johnson-Matthey's unannealed rod; electrical resistivity ratio $\rho(293K)/\rho(20K) = 19.7$; electrical resistivity reported as 0.62, 0.63, 0.67, 0.90, 1.05, 1.46, 2.07, 2.35, 3.04, and 3.51 μohm cm at 11.3, 16.1, 20.5, 32.2, 37.2, 46.9, 59.6, 65.1, 78.4, and 89.4 K, respectively; superconducting transition temp 4.38 K; measured in a magnetic field; in normal state.
8	933	Mendelssohn, K. and Olsen, J. L.	1950	L	2.6-4.2		Very pure; in superconducting state.
9	933	Mendelssohn, K. and Olsen, J. L.	1950	L	2.6-7.9		Very pure; measured in a magnetic field; in normal state.
10	353	Deverall, J. E.	1959	L	373-773		99.896 Ta, 0.0300 Nb, 0.0140 O, 0.0100 W, 0.0100 Zn, 0.0060 N, 0.0050 Mo, 0.0030 each of Pb, Sn, and Zr, 0.0025 C, 0.0025 H, 0.0020 each of Co, Sr, and V, 0.0010 each of Al, Ba, Bi, Cr, Fe, and Ni, 0.0005 each of Ag and Ti, 0.0003 each of B, Mn, Si, and Na, 0.0002 Be, and 0.0001 each of Ca, Cu, and Mg; specimen bar machined from a rod obtained from Fansteel Metallurgical Corp; data taken from smoothed curve.
11	50	Allen, R. D., Glasier, L. F., Jr., and Jordan, P. L.	1960	E	2343-3148	1	<0.02 Si, 0.005 Fe, 0.003 Mo, 0.0008 C, and 0.052 others; prepared by pressing and sintering tantalum powder, then hot and cold rolled.
12	50	Allen, R. D., et al.	1960	E	2326-3071	2	0.0032-0.005 O, 0.0035 Nb, 0.0028 Fe, 0.0016 C, <0.001 N, and 0.0175 others; cast in vacuum, cold rolled, swaged, and cold drawn.
13	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-21	JM 3804 Ta 1	99.98 pure; 1-2 mm dia x 5 cm long; obtained from Johnson, Matthey and Co., Ltd; measured in a magnetic field; in normal state.
14	937	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-3.9	Ta 1	The above specimen in superconducting state.

TABLE 154. THERMAL CONDUCTIVITY OF TANTALUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
15	291	Connolly, A. and Mendelssohn, K.	1962	L	0.23-1.2	Ta II	Single crystal; specimen dia 6.1 mm; ratio of length to cross-sectional area 16.6 cm^{-1}; obtained by floating-zone melting polycrystalline rod in a vacuum; electrical resistivity ratio $\rho(298K)/\rho_0$ = 47.0.
16	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.60-0.86	Ta 1	99.98 pure; polycrystalline; affected by "frozen in" magnetic field; in superconducting state.
17	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.79-1.0	Ta 1	Separate run of the above specimen; in superconducting state.
18	1554	White, G.K. and Woods, S.B.	1959	L	4.4-114	Ta 3	99.9 pure; specimen consisted of four 1.5 mm wires supplied by Fansteel Metallurgy Corp; annealed in vacuum at 2500 C; ideal electrical resistivity reported as 0.0032, 0.017, 0.051, 0.12, 0.23, 0.54, 0.95, 1.43, 1.96, 2.50, 3.03, 3.55, 4.6, 5.6, 6.65, 7.65, 8.6, 9.6, 11.0, 12.1, and 13.1 μohm cm at 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 220, 250, 273, and 295 K, respectively; electrical resistivity ratio $\rho(295K)/\rho_0$ = 62.1.
19	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.42-1.2	JM 3804	99.98 pure; polycrystalline; in superconducting state.
20	233	Calverley, A., Mendelssohn, K., and Rowell, P.M.	1961	L	0.95-4.3		0.005 Fe, 0.003 Si, 0.0003 O, and 0.00025 H; single crystal; specimen obtained by floating-zone melting polycrystalline rod; electrical resistivity ratio $\rho(298K)/\rho_0$ = 63; measured in a magnetic field; in normal state.
21	233	Calverley, A., et al.	1961	L	0.95-4.4		The above specimen in superconducting state.
22	233	Calverley, A., et al.	1961	L	0.92-4.0		0.1 Nb, 0.01 C, 0.01 Fe, 0.01 Mo, 0.01 W, 0.001 O, 0.00075 N, and 0.00045 H; polycrystalline; electrical resistivity ratio $\rho(298K)/\rho_0$ = 31; measured in a magnetic field; in normal state; specimen same as that used by Rosenberg in 1955 (curve 7).
23	233	Calverley, A., et al.	1961	L	1.0-4.3		The above specimen in superconducting state.
24	312	Cutler, M., Snodgrass, H.R., Cheney, G.T., Appel, J., Mallon, C.E., and Meyer, C.H., Jr.	1961	E	299-1000	No. 9	99.9 pure; obtained from Fansteel Metallurgical Corp; density 16.4 g cm^{-3}; electrical resistivity reported as 15.1, 34.3, 35.0, 41.3, 48.2, and 48.8 μohm cm at 297, 670, 685, 840, 980, and 1000 K, respectively.
25	1437	Tye, R.P.	1961	L, C	323-523	JM 615	Spectrographically standardized tantalum; obtained from Johnson, Matthey and Co., Ltd; about 4.5 mm in dia and 10 cm long; electrical resistivity reported as 14.5, 15.45, 17.72, 22.25, and 24.4 μohm cm at 293, 323, 373, 473, and 523 K, respectively.
26	566, 565, 477	Gumenyuk, V.S., Ivanov, V.E., and Lebedev, V.V.	1962	E	1233-2793		1 mm in dia, 30 mm long; electrical resistivity reported as 50, 73, 89, and 109 μohm cm at 900, 1500, 2000, and 2500 C, respectively.
27	1533	Wheeler, M.J.	1965	P	1460-2820		~99.89 Ta (by difference), <0.1 Nb, <0.01 C, and traces of other elements; 0.040 in. thick sheet; obtained from Murex Co.; vacuum beam melted; average grain size after testing 140 μ; density 16.6 g cm^{-3}; thermal conductivity values calculated from data of thermal diffusivity using the specific heat data of Kubaschewski, O. and Evans, L.Ll., (Metallurgical Thermochemistry, London, Pergamon, 1956).

TABLE 154. THERMAL CONDUCTIVITY OF TANTALUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
28	302	Cox, M.	1943	E	273, 373		99.9 pure; 0.01 in. in dia and ~15.7 in. long (40 cm); obtained from Fansteel Corp; electrical resistivity reported as 2.46, 12.41, and 17.18 μohm cm at 77.33, 273.2, and 373.4 K, respectively; measured in a vacuum of 10^{-6} mm Hg. (The 10-90% uncertainty reported arises from lack of knowledge of emissivity).
29	699	Jun, C.K. and Hoch, M.	1966	→	1578-2007	No. 1	0.0019 C, 0.0017 H, 0.0017 N, and 0.0017 O; specimen 2.4892 cm in dia and 0.3927 cm thick; average grain size 0.26 mm; density 16.65 g cm^{-3}; thermal conductivity derived from the temp distribution on the flat surface of the cylindrical disc specimen heated in high vacuum (10^{-6} mm Hg) by high frequency induction.
30	699	Jun, C.K. and Hoch, M.	1966	→	1700-2398	No. 2	0.0655 O, 0.0137 C, 0.0016 N, and 0.00027 H; machined from the same bar as the above specimen; 2.2232 cm in dia and 0.2125 cm thick; density 16.63 g cm^{-3}; measuring method same as above.
31	699	Jun, C.K. and Hoch, M.	1966	→	1660-2490	No. 3	0.0114 O, 0.003 C, and 0.0016 N, and 0.00027 H; machined from the same bar as the above specimen; 2.2232 cm in dia and 0.2018 cm thick; avg. grain size 1.04 mm dia; density 16.62 g cm^{-3}; measuring method same as above.
32	699	Jun, C.K. and Hoch, M.	1966	→	1563-2142	No. 4	0.0036 O, 0.0018 N, 0.0009 H, and 0.00005 C; machined from the same bar as the above specimen; 1.9075 cm in dia and 0.2316 cm thick; avg. grain size 1.23 mm dia; density 16.63 g cm^{-3}; measuring method same as above.
33	309	Cutler, M.	1962	T	300-995		No details given for the specimen; thermal conductivity measured by the "small area contact method".
34	1299	Sharma, J.K.N.	1967	L	0.44-0.86		99.994 pure; single crystal; prepared by zone-refining technique in a vacuum of 10^{-6} mm Hg; the starting material of 99.9 percent purity supplied by Murex Ltd; form factor $(\ell/a) = 1.82 \times 10^{2}$ cm^{-1}; electrical resistivity 0.173 μohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 80$; in superconducting state; run No. 35.
35	1299	Sharma, J.K.N.	1967	L	0.41-0.78		The above specimen in superconducting state; run No. 44.
36	1299	Sharma, J.K.N.	1967	L	0.43-0.97		The above specimen in superconducting state; run No. 45.
37	1299	Sharma, J.K.N.	1967	L	0.66-0.96		The above specimen measured in a magnetic field of 1.5 kilogauss; in normal state; run No. 46.
38	1299	Sharma, J.K.N.	1967	L	0.41-0.97		The above specimen in normal state; anomalous peak observed at 0.57 K; run No. 47.
39	1299	Sharma, J.K.N.	1967	L	1.3-3.3		The above specimen measured in a different cryostat; in superconducting state.
40	1299	Sharma, J.K.N.	1967	L	1.4-3.0		The above specimen measured in a magnetic field of 1.5 kilogauss; in normal state.
41	1364	Kraev, O.A. and Stel'makh, A.A.	1966	P	1873-2873		Thermal conductivity values calculated from measured thermal diffusivity data with density data taken from Chirkin, V.C. (Teploprovodnost Promizhlennich Materialov. M., Mazhgiz, 1962) and specific heat data taken from Kraftmakher, Ya.A. (Zh. Prikl. Mekhan. i Tekhn. Fiz., (2), 158-60, 1963).

TABLE 154. THERMAL CONDUCTIVITY OF TANTALUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
42*	1520	Wechsler, A.E.	1967	C	311.7	42A	0.0044 O, 0.0042 Nb, <0.004 W, 0.0033 C, <0.001 each of Al, Mo, and Si, 0.0008 N, 0.0007 Fe, <0.0005 Ti, <0.0001 each of Cr, Cu, and Ni; specimen 0.62 in. in dia and 0.61 in. thick; supplied by National Research Corp., Cambridge, Mass; density 16.64 g cm^{-3}; electrical resistivity 13.9 and 2.98 μohm cm at 293.2 and 77 K, respectively; Armco iron used as comparative material; preliminary data.
43*	1520	Wechsler, A.E.	1967	C	312.1	44B	Similar to the above specimen.
44*	1520	Wechsler, A.E.	1967	C	311.3	55A	Similar to the above specimen except heated at 2040 C for 10 hrs; electrical resistivity 13.70 and 2.83 μohm cm at 293.2 and 77 K, respectively.
45*	1520	Wechsler, A.E.	1967	C	311.3	56B	Similar to the above specimen except electrical resistivity 13.30 and 2.73 μohm cm at 293.2 and 77 K, respectively.
46*	1520	Wechsler, A.E.	1967	C	310.3	86A	Similar to the above specimen except heated at 2040 C for 20 hrs; electrical resistivity 13.73 and 2.91 μohm cm at 293.2 and 77 K, respectively.
47*	1520	Wechsler, A.E.	1967	C	310.6	87B	Similar to the above specimen.
48*	1045	Null, M.R. and Lozier, W.W.	1969	P	1750		Specimen 12.7 mm in dia and 10.6 mm thick; electrical resistivity 13.08 μohm cm at room temp; thermal conductivity value calculated from the measurement of thermal diffusivity, using the specific heat data of Spence, G.B., (WADD Tech. Report 61-72, Vol. XLI, Nov. 1963), and the density 16.6 g cm^{-3} at room temp.
49	1020	Neimark, B.E. and Voronin, L.K.	1968	E	1255-1946		0.3 Nb, 0.015 C, 0.003 O, 0.002 N, and 0.001 H; specimen ~2 mm in dia and 140-160 mm long; electrical resistivity reported as 60, 61, 64, 65, 67, 70, 73, 75, 77, 79, 84, and 86 μohm cm at 1161, 1186, 1263, 1274, 1367, 1450, 1539, 1600, 1667, 1747, 1864, and 1946 C, respectively; Lorenz function reported as 2.60, 2.58, 2.56, 2.54, 2.52, 2.51, 2.50, 2.48, 2.47, 2.47, 2.46, 2.46, 2.45, 2.44, and 2.44 x 10^{-8} V^2 deg^{-2} at 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1400, 1500, 1600, and 1700 C, respectively.
50	1020	Neimark, B.E. and Voronin, L.K.	1968	E	364-1245		The above specimen measured in different apparatus; electrical resistivity reported as 16, 17, 18, 20, 22, 23, 25, 27, 28, 30, 33, 34, 37, 39, 40, 42, 44, 45, 47, 50, 52, 54, and 55 μohm cm at 10, 50, 78, 127, 156, 184, 227, 278, 313, 351, 394, 444, 501, 544, 594, 645, 692, 746, 774, 840, 921, 969, and 981 C, respectively.
51	975	Minges, M.L.	1969	C	325-847	Metallurgical grade	99.8 minimum Ta, 0.03 each of C, W, and O, 0.02 each of Ni, Fe, and Si, 0.015 N, 0.01 Ti, and 0.01 H; specimen 1.0 in. in dia and 2.0 in. long; supplied by Fansteel Metallurgical Corp, Chicago, Ill; sintered; density 16.56 g cm^{-3} (99.4% of theoretical value); measured in a vacuum between 1.0 x 10^{-5} and 1.2 x 10^{-6} torr; Armco iron used as comparative material.
52	1157	Pozdnyak, N.Z. and Akhmetzyanov, K.G.	1963	E	273-1273		99.4^{+} Ta, 0.5 Nb, 0.06 Fe, 0.008 Ti, 0.005 W, 0.003 Si, 0.002 C, and 0.001 Mo; cylindrical specimen 4 mm in dia and 100 mm long sintered from electrolytic powder of tantalum; rectangular sample from tantalum powder was compressed under a pressure of 2.5 ton cm^{-2}; sintered in vacuum (residual pressure 10^{-3} mm Hg) for 5 hrs at 1723 K, resintered in a vacuum of 10^{-5} mm Hg for 5 hrs at 2873 K, then forged to the desired dia, refined twice by the method of zone-melting; electrical conductivity at 273, 473, 673, 873, 1073, and 1273 K was, respectively, 8.0, 4.35, 2.86, 2.26, 2.0, and 1.66 x 10^4 ohm^{-1} cm^{-1}.

TABLE 154. THERMAL CONDUCTIVITY OF TANTALUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
53	343	Denman, G. L.	1969	P	323-1573		0.02 Nb, 0.01 Fe, 0.01 Zr, 0.002 Cr, 0.008 O, 0.0021 N, 0.0017 C, 0.00005 H; 0.686 cm dia x 0.152 cm thick; supplied by Fansteel Met. Corp; manufactured by powder metallurgy; density 16.50 g cm^{-3}; electrical resistivity reported as 14.0, 14.2, 16.7, 21.5, 25.6, 26.6, 29.8, 31.4, 34.1, and 35.8 μohm cm at 24, 31, 88, 189, 282, 306, 372, 422, 480, and 521 C, respectively; thermal conductivity values calculated from measured thermal diffusivity data, specific heat values taken from Hultgren, R., Orr, R. L., Anderson, P. D., and Kelley, K. K. ("Selected values of thermodynamic properties of metals and alloys," John Wiley and Sons, 271-275, 1963), and density values obtained by using literature values for thermal expansion of tantalum; reported values taken from smooth curve.
54	782	Kraev, O. A. and Stel'makh, A.A.	1964	P	1900-3150		8-9 mm dia x 0.2 mm thick; thermal conductivity values not given in the paper but calculated by TPRC using the author's thermal diffusivity data and using the TPRC selected density and specific heat values from Thermophysical Properties of High Temperature Solid Materials, Vol. 1, MacMillan, 1967, and the density further calculated from the thermal expansion values.
55	1076	Peletskii, V. E. and Voskresenskii, V. Yu.	1966	L	1208-2900		99.61 Ta, 0.33 Nb, 0.02 Mo, 0.014 W, <0.01 Fe, <0.01 Si, and <0.01 Ti; 7.28 mm in dia and 65.8 mm long; prepared from a bar produced by electron-beam melting in vacuum; density 16.57 g cm^{-3} at 20 C; electrical resistivity reported as 54.8, 63.3, 64.5, 72.4, 80.7, 90.5, 100.4, and 105.2 μohm cm at 1243, 1488, 1512, 1750, 2010, 2350, 2623, and 2782 K, respectively.
56	1396	Taylor, R.E., Davis, F.E., Powell, R.W., and Kimbrough, W.D.	1969	E	1449-2272	Metallurgical grade	99.9 pure with small amounts of Ca, Cu, Mg, and Si, and traces of Fe, Ni, and Zr; specimen 0.040 in. I.D., 0.125 in. O.D., and 7 in. long; supplied by Uniform Tubes, Inc., Collegeville, Pa.; density 16.6 g cm^{-3}; electrical resistivity reported as 46.1, 46.9, 47.3, 48.6, 49.0, 49.5, 50.9, 51.9, 52.3, 53.0, 53.9, 55.2, 56.2, 57.2, 58.1, 60.1, 61.8, 63.0, 63.5, and 64.8 μohm cm at 1061, 1078, 1088, 1121, 1133, 1152, 1187, 1202, 1232, 1251, 1268, 1308, 1331, 1367, 1384, 1439, 1487, 1524, 1534, and 1578 K, respectively.
57	1178	Rasor, N.S. and McClelland, J.D.	1957	R	1314-2737		Before test: 0.73 Cu, 0.73 Zr, 0.21 Fe, 0.09 Ni, 0.08 C, 0.07 Co, 0.03 Mn, 0.02 Si, 0.017 Al, 0.0047 Cr, and 0.0033 Ca; after test: 0.015 C, 0.013 Si, 0.0023 Cr, and 0.0019 Cu; obtained from Fansteel Metallurgical Co.; 0.5 in. I.D., 2 in. O.D., and 3 in. long, fabricated from 12 disks; sintered; density 14.6 g cm^{-3}.
58	1178	Rasor, N.S. and McClelland, J.D.	1957	R	1644-2514		The above specimen measured at decreasing temps.

Technetium

Values of the thermal conductivity of technetium for the temperature range 298 to 838 K have been derived by Baker [109] (curve 1) from determinations of the thermal diffusivity of this metal, and a smooth curve has been drawn through the points so obtained. The thermal conductivity is constant to within 3 or 4 percent over the range studied.

The corresponding moderate- and high-temperature electrical resistivity determinations do not appear to have been reported, although technetium is known to become superconducting at the relatively high temperature of 8.22 K [1238]. Indeed, Meaden [913] has estimated the electrical resistivity of technetium at 295 K to be 14 to 15 $\mu\Omega$ cm, by using the foregoing thermal conductivity data and assuming the theoretical value to hold for the Lorenz function. Baker had used the flash heating method and of course this required no knowledge of the electrical resistivity. Technetium is probably the only metal for which an electrical resistivity value has first been derived from knowledge of the thermal conductivity.

The values are thought to be accurate to within ±10 percent near room temperature and ±20 percent at the highest temperatures.

TABLE 155. Recommended thermal conductivity of technetium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	573.2	0.499
273.2	0.509*	600	0.499
298.2	0.507	673.2	0.504
300	0.507	700	0.507
323.2	0.504	773.2	0.515
350	0.502	800	0.519
373.2	0.501	873.2	0.530*
400	0.500	900	0.534*
473.2	0.498		
500	0.498		

†For well-annealed high-purity technetium.
*Extrapolated.

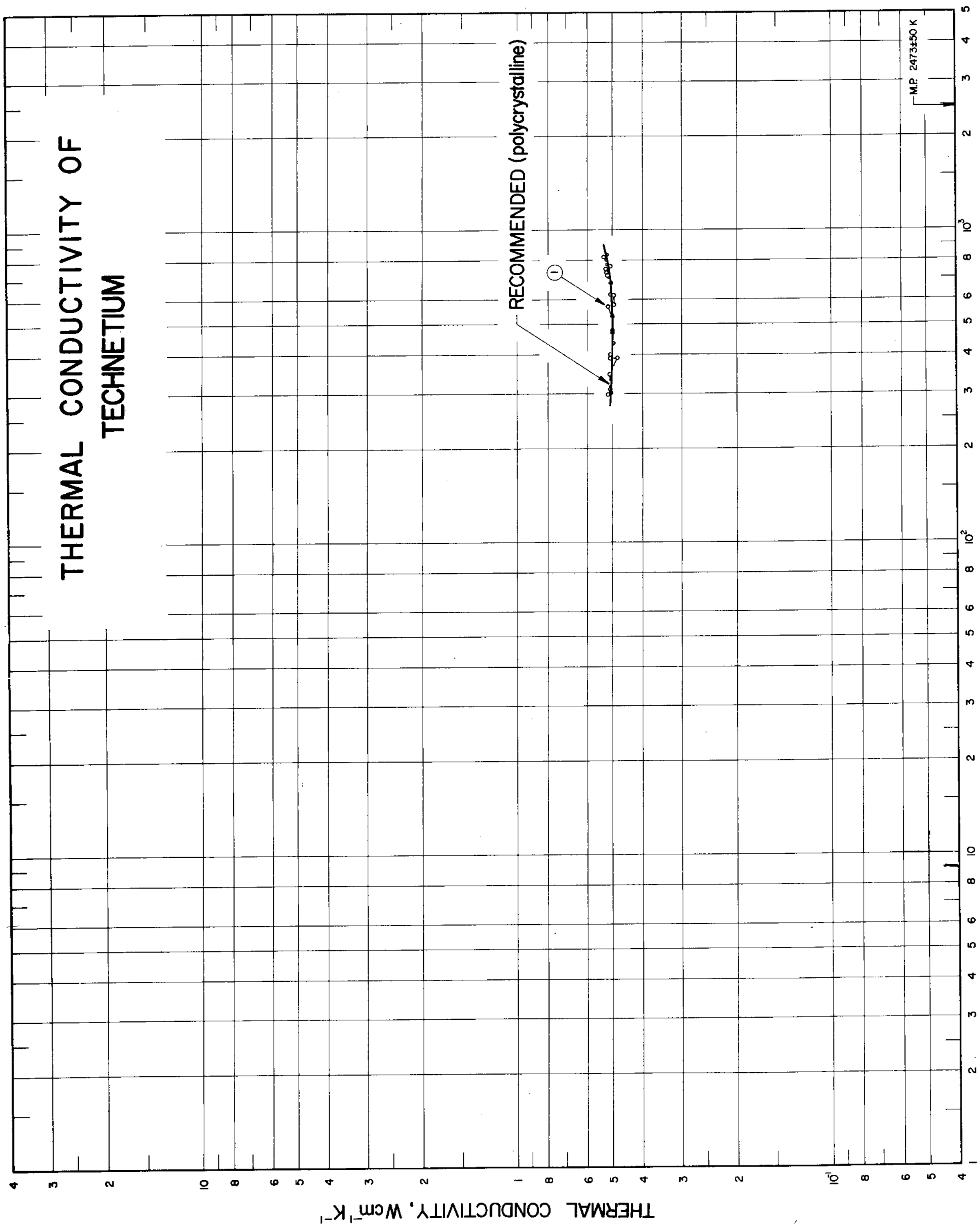

THERMAL CONDUCTIVITY OF TECHNETIUM
RECOMMENDED (polycrystalline)
M.P. 2473±50 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, $Wcm^{-1}K^{-1}$
TPRC

FIGURE 155

TABLE 156. THERMAL CONDUCTIVITY OF TECHNETIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Compsotion (weight percent), Specifications and Remarks
1	109	Baker, D.E.	1965	P	298-838		Total impurities ~ 0.0150; specimen ~0.12 cm thick and 2.3 cm in dia; prepared from reduced metal recovered from fission-product wastes; the material melted in an electron-beam evaporator, heated to 1540 C by induction, press forged, and ground to final shape; thermal conductivity values calculated from measured data of thermal diffusivity, the measured density (11.492 g cm^{-3}), and the heat capacity data taken from Stull, D.R. and Sinke, G.C. (Thermodynamic Properties of the Elements, American Chemical Soc., Washington, D.C., pp.198-9, 1956).

Tellurium

Since tellurium has a hexagonal crystal structure, it is an element for which anisotropic conducting properties are to be expected. This has been confirmed for the temperature range 1.8 to about 100 K by Adams, Baumann, and Stuke [22] (curves 24 and 25) and by Oskotskii, Pogarskii, Timchenko, and Shalyt [1057] (curves 30–33), and from 120 to 600 K by Amirkhanov, Bagduev, and Kazhlayev [59] (curves 7–9). Except at the lowest temperatures where size effects or structural defects could become important, the ratio $k_{\parallel}/k_{\perp}$ was of the order of 2. The proposed curves for the parallel and perpendicular directions have been drawn based upon these data, giving $k_{\parallel}/k_{\perp}=2$.

For molten tellurium ten sets of data cover small temperature ranges. Those of Amirkhanov, Bagduev, and Kazhlayev [58] (curve 1) and of Cutler and Mallon [311] (curve 19) are in fair agreement, but their values considerably exceed those of the solid and decrease strongly with increase in temperature. The subsequent determinations by Benguigui [130] (curve 23) cover a larger temperature range, are lower in value, and increase with temperature. These values indicate a Lorenz function which decreases from 4.4×10^{-8} to 3.2×10^{-8} V^2 K^{-2} over the range 743 to 923 K. The more recent determinations by Yurchak, Smirnov, and Kanevskaya [1596] (curve 38) and by Shadrichev and Smirnov [1292] (curves 28 and 29) and Shadrichev, Smirnov, and Kutasov [1293] (curves 35–37) using two quite different methods are still lower but in fair mutual agreement. The last mentioned values follow closely the predictions of the Wiedemann-Franz-Lorenz law and the theoretical Lorenz function, which would indicate liquid tellurium to have metallic properties. The recommended curve follows the data of Shadrichev, et al. [1293] and of Shadrichev and Smirnov [1292].

The proposed values at temperatures above 50 K are recommended values and are thought to be accurate to within ±10 to ±15 percent for the solid and ±10 to ±20 percent for the liquid phase. Below 50 K they are merely typical values and represent two typical curves serving only to indicate the general trend of the thermal conductivity, since in this region the thermal conductivity is highly conditioned by purity and imperfection.

TABLE 157. Recommended thermal conductivity of tellurium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to c-axis k	⊥ to c-axis k	T	∥ to c-axis k	⊥ to c-axis k
0	0	0	60	0.180	0.0870
1	0.710*	0.198*	70	0.146	0.0723
2	3.14	0.906	80	0.122	0.0618
3	5.75	1.87	90	0.104	0.0542
4	6.72	2.50	100	0.0912	0.0484
5	6.59	2.67	123.2	0.0716	0.0396
6	5.92	2.56	150	0.0585	0.0328
7	5.04	2.28	173.2	0.0513	0.0291
8	4.33	1.91	200	0.0455	0.0259
9	3.66	1.57	223.2	0.0417	0.0239
10	3.09	1.30	250	0.0383	0.0221
11	2.67	1.10	273.2	0.0360	0.0208
12	2.31	0.943	298.3	0.0338	0.0197
13	2.01	0.823	300	0.0337	0.0196
14	1.77	0.728	323.2	0.0320	0.0188
15	1.57	0.649	350	0.0304	0.0180
16	1.40	0.583	373.2	0.0292	0.0173
18	1.14	0.482	400	0.0280	0.0168
20	0.950	0.407	473.2	0.0256	0.0156
25	0.660	0.289	500	0.0250	0.0152
30	0.494	0.221	573.2	0.0236	0.0146
35	0.391	0.178	600	0.0234	0.0144
40	0.321	0.148	673.2	0.0230	0.0141
45	0.271	0.127	700	0.0229	0.0141
50	0.233	0.110	722.7	0.0229	0.0140

Liquid

T	k
722.7	0.0290
773.2	0.0381
800	0.0424
873.2	0.0522
900	0.0554
973.2	0.0630
1000	0.0651
1073.2	0.0696
1100	0.0709*

†The values are for well-annealed high-purity tellurium, and those below 50 K are merely typical values.

* Extrapolated.

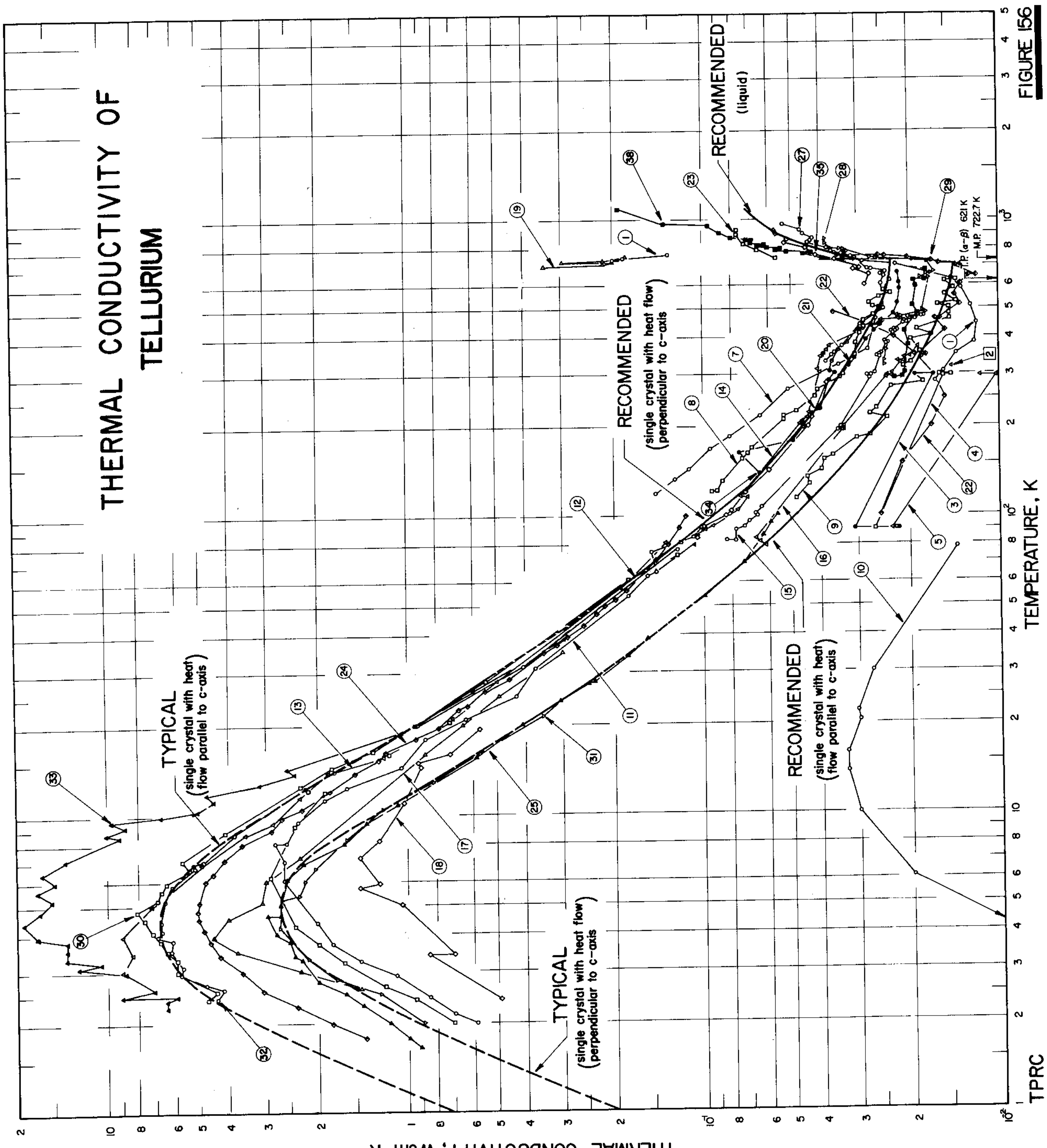

THERMAL CONDUCTIVITY OF TELLURIUM
FIGURE 156
RECOMMENDED (liquid)
RECOMMENDED (single crystal with heat flow perpendicular to c-axis)
RECOMMENDED (single crystal with heat flow parallel to c-axis)
TYPICAL (single crystal with heat flow parallel to c-axis)
TYPICAL (single crystal with heat flow perpendicular to c-axis)
T.P. (α–β) 621 K
M.P. 722.7 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

TABLE 158. THERMAL CONDUCTIVITY OF TELLURIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	58	Amirkhanov, Kh.I., Bagduev, G. B., and Kazhlayev, M.A.	1957	L	285-763		Spectrally pure; polycrystalline; bar specimen prepared by triple fractional distillation in vacuum of 10^{-4} mm Hg, cold pressing under 4000 kg cm^{-2}, and hot pressing at 673 K under 380 kg cm^{-2} for 6 hrs; melting point 452 C; measured in both solid and liquid states.
2	1573	Wold, P.I.	1916	P	318.5		Material supplied by Eimer and Amend; melted and cast in a hydrogen atmosphere; density 6.25 g cm^{-3}; thermal conductivity value calculated from measured thermal diffusivity using specific heat value taken from literature.
3	242	Cartwright, C.H.	1933	L	90-298		< 0.01 impurities; single crystal; electrical resistivity reported as 0.021 and 0.035 ohm cm at 90 and 298 K, respectively; heat flow parallel to crystal axis.
4	242	Cartwright, C.H.	1933	L	90-299		< 0.01 impurities; polycrystalline; cast; electrical resistivity 0.030 ohm cm at 296 K.
5	242	Cartwright, C.H.	1933	L	90-296		< 0.01 impurities; polycrystalline; cast; electrical resistivity 0.200 ohm cm at 296 K.
6*	60	Amirkhanov, Kh.I., Daibov, A.Z., and Zhuze, V.P.	1954	L, C	298.2		15 mm dia disk; electrical resistivity reported as 0.235 ohm cm at 298 K; concentration of current carriers = 3.46×10^{16} cm^{-3}.
7	59	Amirkhanov, Kh.I., Bagduev, G. B., and Kazhlayev, M.A.	1959		118-462	1	Single crystal; tempered in vacuum for 24 hrs at 673 K; heat flow parallel to principal crystal axis.
8	59	Amirkhanov, Kh.I., Bagduev, G. B., and Kazhlayev, M.A.	1959		122-622	2	Single crystal; heat flow parallel to principal crystal axis.
9	59	Amirkhanov, Kh.I., Bagduev, G. B., and Kazhlayev, M.A.	1959		115-622	3	Single crystal; heat flow perpendicular to principal crystal axis.
10	439	Fischer, G., White, G.K., and Woods, S.B.	1957	L	2.0-78	Te 1	~99.5 pure; polycrystalline; 5 mm dia, 1.5 cm long; broken from a longer rod; supplied by Messrs. A.D. MacKay, Inc.
11	439	Fischer, G., White, G.K., and Woods, S.B.	1957	L	2.0-92	Te 2	99.99 pure; polycrystalline; individual crystals 1 or 2 mm wide and up to 1 cm long; specimen 3 mm in dia, ~5 cm long; fabricated from pure crystalline lump supplied by Messrs. A.D. MacKay, Inc., zone refined, etched, melted under vacuum in Pyrex tube and allowed to recrystallize.
12	439	Fischer, G., White, G.K., and Woods, S.B.	1957	L	2.0-74	Te 3	Similar to above but the specimen composed of only 5 or 6 crystals of larger size.
13	439	Fischer, G., White, G.K., and Woods, S.B.	1957	L	3.0-82	Te 5	The above specimen annealed for about 5 days at a temp just below the melting point, then cooled slowly for 24 hrs to produce a single crystal; crystallographic axis at about 80° to the axis of cylindrical specimen.
14	355	Devyatkova, E.D., Moizhes, B. Ya., and Smirnov, I.A.	1959	L	85-472	I	Single crystal; 0.72 x 1.06 x 1.95 cm; hole concentration 1×10^{15} cm^{-3}; heat flow in direction of main crystallographic axis.
15	355	Devyatkova, E.D., Moizhes, B. Ya., and Smirnov, I.A.	1959	L	83-471	II	Single crystal; 0.48 x 0.84 x 1.67 cm; prepared by recrystallization of Te distilled two or three times, slow cooling in a sealed evacuated ampule made of high melting-point glass; hole concentration 9×10^{16} cm^{-3}; heat flow in direction of main crystallographic axis.

* Not shown in figure.

TABLE 158. THERMAL CONDUCTIVITY OF TELLURIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	355	Devyatkova, E.D., Moizhes, B.Ya., and Smirnov, I.A.	1959	L	80-373	III	Sb-doped; single crystal; 0.77 x 0.80 x 2.03 cm; prepared in same manner as the above specimen, except some antimony added to the twice-distilled tellurium; hole concentration 5 x 10^{18} cm^{-3}.
17	1409	Timchenko, I.N. and Shalyt, S.S.	1962	L	2.6-35	No. 1	Single crystal; 28 x 0.31 x 0.3 cm; specimen axis along principal crystal axis; prepared by zone melting; annealed for 70 hrs at 593 K; etched in SR-4; carrier concentration 3 x 10^{14} cm^{-3} at 77 K.
18	1409	Timchenko, I.N. and Shalyt, S.S.	1962	L	2.4-20	No. 2	Single crystal; 17 x 0.36 x 0.33 cm; specimen axis along principal crystal axis; prepared by zone melting; etched in HNO_3; carrier concentration 7 x 10^{14} cm^{-3} at 77 K.
19	311	Cutler, M. and Mallon, C.E.	1962	→	696-750		Pure; liquid specimen contained in a sealed Pyrex glass vessel; electrical resistivity reported as 0.77, 0.68, 0.58, 0.49, 0.48, 0.45, 0.44, and 0.41 milliohm cm at 394, 404, 433, 469, 472, 496, 502, and 528 C, respectively; data corrected for conduction of heat through the current lead.
20	1326	Smirnov, I.A. and Shadrichev, E.V.	1962	L	84-280	No. 1	Single crystal; specimen cut from single crystal ingot obtained by slow cooling of molten tellurium in a sealed evacuated ampoule; annealed in sealed ampoule for 90 hrs at 613 K; hole concentration ~2 x 10^{16} cm^{-3} at 80 K; measured under atm of argon, with heat flow along the c-axis.
21	1326	Smirnov, I.A. and Shadrichev, E.V.	1962	C	320-660	No. 1	The above specimen measured by a comparative method using fused quartz as comparative material.
22	1377	Süsmann, H.	1961	C	100-485		99.6 pure; polycrystalline; specimen 0.3 cm long and 0.5 cm in dia; hole concentration 3 x 10^{16} cm^{-3} (as calculated from Hall effect); brass (38.5 Zn, 61.5 Cu) used as comparative material; data taken from smoothed curve of 4 measurements.
23	130	Benguigui, L.	1966	L	743-923		99.995 pure; molten specimen contained in a short cylindrical cell.
24	22	Adams, A.R., Baumann, F., and Stuke, J.	1967	L	1.8-98		Single crystal; specimen 2.09 mm^2 in cross section and of sufficient length to use a spacing of 2.3 cm between the temperature points; heat flow parallel to the c-axis; (additional information and the tabulated data obtained from author).
25	22	Adams, A.R., Baumann, F., and Stuke, J.	1967	L	1.7-101		Single crystal; specimen 2.412 mm^2 in cross section and of sufficient length to use a spacing of 0.665 cm between the temperature points; heat flow perpendicular to the c-axis; (additional information and the tabulated data obtained from author).
26*	1292	Shadrichev, E.V. and Smirnov, I. A.	1967	L	332-685	1	Single crystal; electrical conductivity 9.0, 11.6, 15.5, 20.3, 24.8, 28.2, 32.6, 37.3, 41.8, 48.9, 55.4, 61.3, 67.0, 74.0, 80.1, 87.4, 94.4, 102.8, 115.0, and 125.2 ohm^{-1} cm^{-1} at 355, 382, 408, 441, 458, 473, 494, 511, 526, 546, 565, 580, 593, 608, 620, 633, 645, 658, 677, and 690 K, respectively; measured without container.
27	1292	Shadrichev, E.V. and Smirnov, I. A.	1967	L	333-969	2	Similar to above but measured with container in both solid and liquid states.
28	1292	Shadrichev, E.V. and Smirnov, I. A.	1967	L	324-867		Polycrystalline; electrical conductivity 3.7, 6.7, 11.1, 17.6, 26.8, 48.4, 61.3, 73.8, 88.1, 96.2, 106.7, 1674, 1900, 2034, 2197, 2340, 2461, 2553, 2623, 2661, 2664, and 2648 ohm^{-1} cm^{-1} at 295, 359, 405, 450, 497, 588, 631, 667, 696, 709, 726, 726, 755, 776, 805, 840, 877, 914, 953, 998, 1010, and 1080 K, respectively; measured in both solid and liquid states.

* Not shown in figure.

TABLE 158. THERMAL CONDUCTIVITY OF TELLURIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
29	1292	Shadrichev, E. V. and Smirnov, I. A.	1967	L	346-807		Similar to above but electrical conductivity 2.9, 4.0, 5.5, 7.2, 9.8, 13.2, 16.0, 20.1, 24.0, 28.3, 35.6, 41.5, 48.7, 56.1, 60.5, 67.7, 75.8, 85.0, and 95.6 ohm^{-1} cm^{-1} at 297, 323, 360, 387, 411, 437, 457, 486, 509, 531, 564, 588, 616, 638, 658, 676, 692, 710, and 723 K, respectively.
30	1057	Oskotskii, V. S., Pogarskii, A. M., Timchenko, I. N., and Shalyt, S. S.	1968	L	2.4-82		Natural form Te composed of 1/3 of Te^{128} isotope, 1/3 of Te^{130} isotope, and 1/3 of the six isotopes Te^{126}, Te^{125}, Te^{124}, Te^{122}, Te^{123}, and Te^{120}; single crystal grown by Czochralskii method; specimen 40-50 mm long, 3 mm dia of the circle inscribed in the hexagon; hole concentration 10^{14}-10^{15} cm^{-3}; heat flow parallel along c-axis.
31	1057	Oskotskii, V. S., et al.	1968	L	2.0-80		Similar to the above except the cross section perpendicular to the length of the single crystal was oval shape with a ratio of 2:3 between transverse dimensions; heat flow perpendicular to c-axis.
32	1057	Oskotskii, V. S., et al.	1968	L	2.5-78		Similar to the above except specimen 3 mm in dia and heat flow parallel along c-axis.
33	1057	Oskotskii, V. S., et al.	1968	L	2.3-81		Similar to the above except with an enrichment to 92% of the isotope Te^{128}.
34	1378	Sutter, P. H. and Gallo, C.	1961	L	141-440		Single crystal; ~0.5 in. in cross-section and 0.5 in. long; electrical resistivity 7.66, 7.66, 9.18, 9.44, 9.30, 8.44, 5.58, 3.23, 1.42, 0.538, 0.352, 0.337, 0.175, 0.101, 0.0741, 0.0547, and 0.0422 ohm cm at 78, 84, 122, 145, 165, 180, 200, 220, 244, 280, 298, 298, 330, 364, 386, 413, and 438 K, respectively; heat flow along c-axis.
35	1293	Shadrichev, E. V., Smirnov, I. A., and Kutasov, V. A.	1969	L	600-917		In solid and liquid states.
36*	1293	Shadrichev, E. V., et al.	1969	L	744-863		In liquid state.
37*	1293	Shadrichev, E. V., et al.	1969	L	762-804		In liquid state.
38	1596	Yurchak, R. P., Smirnov, B. P., and Kanevskaya, L. C.	1969	E	290-1018		In solid and liquid states; measured in a vacuum of 10^{-5} mm Hg.

* Not shown in figure.

Terbium

In the past three years much experimental information on the thermal conductivity of terbium has become available, and the number of available data sets has increased from four to eleven. At the present time five sets of single-crystal data and six sets of data for polycrystalline terbium are available. Most curves are approximately in the same general trend except for those of Aliev and Volkenshtein [48] (curves 3 and 4) and Karagezyan and Rao [715] (curves 5–7) which are odd.

The provisional curves for $k_{\|}$ and $k_{\perp}$ of terbium single crystal have been drawn through the data of Nellis and Legvold [1021] (curves 8 and 9). Their samples for $k_{\|}$ and $k_{\perp}$ were stated to have the respective electrical resistivities of 1.87 and 2.37 $\mu\Omega$ cm at 4.2 K and the respective electrical resistivity ratios, $\rho_{300K}/\rho_{4.2}$, of 54.5 and 52.1. The Lorenz functions for $k_{\|}$ were 5.49 and 5.05 $\times$ 10^{-8} V^2 K^{-2} at 4.7 and 300 K, respectively, and for $k_{\perp}$ were 4.47 and 3.8 $\times$ 10^{-8} V^2 K^{-2} at 6.1 and 300 K, respectively.

The provisional values for polycrystalline terbium have been derived from the single-crystal values for $k_{\|}$ and $k_{\perp}$ assuming the value for polycrystalline sample to be the mean of those given by equations (11) and (12). At 291 K the derived value is only 5 percent above the mean of the data of Powell and Jolliffe [1127] (curve 1). This curve has been extrapolated from 4.5 K down to 1 K following the slope of the curve of Ratnalingam [1181] (curve 11).

The provisional values are thought to be accurate to within ±15 percent of the true values near room temperature and ±20 percent down to 50 K. The values below 50 K are very uncertain. At temperatures below 150 K the values for $k_{\|}$, $k_{\perp}$, and k_{poly} are applicable only to samples having ρ_0 = 1.87, 2.37, and 2.19 $\mu\Omega$ cm, respectively.

TABLE 159. Provisional thermal conductivity of terbium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	‖ to c-axis k	⊥ to c-axis k	Polycrystalline k	T	‖ to c axis k	⊥ to c-axis k	Polycrystalline k
0	0	0	0	30	0.262	0.192	0.213
1			0.0180	35	0.245	0.184	0.202
2			0.0383	40	0.231	0.174	0.191
3			0.0602	45	0.221	0.166	0.183
4			0.0842	50	0.214	0.160	0.176
5	0.146	0.0939	0.109	60	0.205	0.151	0.168
6	0.179	0.112	0.131	70	0.198	0.144	0.160
7	0.208	0.127	0.150	80	0.190	0.138	0.153
8	0.231	0.140	0.166	90	0.183	0.132	0.147
9	0.249	0.151	0.179	100	0.177	0.127	0.142
10	0.263	0.160	0.189	123.2	0.164	0.117	0.131
11	0.273	0.168	0.198	150	0.152	0.106	0.119
12	0.281	0.173	0.204	173.2	0.143	0.0988	0.112
13	0.288	0.178	0.209	200	0.132	0.0902	0.103
14	0.292	0.182	0.213	223.2	0.124	0.0828	0.0950
15	0.295	0.186	0.217	230	0.122	0.0800	0.0924
16	0.296	0.189	0.220	250	0.131	0.0846	0.0979
18	0.296	0.193	0.223	273.2	0.138	0.0900	0.104
20	0.294	0.196	0.225	298.2	0.147	0.0956	0.111
25	0.279	0.196	0.221	300	0.148	0.0959	0.111

†The values are for well-annealed high-purity terbium, and those below 150 K for $k_{\|}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 1.87, 2.37, and 2.19 $\mu\Omega$ cm, respectively.

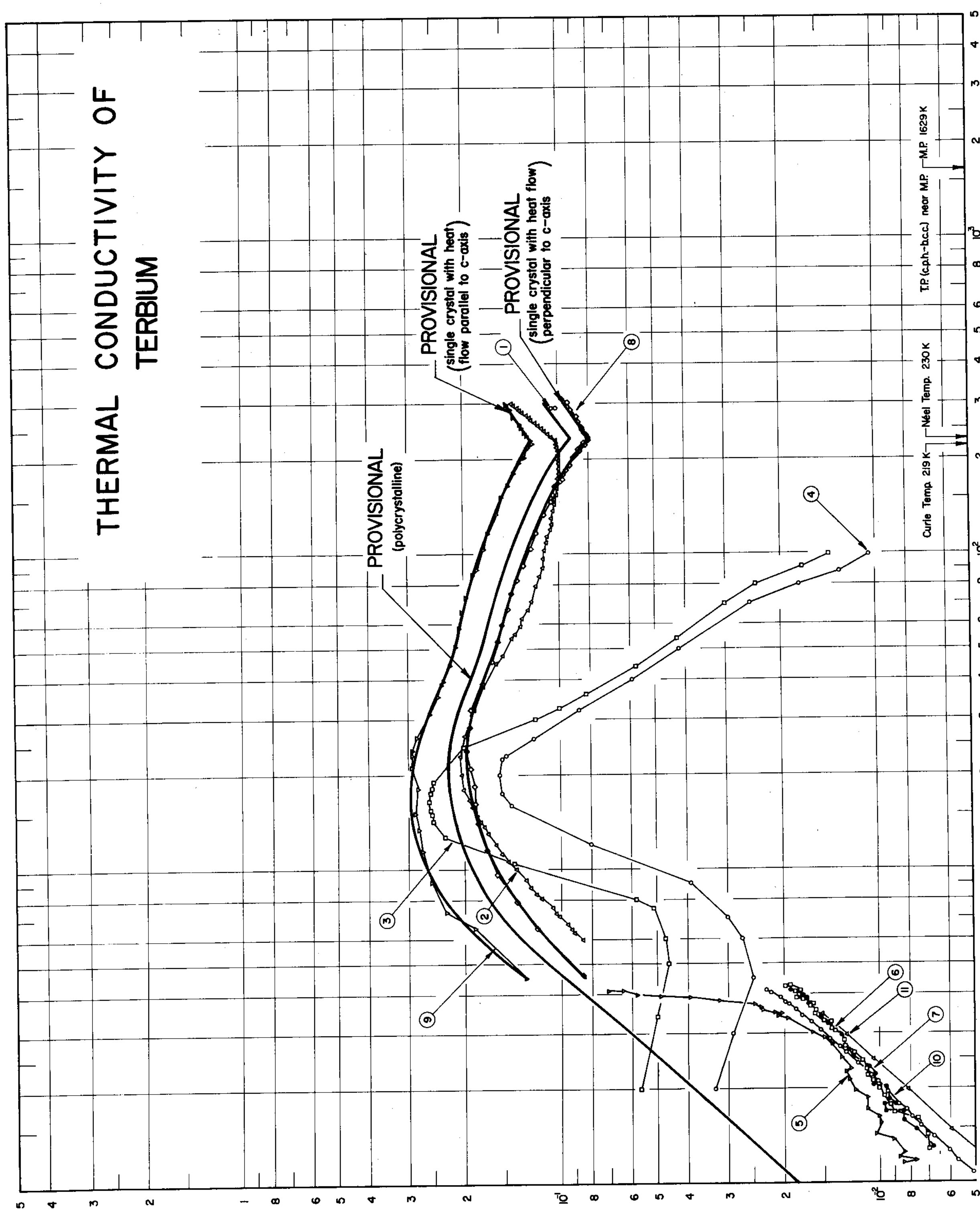

THERMAL CONDUCTIVITY OF TERBIUM
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
Curie Temp. 219 K
Néel Temp. 230 K
T.P. (c.p.h.-b.c.c.) near M.P.
M.P. 1629 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 157

TABLE 160. THERMAL CONDUCTIVITY OF TERBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	1127	Powell, R.W. and Jolliffe, B.W.	1965	C	291.2		High purity; polycrystalline; specimen 0.25 in. in dia and 0.25 in. long; supplied by Johnson Matthey Co.; electrical resistivity reported as 119 μ ohm cm at about 18 C; Monel metal used as comparative material; two measurements made using different thermal comparators.
2	82	Arajs, S. and Colvin, R.V.	1964	L	6.0-300		0.08 O, 0.06 Y, 0.01 Cu, 0.01 Si, and 0.003 Mg; polycrystalline; specimen 0.476 cm in dia and 6 cm long; supplied by Research Chemicals; arc-melted for 12 min, machined, swaged, heated in vacuum of 10^{-5} mm Hg at 790 K for 40 hrs and cooled to room temp in about 3 hrs; measured in vacuum of 6 x 10^{-6} mm Hg; electrical resistivity reported as 4.851, 5.006, 5.843, 7.041, 11.196, 14.998, 19.637, 23.504, 28.815, 41.320, 57.922, 85.109, 105.708, 112.480, 116.077, 117.000 119.308, 121.842, and 123.686 μohm cm at 4.18, 12.62, 20.09, 25.37, 37.21, 45.71, 55.37, 63.13, 73.61, 97.72, 128.29, 175.61, 212.73, 223.27, 231.13, 241.45, 264.35, 287.39, and 303.59 K, respectively; ferromagnetic-antiferromagnetic and antiferromagnetic-paramagnetic transitions occurred at 219 K and 230 K, respectively.
3	48	Aliev, N.G. and Volkenstein, N.V.	1966		2.0-99	Tb 1	99.9 pure; specimen 0.25 mm in dia; baked for 1.5 hrs at 650 C; measured in helium atmosphere; electrical resistivity 4.13 μohm cm at 4.2 K; electrical resistivity ratio ρ(293 K)/ρ(4.2 K) = 30; data taken from smoothed curve.
4	48	Aliev, N.G. and Volkenstein, N.V.	1966		2.0-99	Tb 2	99.9 pure; specimen 0.25 mm in dia; baked for 1.5 hrs at 650 C; measured in helium atmosphere; electrical resistivity 7.90 μohm cm at 4.2 K; electrical resistivity ratio ρ(293 K)/ρ(4.2 K) = 15.6; data taken from smoothed curve.
5	715	Karagezyan, A.G. and Rao, K.V.	1968	L	1.2-4.1	1	Polycrystalline; specimen 1.47 mm in dia and 3.2 cm long; supplied by Johnson Matthey and Co., Ltd; residual electrical resistivity 4.903 μohm cm; electrical resistivity ratio ρ(293K)/ρ(4.2K) = 26.54; Lorenz number 7.3 x 10^{-8} V^2 K^{-2} at 4.2 K.
6	715	Karagezyan, A.G. and Rao, K.V.	1968	L	1.3-4.3	2	Single crystal; specimen 3.78 mm in dia and 6.2 cm long; grown by Metals Research, Ltd, using the zone melting technique in an argon atm, with c-axis and crystal axis forming 78 degree angle; residual electrical resistivity 5.35 μohm cm; electrical resistivity ratio ρ(293K)/ρ(4.2K) = 20.1; Lorenz number 2.55 x 10^{-8} V^2 K^{-2} at 4.2 K.
7	715	Karagezyan, A.G. and Rao, K.V.	1968	L	1.3-4.2	2	The above specimen measured in the magnetic field of H = 1 kOe.

TABLE 160. THERMAL CONDUCTIVITY OF TERBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
8	1021	Nellis, W. J. and Legvold, S.	1969	L	4.6-309	a-axis	<0.0200 Gd, <0.0200 Ta, 0.0160 O_2, <0.0100 Dy, <0.0050 Fe, and <0.0020 Ni; single crystal; specimen 2 x 2 x 6-20 mm; grown by the strain-anneal technique; mechanically polished, etched, and electropolished; residual electrical resistivity 2.37 μohm cm at 4.2 K; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 52.1; electrical resistivity reported as 3.0, 3.5, 5.4, 10.3, 17.7, 26.5, 34.4, 46.6, 64.4, 80.2, 94.2, 100.5, 104.2, 107.6, 110.5, 112.8, 114.4, 115.5, 117.2, 120.1, and 122.7 μohm cm at 15.0, 19.6, 28.4, 40.9, 56.3, 74.4, 89.8, 112.2, 144.8, 172.9, 198.1, 209.9, 215.7, 220.7, 224.4, 229.1, 233.8, 240.5, 252.4, 278.2, and 298.6 K, respectively; Lorenz function 4.47, 3.71, 3.22, 3.18, 3.22, 4.07, 4.40, 4.66, 4.88, 4.95, 4.88, 4.74, 4.54, 4.28, 4.12, 4.10, 4.08, 3.97, 4.00, and 3.80 x 10^{-8} V^2 K^{-2} at 6.1, 10.3, 15.3, 17.5, 20.1, 40.0, 48.7, 47.6, 69.8, 82.4, 107.5, 135.3, 162.9, 192.9, 210.5, 216.8, 224.3, 230.7, 257.0, and 300.0 K, respectively; heat flow measured along the <11$\bar{2}$0> direction (a-axis) of the hexagonal close-packed crystal structure.
9	1021	Nellis, W. J. and Legvold, S.	1969	L	4.5-299	c-axis	Similar to the above except residual electrical resistivity 1.87 μohm cm at 4.2 K; electrical resistivity ratio $\rho(300K)/\rho(4.2K)$ = 54.5; electrical resistivity reported as 2.3, 2.3, 2.5, 2.5, 2.7, 8.5, 19.0, 33.9, 57.8, 84.4, 94.2, 99.1, 101.9, 104.0, 104.4, 102.5, 101.2, 100.5, 100.3, 100.6, and 101.4 μohm cm at 5.7, 11.5, 14.0, 18.1, 20.4, 40.5, 63.7, 94.5, 139.0, 184.6, 204.6, 216.4, 220.2, 222.2, 227.2, 231.4, 239.5, 250.3, 266.1, 286.0, and 300.0 K, respectively; Lorenz function 5.49, 4.07, 3.97, 4.04, 6.38, 6.50, 6.39, 6.17, 5.75, 5.70, 5.45, and 5.05 x 10^{-8} V^2 K^{-2} at 4.7, 15.5, 18.1, 21.1, 83.2, 95.3, 159.0, 189.7, 218.3, 226.4, 246.0, and 300.0 K, respectively; heat flow measured along the <0001> direction (c-axis) of the hexagonal close-packed crystal structure.
10	1174	Rao, K. V., Loo, H. Y., and Meaden, G. T.	1970	L			Monocrystalline; annealed; heat flow measured along the basal plane.
11	1181	Ratnalingam, R.	1970	L	0.5-4.0	Tb 1	Electrical resistivity 138.45 μohm cm at 295 K; residual electrical resistivity 6.61 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0$ = 20.9; thermal conductivity values calculated from the formula k = 3.64 T + 0.203 T^2 (mW cm^{-1} K^{-1}) given by the author.

Thallium

No thermal conductivity measurements have been made above 490 K on solid thallium and the value for 490 K was considered doubtful by the author [608], so information about this property in the transformation region is entirely lacking. Except for the four sets of measurements made by Zavaritskii [1602] (curves 33–36), which only covered the range 0.19 to 5.6 K, the relatively few thermal conductivity determinations on thallium have been for polycrystalline samples. Zavaritskii made measurements, which included the superconducting state, for three samples having sample axes at 20, 30, and 80 degrees to the *c*-axis of the crystal. These samples gave maximum values of 12.0, 46.0, and 7.8 W cm^{-1} K^{-1}, respectively, and do not appear to represent samples from the same crystal. Until information becomes available for samples from the same crystal but cut in widely different directions it is possible only to consider data for polycrystalline material. Since the highest conducting of Zavaritskii's samples gave the highest value in the low temperature range, a curve has been mathematically fitted to these data, using equation (7) and using the constants m, n, and α'' as given in table 1 and a value of 0.00982 for β, as representing the thermal conductivity of non-superconducting thallium up to 5.6 K. At this temperature the curve is 46 percent above another (curve 3) due to Rosenberg [1220] which contains data to 31 K, but has a sharp drop at 27.5 K, and the proposed curve has been continued with a steady fall to pass about 6.5 percent above Rosenberg's curve at 27.5 K.

Between 31 K and room temperature the only available values are the 1927 measurements of Eucken and Dittrich [404] (curve 1) at 80 and 273 K, and the proposed curve continues to pass some 8 or 9 percent below these two points, 2 percent above the single value by Smith [1327] (curve 32) at 333 K, and from 8 to 16 percent above the measurements of Brown [219] (curve 2) except for his last data point at 490 K which is 9 percent above the recommended value. Since these measurements are few and were all made in the 1920's, so probably relate to somewhat impure material, the curve at present proposed is subject to considerable uncertainty and thallium is another metal that should be further examined particularly from 80 K upward.

No attempt has been made to extend the curve into the molten state, since the only available determination is a single value of 0.247 W cm^{-1} K^{-1} at 626 K which Brown reported, but was considered doubtful by him. It is of interest to note that Gotgil'f, et al. [519] have reported anomalies in the electrical resistivity and viscosity of liquid thallium in the range 623 to 673 K, which indicate the possible occurence of some structural changes.

The recommended values are thought to be accurate to within ±10 percent at temperatures above 100 K and ±15 percent from 300 to 100 K. Values below 30 K are provisional and furthermore they are only for thallium having a residual electrical resistivity of 0.000240 μΩ cm. These provisional values are probably good to within ±20 percent.

TABLE 161. Recommended thermal conductivity of thallium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	60	0.607*
1	82.7*	70	0.590*
2	63.4*	80	0.578
3	33.2	90	0.567
4	17.6	100	0.556
5	10.2	123.2	0.538
6	6.19	150	0.519
7	4.04	173.2	0.506
8	2.95	200	0.494
9	2.30	223.2	0.485
10	1.87	250	0.476
11	1.60	273.2	0.469
12	1.40	298.2	0.461
13	1.27	300	0.461
14	1.16	323.2	0.455
15	1.07	373.2	0.443
16	1.00	400	0.438
18	0.889	473.2	0.425
20	0.811	500	0.421*
25	0.718		
30	0.682		
35	0.665*		
40	0.650*		
45	0.637*		
50	0.626*		

†The values are for well annealed high-purity thallium, and those below 30 K are applicable only to a specimen having $\rho_0 = 0.000240$ μΩ cm. The values below 30 K are provisiona .

*Extrapolated or interpolated.

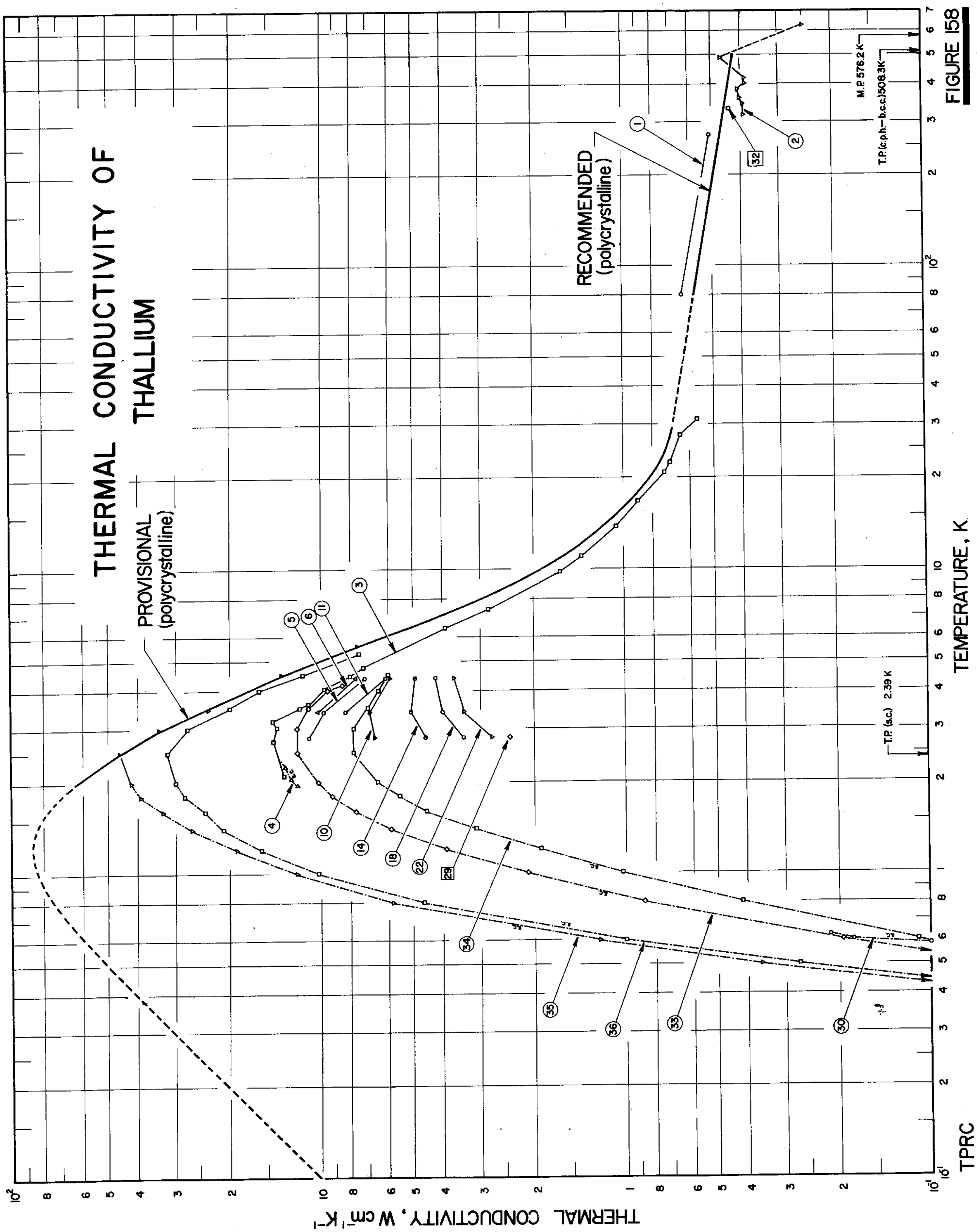

THERMAL CONDUCTIVITY OF THALLIUM
FIGURE 158
RECOMMENDED (polycrystalline)
PROVISIONAL (polycrystalline)
M.P. 576.2 K
T.P. (c.p.h.–b.c.c.) 508.3 K
T.P. (s.c.) 2.39 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC

TABLE 162. THERMAL CONDUCTIVITY OF THALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	404	Eucken, A. and Dittrich, K.	1927	L	80, 273		Pure thallium (electrolytic); electrical conductivity reported as 27.8 and 6.73 x 10^4 ohm^{-1} cm^{-1} at 80 and 273 K, respectively.
2	219	Brown, W.B.	1923	L	318-626		Cylindrical specimen 1.5 cm in dia and 12 cm long; in both solid and liquid states.
3	1220	Rosenberg, H.M.	1955	L	2.1-31	JM 2544;Tl1	99.99 pure; polycrystalline; 2.99 cm long and 0.16 cm in dia; supplied by Johnson, Matthey and Co.; annealed in vacuo for several hrs and coated with celluloid varnish to prevent oxidation; measured in a magnetic field; in normal state.
4	1220	Rosenberg, H.M.	1955	L	2.0-2.3	JM 2544;Tl1	The above specimen in superconducting state.
5	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8-4.4	JM 2544;Tl1	99.99 pure; polycrystalline; 5 cm long and ~0.2 cm in dia; supplied by Johnson, Matthey and Co.; measured in a transverse magnetic field of 0.34 kOe.
6	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4, 4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 0.34 kOe.
7*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 0.51 kOe.
8*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 0.71 kOe.
9*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 0.71 kOe.
10	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8-4.4	Tl 1	The above specimen measured in a transverse magnetic field of 1.09 kOe.
11	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4, 4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 1.09 kOe.
12*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 1.42 kOe.
13*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 1.42 kOe.
14	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8-4.4	Tl 1	The above specimen measured in a transverse magnetic field of 1.79 kOe.
15*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4, 4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 1.79 kOe.
16*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 2.14 kOe.
17*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 2.14 kOe.
18	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8-4.4	Tl 1	The above specimen measured in a transverse magnetic field of 2.5 kOe.

* Not shown in figure.

TABLE 162. THERMAL CONDUCTIVITY OF THALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
19*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4, 4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 2.5 kOe.
20*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 2.85 kOe.
21*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 2.85 kOe.
22	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8–4.4	Tl 1	The above specimen measured in a transverse magnetic field of 3.22 kOe.
23*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4, 4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 3.22 kOe.
24*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 3.59 kOe.
25*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 3.59 kOe.
26*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4	Tl 1	The above specimen measured in a longitudinal magnetic field of 3.70 kOe.
27*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	4.4	Tl 1	The above specimen measured in a transverse magnetic field of 3.79 kOe.
28*	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	3.4	Tl 1	The above specimen measured in a transverse magnetic field of 3.82 kOe.
29	938	Mendelssohn, K. and Rosenberg, H.M.	1953	L	2.8	Tl 1	The above specimen measured in a transverse magnetic field of 3.91 kOe.
30	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.29–0.63	Tl 1	The above specimen measured at low temperatures; in superconducting state; preliminary results reported.
31*	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.26–0.84	Tl 1	More complete results from the same thallium batch (JM 2544) as the above specimen; in superconducting state.
32	1327	Smith, A.W.	1925	L	333		Specimen 1.9 cm in dia, 10 cm long; made from pure thallium from Eimer and Amend; electrical conductivity 5.88×10^4 $ohm^{-1} cm^{-1}$ at 25 C.
33	1602	Zavaritskii, N.V.	1961	L	0.41–4.2	Tl-3	Pure; specimen 1 mm in dia; made from single crystal; specimen axis at 20 degrees with the crystal hexagonal axis; residual electrical resistivity 0.0026 μ ohm cm.
34	1602	Zavaritskii, N.V.	1961	L	0.19–5.2	Tl-4	Pure; specimen 1.1 mm in dia; made from single crystal; specimen axis at 80 degrees with the crystal hexagonal axis; residual electrical resistivity 0.0050 μ ohm cm.

* Not shown in figure.

TABLE 162. THERMAL CONDUCTIVITY OF THALLIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
35	1602	Zavaritskii, N.V.	1961	L	0.21-5.6	Tl-7	Pure; specimen 1.6 mm in dia; specimen axis at 30 degrees with the crystal hexagonal axis; residual electrical resistivity 0.00024 ± 0.00003 μ ohm cm.
36	1602	Zavaritskii, N.V.	1961	L	0.34-5.3	Tl-8	0.9 mm in dia; obtained by etching the above specimen; residual electrical resistivity 0.00045 μ ohm cm.

Thorium

The early measurements of the thermal conductivity of thorium have been limited to temperatures within the range 293 to 923 K and each has indicated a positive temperature coefficient. The samples were probably of low purity. Only Powell [1111] (curve 5) included electrical resistivity data, the high values of 27.5 and 32 μΩ cm being reported at 293 and 373 K for a sample known to contain an appreciable amount of thorium dioxide. At these temperatures the respective Lorenz functions were 2.76×10^{-8} and 2.68×10^{-8} V² K⁻².

Thermal conductivity values for temperatures below normal have recently become available from determinations by Haen and Meaden [574] (curve 6) and by Schettler, et al. [1259, 1260] (curves 8–10). Schettler, et al. examined three thorium samples for which the residual resistance ratios were 480, 140, and 31 and that of Haen and Meaden's sample was 20.5. The curve for which provisional values are tabulated is based on the measurements up to 60 K on the purest of these samples (curve 8) and these values for low temperatures are applicable only to thorium having $\rho_o = 0.0268$ μΩ cm. The values below about 1.5 T_m are calculated to fit the experimental data by using equation (7) and using the constants m, n, and α'' as given in table 1 and a value of 1.07 for β.

The observed values for this purest sample remain almost constant from 60 to 200 K. At room temperature the value is about 14 percent above the 200 K value. Not only does this temperature coefficient appear rather large, but the derived Lorenz function of 3.8×10^{-8} V² K⁻² is also high and by 1000 K would increase to about 6.0×10^{-8} V² K⁻² if both the present thermal conductivity and electrical resistivity curves are extrapolated. These Lorenz function values are much greater than those of Powell [1111] for his much lower purity sample, which seems difficult to understand since for many metals reduced purity increases the Lorenz function. Another difficulty relates to the large difference between the room temperature thermal conductivity value of 0.76 W cm⁻¹ K⁻¹ indicated by this recent work and the highest of the earlier values, 0.412 W cm⁻¹ K⁻¹ by Sidles and Danielson [1313] (curve 2). This was for a sample of 99.85 percent thorium for which the thermal conductivity, as derived from thermal diffusivity determinations, remained almost constant up to 697 K.

The values of Haen and Meaden had commenced to increase at temperatures above 50 K. No corresponding increase is evident in the measurements by Schettler, et al. This up-turn may therefore be the result of some experimental factor such as the underestimation of a radiation correction. In the measurements of Schettler, et al., there is again the possibility that at some higher temperature a similar unwanted factor affected these values. The provisionally recommended curve has therefore been very tentatively continued above 60 K to deviate gradually below the upper of the two curves of Schettler, et al. and to have a very shallow minimum in the region of room temperature. These values yield a nearly constant Lorenz function of 3.1×10^{-8} V² K⁻² from 500 to 1100 K. High purity thorium requires further study from room temperature upwards.

The uncertainty of the provisional values is probably of the order of ±15 percent below 100 K, ±20 percent from 100 to 500 K, and ±25 percent above 500 K. The values below 150 K are of course only for thorium having $\rho_o = 0.0268$ μΩ cm.

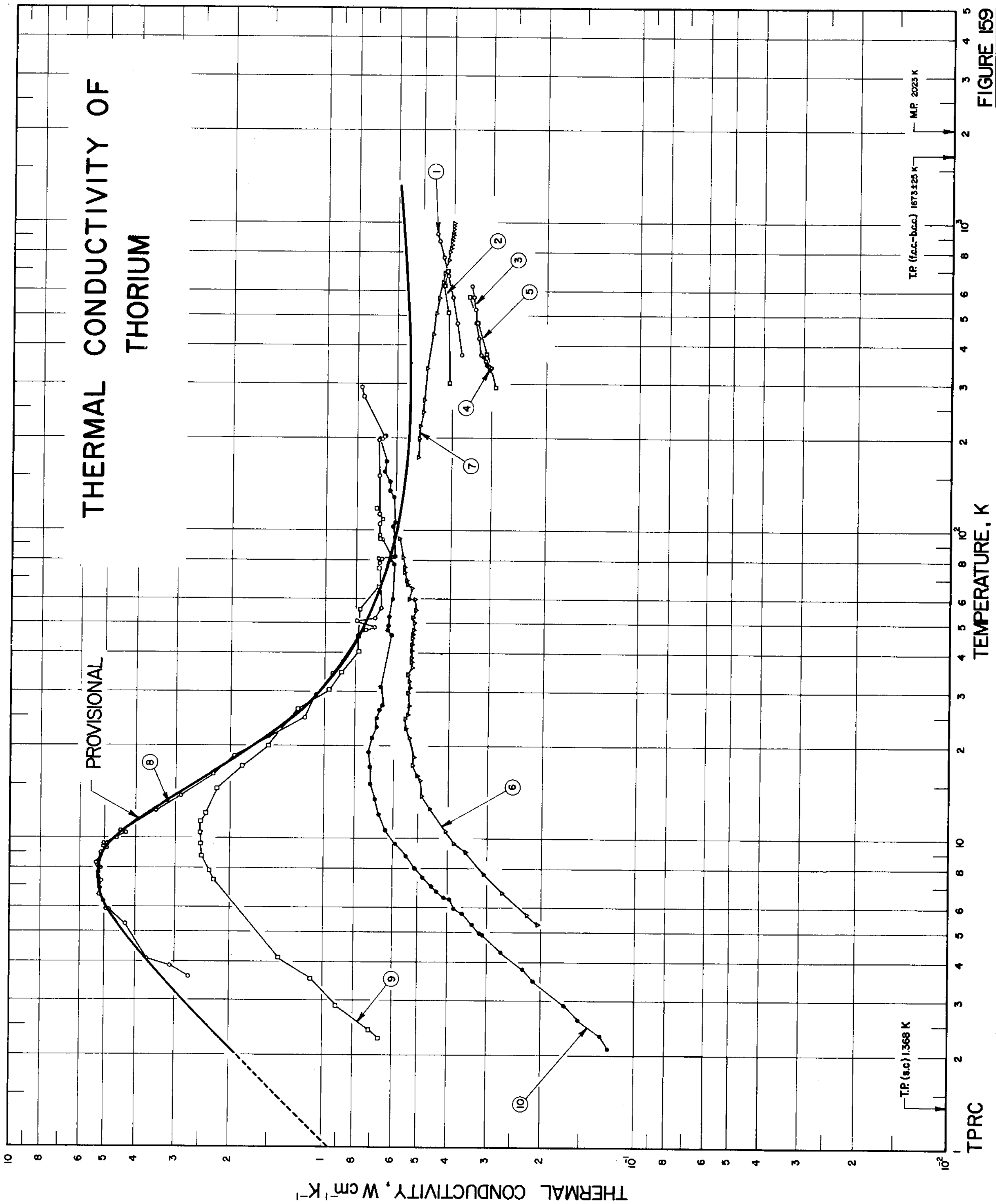
TABLE 163. Provisional thermal conductivity of thorium†

(Temperature, T, K; Thermal Conductivity, k, W cm⁻¹ K⁻¹)

Solid			
T	k	T	k
0	0	123.2	0.578
1	0.938*	150	0.563
2	1.87	173.2	0.554
3	2.78	200	0.546
4	3.64	223.2	0.543
5	4.37	250	0.541
6	4.91	273.2	0.540
7	5.20	298.2	0.540
8	5.23	300	0.540
9	5.02	323.2	0.541
10	4.66	350	0.542
11	4.20	373.2	0.543
12	3.72	400	0.545
13	3.30	473.2	0.549
14	2.96	500	0.551
15	2.66	573.2	0.556
16	2.41	600	0.558
18	2.01	673.2	0.563
20	1.70	700	0.564
25	1.26	773.2	0.568
30	1.04	800	0.569
35	0.917	873.2	0.572
40	0.841	900	0.573
45	0.788	973.2	0.577
50	0.747	1000	0.578
60	0.690	1073.2	0.581
70	0.655	1100	0.583
80	0.630	1173.2	0.586
90	0.612	1200	0.587
100	0.598	1273.2	0.589
		1300	0.590

†The provisional values are for well-annealed high-purity thorium and those below 150 K are applicable only to a specimen having $\rho_o = 0.0268$ μΩ cm.

*Extrapolated.


THERMAL CONDUCTIVITY OF THORIUM
PROVISIONAL
FIGURE 159
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
T.P. (s.c.) 1.368 K
T.P. (f.c.c.-b.c.c.) 1673±25 K
M.P. 2023 K

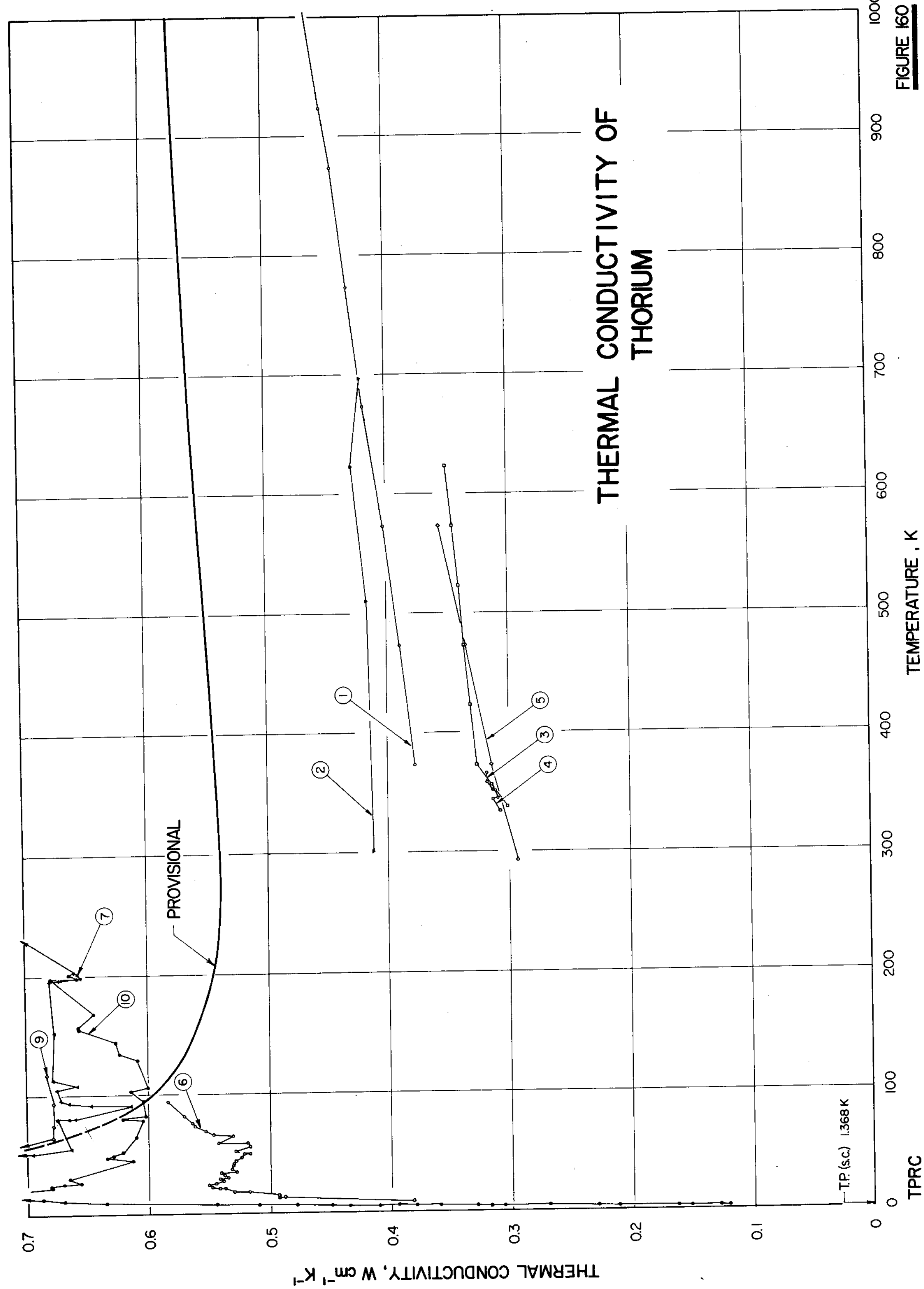

THERMAL CONDUCTIVITY OF THORIUM
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
PROVISIONAL
T.P. (s.c.) 1.368 K
TPRC
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
100
200
300
400
500
600
700
800
900
1000
1
2
3
4
5
6
7
9
10

FIGURE 160

TABLE 164. THERMAL CONDUCTIVITY OF THORIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	236, 885	March, L.L., Jr. and Keeler, J.R. (compilers)	1951		373-923	Ames Thorium	Specimen hot rolled at 788 C and air cooled; density 11.6 g cm^{-3}; melting point 1680± 25 C; data determined in an atmosphere of purified argon.
2	1312, 1313	Sidles, P.H. and Danielson, G.C.	1951	P	301-697		99.85 pure; specimen 0.125 in. in dia, ~50 cm long; thermal conductivity values calculated from measured data of thermal diffusivity using measured density 11.558 g cm^{-3} and the specific heat of 0.1188 joules g^{-1} C^{-1} (from C.F. Miller for the range 0 to 200 C, and assumed constant to higher temperatures).
3	93, 122	Battelle Memorial Institute	1945		338-623		Specimen made from Ames extruded thorium.
4	93, 1167	Raeth, C.H.	1944	L	335-367		Pure; specimen 1.618 cm long, cross-sectional area 5.042 cm^2.
5	1111	Powell, R.W.	1945		293-573		Specimen ~6 cm long, 1 cm in dia; manufactured by Westinghouse Lamp Co.; x-ray analysis after test showed the presence of thorium oxide (probably formed during the test); electrical resistivity reported as 27.5 and 32 μohm cm at 20 and 100 C, respectively; Lorenz function 2.76 and 2.68 x 10^{-8} V^2 K^{-2} at 20 and 100 C, respectively.
6	574	Haen, P. and Meaden, G.T.	1965	L	5.3-94		Cylindrical specimen 4 mm in dia and 30 mm long; supplied by Dr. J.A. Lee, A.E.R.E. Harwell; machined from an ingot of argon-arc-melted van Arkel metal of high purity; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 20.49; residual electrical resistivity 0.72 μohm cm; electrical resistivity reported as 0.72, 0.75, 0.91, 1.26, 1.82, 2.39, 2.97, 4.06, 5.15, 14.7, and 15.9 μohm cm at 4.2, 10, 20, 30, 40, 50, 60, 80, 100, 273.15, and 295 K, respectively; Lorenz function reported as 2.85, 2.67, 2.45, 2.28, 2.24, 2.49, 2.82, and 3.02 x 10^{-8} V^2 K^{-2} at 5, 15, 18, 25, 30, 50, 75, and 100 K, respectively; thermal conductivity data averaged from the results of several separate runs.
7	66	Anderson, R.L., Grotzky, D.H., and Kienzle, W.E.	1970	P	174-995		99.85 Th, ~0.0075 C, and ~0.0058 O; iodide thorium specimen prepared by the Metallurgy Section at Ames Lab., using the deBoer van Arkel process; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 55.2; electrical resistivity reported as 0.58, 0.72, 0.95, 1.05, 1.15, 1.20, 1.28, 1.38, 1.47, 1.60, 2.13, 2.55, 3.12, 3.93, 4.45, 4.94, 5.43, and 5.62 x 10^{-5} ohm cm at 116, 140, 182, 199, 222, 230, 242, 258, 275, 293, 382, 453, 550, 694, 792, 884, 988, and 1030 K, respectively; Lorenz function reported as 2.68, 2.68, 2.67, 2.66, 2.65, 2.64, 2.64, 2.63, 2.63, 2.60, 2.60, 2.52, 2.49, 2.43, 2.26, 2.24, 2.21, 2.19, and 2.16 x 10^{-8} V^2 K^{-2} at 172, 184, 229, 270, 292, 313, 332, 352, 369, 402, 451, 498, 547, 626, 816, 853, 893, 934, and 997 K, respectively; thermal conductivity values calculated from the data of thermal diffusivity (measured by Linear finite-rod pulse-heating method), using the specific heat data of Griffel, M., et al. (J. Am. Chem. Soc., 75, 5150, 1953) and Wallace, D.C. (Physical Review, 120, 84, 1960), and density of 11.60 x 10^3 kg m^{-3} of Sidles, P.H. and Danielson, G.C. (AEC Research and Development Rept. ISC-761, 1956); smooth data reported.

TABLE 164. THERMAL CONDUCTIVITY OF THORIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
8	1259, 1260	Schettler, H. G., Martin, J. J., Schmidt, F. A., and Danielson, G. C.	1969	L	3.6-294	Sample 1	<0.0005 C and <0.0003 N; polycrystalline; specimen 2.42 mm in dia and 30 mm long; purified by electrotransport method, cut from the purest end of refined rod 0.25 cm in dia and 16.0 cm long, heated to 1580 C under a pressure 2 x 10^{-10} torr for 100 hrs; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 480; electrical resistivity reported as 0.0268, 0.0296, 0.0320, 0.0327, 0.0346, 0.0472, 0.2447, 0.5251, 1.6992, 3.1180, 3.7750, 4.3785, 5.8214, 7.8512, and 14.850 μohm cm at 2.22, 7.18, 8.00, 9.05, 10.00, 12.10, 22.80, 30.39, 52.59, 77.80, 90.50, 102.30, 128.80, 166.10, and 292.30 K, respectively.
9	1259, 1260	Schettler, H. G., et al.	1969	L	2.3-118	Sample 2	Specimen 2.47 mm in dia and 35 mm long; cut from the closer to the less pure end of the above thorium rod; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 140; electrical resistivity reported as 0.08, 0.09, 0.09, 0.09, 0.10, 0.10, 0.13, 0.14, 0.27, 0.39, 0.67, 1.23, 1.44, 1.59, 2.14, 2.40, 3.28, 3.85, and 14.19 μohm cm at 2.1, 2.6, 6.5, 7.3, 9.7, 10.6, 12.4, 14.8, 20.6, 24.9, 31.3, 42.1, 45.6, 48.9, 56.7, 62.7, 78.5, 88.1, and 272.9 K, respectively.
10	1259, 1260	Schettler, H. G., et al.	1969	L	2.1-204	Sample 3	0.0135 O, 0.0018 N, and <0.0010 C; specimen 1.46 mm in dia and 20 mm long; cut from the unpurified rod of the above specimen; electrical resistivity ratio $\rho(273K)/\rho(4.2K)$ = 31; electrical resistivity reported as 0.4600, 0.4600, 0.476, 0.539, 0.852, 1.120, 1.621, 2.526, 3.833, 7.952, 10.160, and 14.516 μohm cm at 2.08, 6.52, 10.95, 15.42, 25.20, 30.83, 40.49, 56.50, 79.20, 154.95, 191.00, and 273.14 K, respectively.

Thulium

The thermal conductivity of a polycrystalline sample of thulium has been measured over the range 2.2 to 100 K by Aliev and Volkenshtein [46] (curve 1), and those of two single crystal samples for the main crystal directions have been measured by Edwards and Legvold [389] (curves 3, 4) for the range 5.7 to 298 K. The single crystal samples appeared to be of higher purity, since, for the *c* and *b* axial directions electrical resistivity ratios for room to liquid helium temperatures of 12.9 and 51.0 respectively were obtained, compared with a ratio of 6.2 for the sample studied by Aliev and Volkenshtein. Also the room temperature resistivity of the latter was 79 $\mu\Omega$ cm, whereas the values derived for polycrystalline thulium from the single crystal data were 68.1 or 74.3 $\mu\Omega$ cm, according to whether calculated from the equation of Voigt [1487] or of Nichols [1032] (see Meaden [912]). These yield a mean value of 71.2 $\mu\Omega$ cm which agrees closely with the value of 72 $\mu\Omega$ cm reported by Jolliffe, Tye, and Powell [690] (curve 2) for the only other polycrystalline sample for which thermal conductivity measurements have been made. The corresponding thermal conductivities, as measured by Jolliffe, et al. and as derived in a similar manner from the single crystal data of Edwards and Legvold, differ, however, by about 20 percent. The reason for this is not evident, although this difference would be reduced to about 6 percent if the method of Nichols is more appropriate.

Smooth curves drawn through the two sets of experimental data of Edwards and Legvold are proposed to represent provisionally the thermal conductivity of thulium in directions parallel and perpendicular to the *c*-axis. At 5.7 K the two curves differ by less than 1 percent. This convergence at low temperatures may suggest the sample for the parallel direction to be of higher purity. The fact that the maximum in this curve is at a lower temperature would be consistent with this, but its lower resistivity ratio would suggest the opposite. It would be of interest to know if the indicated low-temperature cross-over would still occur for crystals having exactly the same purity. In the present instance different samples were used for the two crystal directions, and differences in the composition might contribute to the observed convergence. From 5.7 to 42.4 K the thermal conductivity perpendicular to the *c*-axis is the greater, by as much as 40 percent around 23 K, but at 42.4 K the curves again cross and from 58 to 300 K the thermal conductivity parallel to the *c*-axis is greater by amounts varying from 77 to 82 to 72 percent. Both curves show changes which could be associated with a Néel temperature of 53 K.

From these two curves and making no allowances for possible differences in purity, a probable curve for the thermal conductivity of polycrystalline thulium has been derived. This has been rather tentatively extrapolated to 2 K on the basis of the form of curve obtained by Aliev and Volkenshtein. No extrapolation to higher temperatures has been attempted as the necessary electrical resistivity data were not available.

The values above 150 K are thought to be accurate to within ±15 percent. Those below 150 K are very uncertain. Below 100 K the values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_0 = 3.5$, 1.7, and 2.18 $\mu\Omega$ cm, respectively.

TABLE 165. Provisional thermal conductivity of thulium†

(Temperature, *T*, K; Thermal Conductivity, *k*, W cm^{-1}K^{-1})

Solid

T	∥ to *c*-axis *k*	⊥ to *c*-axis *k*	Polycrystalline *k*	*T*	∥ to *c*-axis *k*	⊥ to *c*-axis *k*	Polycrystalline *k*
2			0.0269*	40	0.105	0.110	0.108
3			0.0517	42.4	0.106	0.106	0.106
4			0.0815	45	0.109	0.102	0.104
5			0.113	50	0.119	0.0948	0.103
6	0.139	0.142	0.141	55	0.141	0.0912	0.107
7	0.162	0.170	0.167	58	0.160	0.0911	0.111
8	0.180	0.197	0.191	60	0.164	0.0920	0.113
9	0.196	0.221	0.210	70	0.175	0.0997	0.120
10	0.207	0.236	0.225	80	0.185	0.105	0.126
11	0.210	0.244	0.231	90	0.193	0.108	0.131
12	0.207	0.246	0.232	100	0.200	0.111	0.135
13	0.202	0.245	0.230	123.2	0.214	0.117	0.138
14	0.193	0.243	0.226	150	0.224	0.126	0.152
15	0.183	0.238	0.219	173.2	0.230	0.130	0.157
16	0.173	0.232	0.211	200	0.235	0.134	0.162
18	0.158	0.218	0.194	223.2	0.238	0.136	0.165
20	0.144	0.202	0.179	250	0.241	0.138	0.167
25	0.120	0.167	0.149	273.2	0.242	0.140	0.168
30	0.106	0.141	0.127	298.2	0.242	0.141	0.168
35	0.105	0.123	0.116	300	0.242	0.141	0.168

†The provisional values are for well-annealed high-purity thulium, and those below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_0 = 3.5$, 1.7, and 2.18 $\mu\Omega$ cm, respectively.

*Extrapolated.

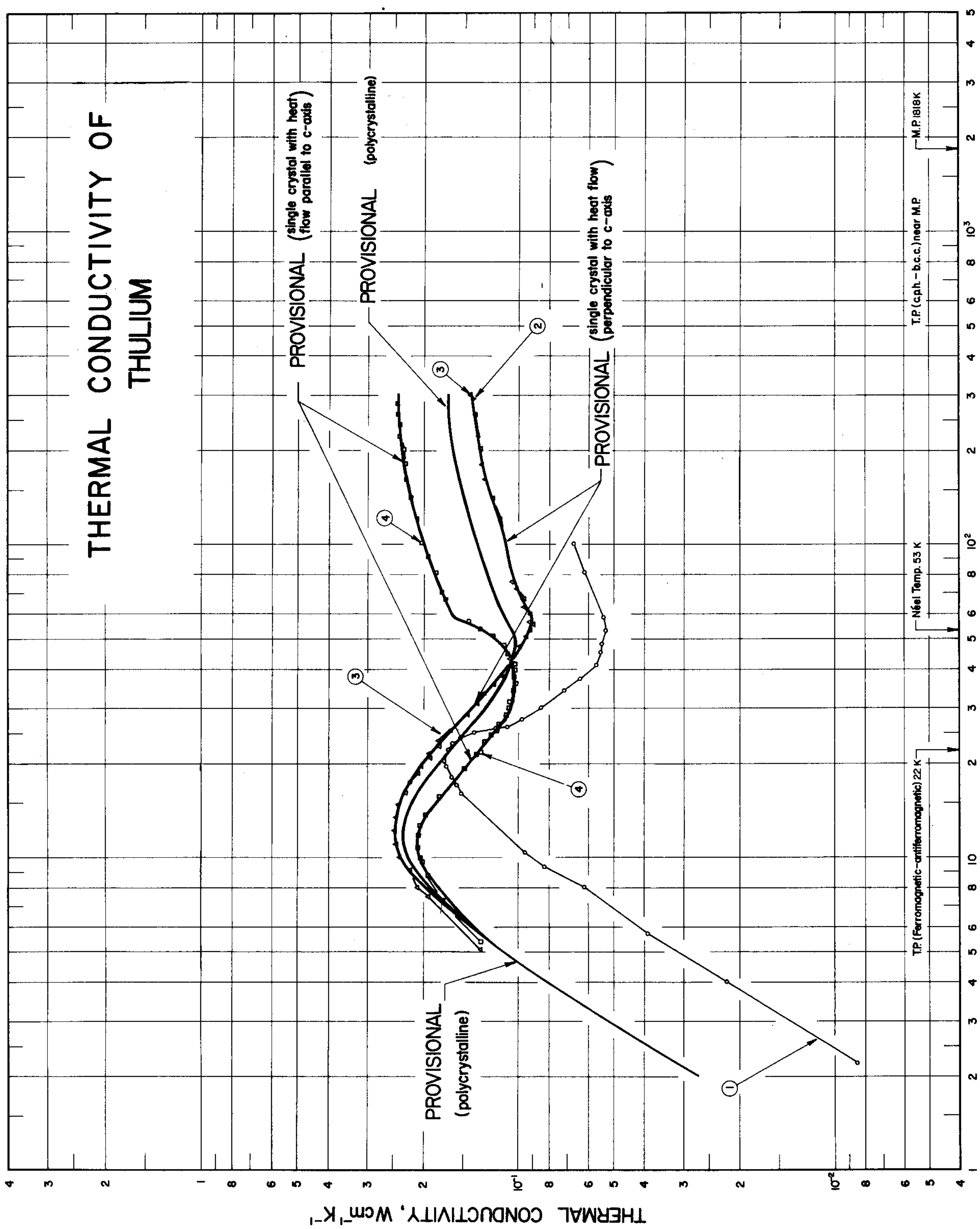

THERMAL CONDUCTIVITY OF THULIUM
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
PROVISIONAL (polycrystalline)
T.P. (Ferromagnetic–antiferromagnetic) 22 K
Néel Temp. 53 K
T.P. (c.p.h. – b.c.c.) near M.P.
M.P. 1818 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 161

TABLE 166. THERMAL CONDUCTIVITY OF THULIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	46	Aliev, N.G. and Volkenshtein, N.V.	1965	L	2.2-100		99.99 pure; polycrystalline; strip specimen 0.25 mm thick; annealed in a stream of helium vapor at 650 C for 3 hrs; electrical resistivity reported as 12.7 and 79 μohm cm at 4.2 and 293 K, respectively; antiferromagnetic - paramagnetic transition at 53 K; Lorenz function reported as 7.30×10^{-8} V^2 K^{-2} in the residual resistance region.
2	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	C	291		<0.1 rare earth metal and ~0.01 base metals; polycrystalline; 1.2 x 1.2 x 0.31 cm; electrical resistivity 72 μohm cm at 291 K; measurements made using two different thermal comparators.
3	389, 390	Edwards, L.R. and Legvold, S.	1967	L	5.1-298		<0.0200 Ho, <0.0200 Lu, <0.0200 Y, 0.0061 O, <0.0060 Al, <0.0060 Si, <0.0050 Fe, <0.0050 Ni, <0.0030 Er, <0.0020 Ca, <0.0020 Cr, <0.0010 Mg, <0.0010 Yb, 0.0001 H, trace of Mn, and faint trace of Dy; single crystal; 7.23 x 1.250 x 1.224 mm; arc-melted ingot suspended and sealed in helium at 0.5 atm in a tantalum bomb, placed in an annealing furnace consisting of a temp gradient region (25 C cm^{-1}) and a constant temp region, annealed at 1200 C for 12 hrs and at 1300 C for 12 hrs in the gradient region, then annealed at 1425 C for 16 hrs in the constant temp region, cut and hand-lapped to size; electrical resistivity reported as 1.730, 1.730, 1.733, 1.746, 1.798, 2.461, 3.633, 5.522, 7.703, 10.35, 15.98, 21.97, 29.07, 31.11, 32.76, 36.23, 39.72, 49.44, 63.25, 76.20, and 88.12 μohm cm at 2.7, 4.2, 6.0, 8.0, 10.0, 16.0, 20.2, 24.5, 28.3, 32.1, 39.3, 46.3, 54.0, 56.5, 60.3, 70.9, 82.7, 120.3, 180.7, 241.6, and 298.9 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 51.0$; residual electrical resistivity 1.73 μohm cm; Lorenz function reported as 4.08, 4.38, 3.45, 3.70, 4.22, 4.66, 4.88, 5.14, 5.20, 5.12, 4.78, 4.49, 4.26, and 4.17×10^{-8} V^2 K^{-2} at 5.1, 9.1, 17.4, 22.6, 31.1, 43.3, 55.2, 59.2, 63.9, 78.4, 135.0, 200.5, 262.2, and 300.0 K, respectively; heat flow along b-axis.
4	389, 390	Edwards, L.R. and Legvold, S.	1967	L	5.4-299		<0.0200 Ho, <0.0200 Lu, <0.0200 Y, 0.0100 O, <0.0060 Al, <0.0060 Si, <0.0050 Fe, <0.0050 Ni, <0.0030 Er, <0.0020 Ca, <0.0020 Cr, <0.0010 Mg, <0.0010 Yb, 0.0004 H, 0.0003 N, traces of Cu and Dy, and faint traces of Mn and W; single crystal; 7.24 x 1.450 x 1.166 mm; same fabrication method as above; electrical resistivity reported as 3.641, 3.647, 3.708, 4.161, 5.558, 8.218, 13.94, 19.37, 24.02, 25.81, 25.85, 25.72, 24.35, 21.24, 19.90, 18.60, 17.80, 17.81, 18.21, 19.68, 20.51, 25.33, 33.93, and 47.05 μohm cm at 1.4, 4.2, 8.0, 12.0, 16.0, 20.0, 26.0, 31.1, 37.6, 44.1, 45.4, 47.1, 51.2, 54.9, 56.0, 56.8, 57.5, 57.9, 61.9, 73.6, 80.1, 120.8, 195.0, and 300.7 K, respectively; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 12.9$; residual electrical resistivity 3.65 μohm cm; Lorenz function reported as 8.87, 8.98, 7.44, 5.98, 5.86, 6.04, 6.75, 6.20, 5.66, 4.81, 4.96, 4.83, 4.68, 4.21, 3.99, and 3.77×10^{-8} V^2 K^{-2} at 4.5, 6.4, 10.7, 15.6, 18.0, 21.8, 31.8, 44.9, 52.3, 56.6, 59.7, 67.4, 86.7, 160.6, 220.2, and 300.1 K, respectively; heat flow along c-axis.

Tin

In this work it is only possible to study white tin. No thermal conductivity data are available for the gray cubic form of tin. The majority of the thermal conductivity determinations are in the superconducting region, and 143 of the available 180 curves are at temperatures below 5 K.

In this low-temperature region the highest thermal conductivity curve is that of Zavaritskii [1602] (curve 94) for a high-purity single crystal in the normal state measured with heat flow perpendicular to the tetragonal axis. The residual electrical resistivity of this sample was reported to be $(1 \pm 0.5) \times 10^{-10}$ Ω cm. He also reported data from 2.6 to 4.6 K for two other single crystals measured with heat flow parallel to the tetragonal axis. All these three crystals are apparently of the same material. These data indicate the thermal conductivity anisotropy ratio $k_\perp/k_\parallel$ to be 1.44.

The available information is, however, not sufficient for deriving a value of m. Using $n = 2.60$ the curves for $k_\parallel$ and $k_\perp$ have been derived for temperatures from 1 to 3 K, which fit Zavaritskii's data from 3 to 4.5 K. The curve for $k_\parallel$ was calculated by using $n = 2.60$, $\alpha' = 0.0000861$, and $\beta = 0.00696$, and it was only for a sample having $\rho_0 = 0.000170$ μΩ cm. The curve for $k_\perp$ was calculated by using $n = 2.60$, $\alpha' = 0.0000588$, and $\beta = 0.00484$, and it is only for a sample having $\rho_0 = 0.000118$ μΩ cm. The values for the corresponding polycrystalline sample were calculated assuming $k_{\text{poly}} = \frac{1}{3}(k_\parallel + 2\,k_\perp)$, and they are applicable only to a sample having $\rho_0 = 0.000132$ μΩ cm.

The recommended values above 3 K were derived in 1966 and have been published in [607]. At that time the only data available from 6 K to room temperature were those of Rosenberg [1220] (curve 8) for a 99.997 percent tin single crystal at temperatures up to 36 K and those of Lees [830] (curve 7) obtained from 99 K to normal temperature for a rod of Kahlbaum pure polycrystalline tin. The curves had been drawn to 36 K following the trend indicated by Rosenberg's curve. Lees appears from general evidence to have been a careful worker, but the purity of his sample may have been rather low, hence for polycrystalline tin a smooth curve has been drawn from 36 K to lie some 2 percent above that of Lees. The continuation of this curve to the melting point conforms reasonably well with most of the higher experimental values for polycrystalline tin in this temperature range. The values of $k_\perp$ and $k_\parallel$ from 36 K to the melting point are derived from values of $k_{\text{polycrys.}}$ based on the assumption that $k_\perp/k_\parallel = 1.44$ is valid also in this temperature range. This anisotropy ratio is further supported by the electrical resistivity measurements of Bridgman [210]. He obtained room-temperature values for $\rho_\parallel$ and $\rho_\perp$ of 14.3 and 9.9 μΩ cm, respectively, which gives $\rho_\parallel/\rho_\perp = 1.44$.

The most recent measurements of Karamargin, et al. [716] (curves 178, 179) on single crystal samples of tin with heat flow at 72 and 6 degrees to the tetragonal axis cover the temperature range from 4.5 to about 80 K and fall in nicely with the recommended curves. Their samples are of lower purity than that of Zavaritskii's and their curves are consequently lower than but parallel to the recommended curves. The ratio of the thermal conductivities in the two directions ranges from 1.4 to 1.5.

At temperatures above normal the curve of Mikryukov and Rabotnov [969] (curve 58) is displaced to much higher values, about 10 percent higher than the recommended curve for $k_\perp$. Their measurements are reported as being made on a single crystal of tin. The crystal direction in which the measurements were made is not stated, but from the reported electrical resistivity, which increases from 14.45 μΩ cm at 117.2° C to 18.94 μΩ cm at 187.1° C, it seems likely that this was the high conductivity direction. It is further noticed that over this temperature range their Lorenz functions vary from 2.94×10^{-8} V² K⁻² to 2.98×10^{-8} V² K⁻² and are probably some 15 to 20 percent too high, since those of Lees [830] and of Jaeger and Diesselhorst [664] (curves 153, 154) are in fair agreement at 291 K with values of 2.47×10^{-8} and 2.53×10^{-8} V² K⁻², respectively.

The elevens sets of data available for the thermal conductivity of molten tin show fair agreement at temperatures near the melting point but differ progressively at higher temperatures. The recommended curve for the thermal conductivity of molten tin has been based on the data of Nikol'skii, et al. [1036] (curve 83), which are well fitted by a straight line drawn through a mean value (0.317 W cm⁻¹ K⁻¹) at 573 K and a derived value at 973 K obtained from the equation

$$k = 2.443 \times 10^{-8}\, T \rho^{-1},$$

when using the value of Roll and Motz [1217] of 59.6 μΩ cm for the value of ρ. It is interesting to note that at 1473 K this line also conforms closely with the value derived from the ρ value of 72.0 μΩ cm which Roll and Motz [1217] obtained. However, at 1500 K the recommended thermal conductivity value is some 70 percent greater than the almost temperature-independent value which Filippov [434, 435] (curve 144) and Yurchak and Filippov [1591] (curve 147) have derived from thermal diffusivity measurements. These Russian values yield Lorenz functions which decrease rapidly with increase in temperature, and by 1000 K are some 25 percent below the theoretical value. Whether this can be accepted as a true result requires independent confirmation. For more detailed discussion on the thermal conductivity of molten tin, the reader is referred to [1122].

At the melting point the ratio of the recommended values for the solid state $k_\perp$, k_{poly}, and $k_\parallel$ to that for the liquid state are, respectively, 2.18, 1.96, and 1.52. The thermal conductivity of molten tin will presumably reach a maximum at a certain high temperature and then start to decrease gradually to a very low value at the critical temperature around 8000 K.

The recommended values for polycrystalline tin are thought to be accurate to within ±3 percent of the true values at moderate temperatures, ±5 percent at high temperatures, and ±15 percent at low temperatures. The values for $k_{\parallel}$ and $k_{\perp}$ of tin single crystals should be accurate to within ±6 percent at moderate temperatures, ±10 percent at high temperatures, and ±15 percent at low temperatures. For molten tin the values are probably good to ±5 percent near the melting point, but an increasing uncertainty remains to be resolved at higher temperatures. Above 873 K the values are provisional. At temperatures below 100 K the tabulated values for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are, of course, only applicable to samples having $\rho_o =$ 0.000170, 0.000118, and 0.000132 $\mu\Omega$ cm, respectively.

TABLE 167. Recommended thermal conductivity of tin†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid

T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k	T	∥ to c-axis k	⊥ to c-axis k	Poly-crystalline k
0	0	0	0	60	0.797	1.16	1.04*
1	142	204	183	70	0.740	1.07	0.958*
2	250	360	323	80	0.705*	1.02*	0.911*
3	230	331	297	90	0.679*	0.980*	0.879*
4	140	202	181	100	0.660*	0.950*	0.852
5	90	130	117	123.2	0.630*	0.906*	0.813
6	59	85.0	76	150	0.602*	0.867*	0.779
7	40	58.0	52	173.2	0.585*	0.842*	0.757
8	28	40.0	36	200	0.567*	0.816*	0.733
9	20.1	29.0	26	223.2	0.553*	0.796*	0.716
10	14.9	21.5	19.3	250	0.538*	0.775*	0.696
11	11.4	16.5	14.8	273.2	0.527*	0.759*	0.682
12	9.0	12.9	11.6	298.2	0.516*	0.743*	0.668
13	7.2	10.4	9.3	300	0.515*	0.742*	0.666
14	5.9	8.5	7.6	323.2	0.506*	0.729*	0.654
15	4.9	7.0	6.3	350	0.496	0.715	0.642
16	4.1	5.9	5.3	373.2	0.489	0.704	0.632
18	3.1	4.5	4.0	400	0.481	0.693	0.622
20	2.5	3.6	3.2	473.2	0.466	0.670	0.602
25	1.72	2.5	2.22	500	0.461	0.664	0.596
30	1.36	2.0	1.76	505.118	0.460	0.662	0.595
35	1.16	1.67	1.50				
40	1.04	1.50	1.33*				
45	0.950	1.37	1.23*				
50	0.886	1.28	1.15*				

Liquid

T	k	T	k
505.118	0.303	1000	0.405
573.2	0.317	1073.2	0.420
600	0.323	1100	0.425
673.2	0.338	1173.2	0.440
700	0.344	1200	0.446
773.2	0.358	1273.2	0.460
800	0.364	1300	0.466
873.2	0.378	1373.2	0.481
900	0.384	1400	0.487
973.2	0.399	1473.2	0.501
		1500	0.507

†The values are for well-annealed high-purity tin, and those below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_o = 0.000170$, 0.000118, and 0.000132 $\mu\Omega$ cm, respectively. The values above 873 K are provisional.

*Interpolated.

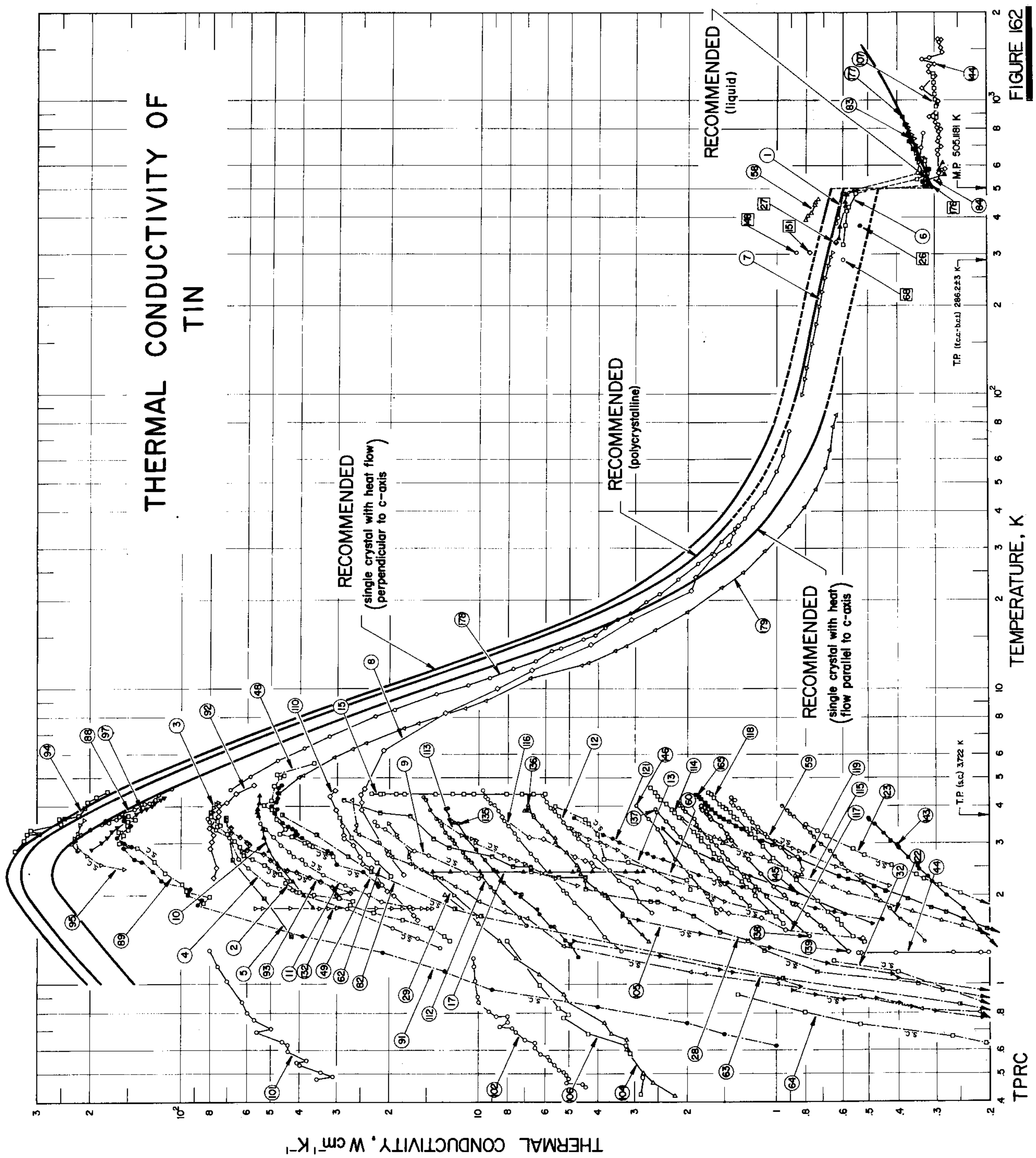

THERMAL CONDUCTIVITY OF TIN
RECOMMENDED (liquid)
RECOMMENDED (polycrystalline)
RECOMMENDED (single crystal with heat flow perpendicular to c-axis)
RECOMMENDED (single crystal with heat flow parallel to c-axis)
M.P. 505.1181 K
T.P. (f.c.c.-b.c.t.) 286.2±3 K
T.P. (s.c.) 3.722 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC

FIGURE 162

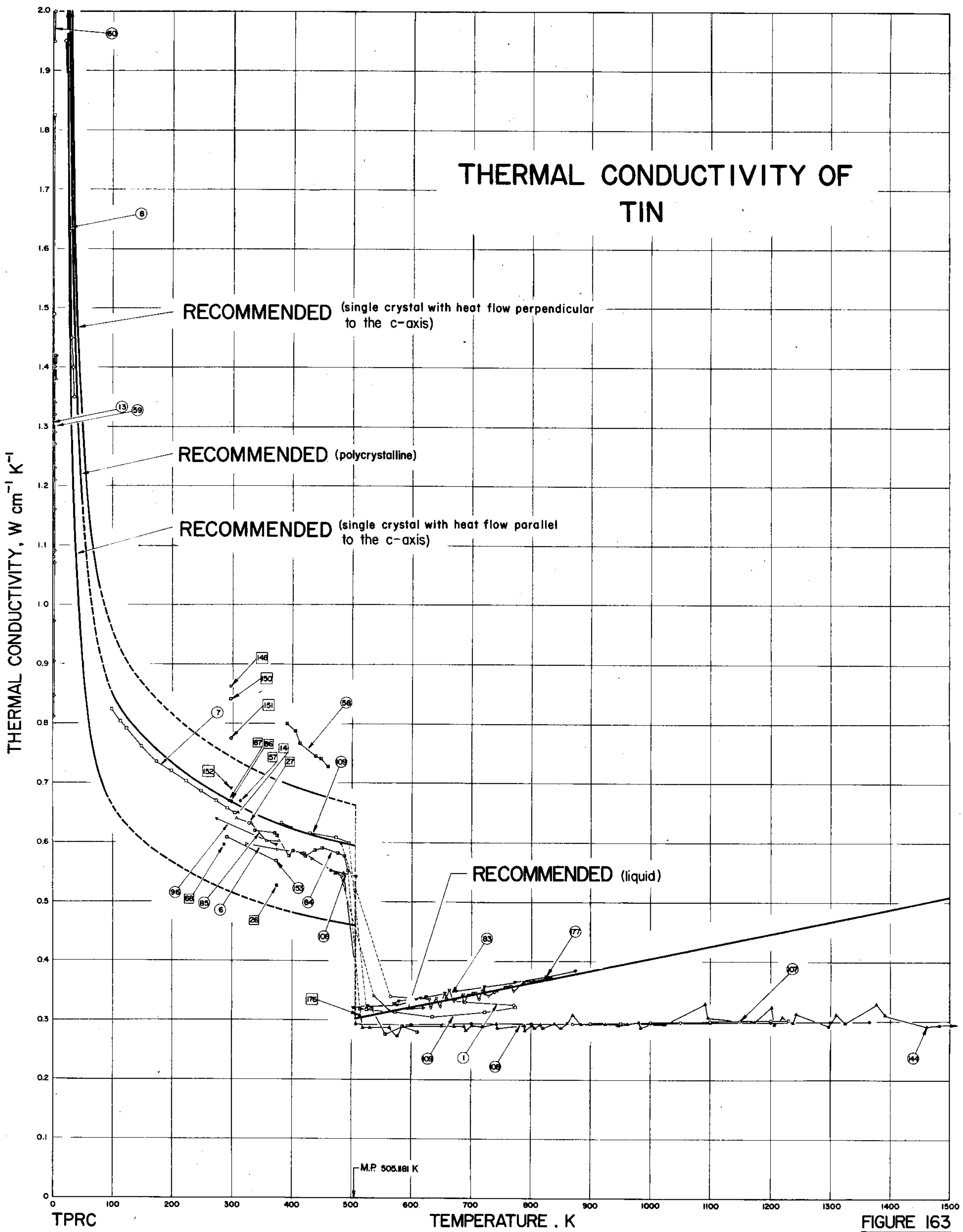

THERMAL CONDUCTIVITY OF
TIN
RECOMMENDED (single crystal with heat flow perpendicular to the c-axis)
RECOMMENDED (polycrystalline)
RECOMMENDED (single crystal with heat flow parallel to the c-axis)
RECOMMENDED (liquid)
M.P. 505.1181 K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE . K
TPRC

FIGURE 163

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	778	Konno, S.	1919	L	381-771		Pure; in both solid and liquid states.
2	1164	Rademakers, A.	1949	L	1.4-3.7	Sn I	99.992$^+$ pure; single crystal; 2.3 mm dia; made of Chempur tin (99.992 pure) purified further by several times melting in vacuo, crystallizing and etching; measured with heat flow at 85 degrees to the tetragonal axis; in superconducting state.
3	1164	Rademakers, A.	1949	L	3.8-4.1	Sn I	The above specimen in normal state.
4	1164	Rademakers, A.	1949	L	1.3-3.6	Sn II	Single crystal; 0.8 mm dia x 70 mm long; made of Chempur tin purified further by several times melting in vacuo, crystallizing and etching; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 16700$; measured with heat flow at 85 degrees to the tetragonal axis; in superconducting state.
5	1164	Rademakers, A.	1949	L	1.5-3.7	Sn II	The above specimen measured in a magnetic field of strength 510 Oe; in normal state.
6	219	Brown, W. B.	1923	L	323-620		Specimen in both solid and liquid states; 12 cm long and 1.5 cm in dia; melting point 232 C.
7	830	Lees, C. H.	1908	L	99-303		Pure; from Kahlbaum; density 7.28 g cm^{-3} at 21 C; electrical resistivity reported as 3.00 and 10.65 μohm cm at -170.4 and 11.6 C, respectively.
8	1220	Rosenberg, H. M.	1955	L	2.3-36	Sn I	99.997 pure; single crystal; 2.95 cm long, 0.389 cm in dia; supplied by Johnson, Matthey Co., Ltd; measured in a magnetic field; in normal state.
9	1220	Rosenberg, H. M.	1955	L	2.3-3.6	Sn 1	The above specimen in superconducting state.
10	641	Hulm, J. K.	1949	L	1.8-4.4	Sn 2	99.997 Sn (by difference), 0.003 impurities; polycrystalline; measured in a longitudinal magnetic field; in normal state.
11	641	Hulm, J. K.	1949	L	1.8-3.5	Sn 2	The above specimen in superconducting state.
12	641	Hulm, J. K.	1949	L	1.8-4.4	Sn 3	99.967 Sn (by difference), 0.033 Hg; polycrystalline; measured in a longitudinal magnetic field; in normal state.
13	641	Hulm, J. K.	1949	L	1.8-3.4	Sn 3	The above specimen in superconducting state.
14	760	King, R. W.	1915	P	308.2		Specimen 25 cm long, 0.25 cm in dia; thermal conductivity value calculated from measured thermal diffusivity using the values of density and specific heat taken from the Tabellen of Landolt and Börnstein.
15	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Sn 1	99.997 pure; single crystal; supplied by Johnson, Matthey Co., Ltd; measured in transverse magnetic fields with strength H ranging from 0.19 to 3.57 kOe.
16*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.0	Sn 1	The above specimen measured in transverse magnetic fields with strength H ranging from 0.29 to 3.57 kOe.
17	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.4	Sn 1	The above specimen measured in transverse magnetic fields with strength H ranging from 0.35 to 3.75 kOe.
18*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.4	Sn 1	The above specimen measured in longitudinal magnetic fields with strength H ranging from 0.29 to 3.75 kOe.
19*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.0	Sn 1	The above specimen measured in longitudinal magnetic fields with strength H ranging from 0.35 to 3.66 kOe.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
20*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.4	Sn 1	The above specimen measured in longitudinal magnetic fields with strength H ranging from 0.35 to 3.75 kOe.
21*	642	Hulm, J.K.	1950	L	2.21	Sn 2	99.996 pure; homogeneous solid solution with few large crystals; superconducting transition point 3.71 K; measured in magnetic fields with strength H ranging from 62 to 1453 gauss.
22*	642	Hulm, J.K.	1950	L	4.29	Sn 2	The above specimen measured in magnetic fields with strength H ranging from 62 to 1453 gauss.
23*	642	Hulm, J.K.	1950	L	2.42	Sn 3	99.967 pure; homogeneous solid solution with few large crystals; superconducting transition point 3.68 K; measured in magnetic fields with strength H ranging from 123 to 1213 gauss.
24*	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.39–0.65	Sn 1	99.997 pure; single crystal; supplied by Johnson, Matthey Co., Ltd; in superconducting state (same specimen as used for curve No. 8).
25*	936	Mendelssohn, K. and Renton, C.A.	1955	L	0.25–0.80		99.997 pure; polycrystalline; supplied by Johnson, Matthey Co., Ltd; in superconducting state.
26	266	Cherpakov, V.P.	1957		373.2		Electrical conductivity 6.6 x 10^4 ohm^{-1} cm^{-1} at 100 C.
27	1327	Smith, A.W.	1925	L	327		0.03 total impurities; specimen 10 cm long and 1.9 cm in dia; electrical conductivity 8.96 x 10^4 ohm^{-1} cm^{-1} at 22 C.
28	810	Laredo, S.J.	1955	L	0.2–4.2	JM 4600; Sn 2	Spectroscopically pure; single crystal with tetragonal axis parallel to rod axis; 2.530 mm dia rod; supplied by Johnson, Matthey Co., Ltd; cast and recrystallized; in superconducting state.
29	810	Laredo, S.J.	1955	L	1.7–3.5	JM 4600; Sn 2	The above specimen measured in a longitudinal magnetic field of 400 gauss; in normal state; data corrected for magneto-conductivity.
30*	810	Laredo, S.J.	1955	L	0.40–0.64	JM 4600; Sn 3	Similar to the above specimen but the dia 5.11 mm; in superconducting state.
31*	810	Laredo, S.J.	1955	L	0.34–0.71	JM 4600; Sn 4	Similar to the above specimen but with tetragonal axis at 88 degrees to the rod axis, and rod dia 2.135 mm; in superconducting state.
32	810	Laredo, S.J.	1955	L	0.24–1.2	JM 4600; Sn 5	Pure; polycrystalline; specimen dia 2.315 mm; cast, recrystallized, and strained; grain size 0.50 mm; in superconducting state.
33*	350, 352	Detwiler, D.P. and Fairbank, H.A.	1952	L	1.59	Sn II	Prepared from Johnson-Matthey 99.996 pure spectroscopically standardized tin JM 2356; polycrystal consisted of several long thin crystals with their geometric axis parallel to the specimen axis; 4.09 mm dia x 10 cm long; material melted in a Pyrex tube, held near 500 C in vacuum for some time, cast in mold, solidified from one end slowly, cooled to room temp, etched; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 8000$; measured in increasing transverse magnetic fields with strength H ranging from zero to 303 gauss.
34*	350, 352	Detwiler, D.P. and Fairbank, H.A.	1952	L	1.59	Sn II	The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 245 to 122 gauss.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used *	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.21	Sn II	The above specimen measured in increasing transverse magnetic fields with strength H ranging from zero to 272 gauss.
36*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.21	Sn II	The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 255 to zero gauss.
37*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.53	Sn II	The above specimen measured in increasing transverse magnetic fields with strength H ranging from 57.8 to 238 gauss.
38*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.53	Sn II	The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 204 to zero gauss.
39*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.18	Sn IV	Single crystal; prepared from the same material as the above specimen; 4.27 mm dia x 10 cm long rod specimen with the tetragonal axis at about 70 degrees from the specimen axis; material melted and outgassed in vacuum in a Pyrex mold, solidified in helium at ~18 psi in a electric furnace with a movable temp gradient; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 11000$; measured in increasing transverse magnetic fields with strength H ranging from zero to 272 gauss and field direction nearly parallel to the tetragonal axis.
40*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.18	Sn IV	The above specimen measured in decreasing transverse magnetic fields nearly parallel to the tetragonal axis with strength H ranging from 245 to zero gauss.
41*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.86	Sn IV	The above specimen measured in increasing transverse magnetic fields with strength H ranging from zero to 204 gauss and field direction at about 20 degrees with the tetragonal axis.
42*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.86	Sn IV	The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 116 to zero gauss and field direction at about 20 degrees with the tetragonal axis.
43*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	3.62	Sn IV	The above specimen measured in transverse magnetic fields with strength H ranging from zero to 34 gauss and field direction at about 20 degrees with the tetragonal axis.
44	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	1.27	Sn-Bi III	99.866 pure; 0.134 Bi; polycrystalline; 5 mm dia x 10 cm long; prepared from Johnson, Matthey tin and bismuth; materials melted, outgassed, and cast in Pyrex in vacuum, cooled freely; annealed at somewhat below the melting point for 20 min; measured in increasing transverse magnetic fields with strength H ranging from zero to 304 gauss.
45*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	1.27	Sn-Bi III	The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 255 to zero gauss.
46*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.5		Spectroscopically pure; polycrystal with a few large crystals; 3-4 mm dia x ~10 cm long; prepared from Johnson-Matthey tin; measured in increasing transverse magnetic fields with strength H ranging from zero to 238.2 gauss.
47*	350, 352	Detwiler, D. P. and Fairbank, H. A.	1952	L	2.5		The above specimen measured in decreasing transverse magnetic fields with strength H ranging from 149.7 to zero gauss.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
48	68, 69	Andrews, F.A., Webber, R.T., and Spohr, D.A.	1950	L	2.7-5.6	Sn 1	99.996⁺ pure; single crystal; supplied by Johnson, Matthey and Co., Ltd; specimen 8 cm long, 4 mm in dia; in superconducting state below transition temp.
49	68, 69	Andrews, F.A., et al.	1950	L	2.1-4.7	Sn II	Similar to the above specimen but with a dia of 2 mm; in superconducting state below transition temp.
50*	68, 69	Andrews, F.A., et al.	1950	L	2.18	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 455.2 gauss.
51*	68, 69	Andrews, F.A., et al.	1950	L	3.19	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 258.7 gauss.
52*	68, 69	Andrews, F.A., et al.	1950	L	3.32	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 376.1 gauss.
53*	68, 69	Andrews, F.A., et al.	1950	L	3.77	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 375.2 gauss.
54*	68, 69	Andrews, F.A., et al.	1950	L	4.38	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 532 gauss.
55*	68, 69	Andrews, F.A., et al.	1950	L	5.02	Sn II	The above specimen measured in longitudinal magnetic fields with strength H ranging from zero to 434.5 gauss.
56*	68, 69	Andrews, F.A., et al.	1950	L	2.2-3.7	Sn II	The above specimen; superconducting transition point 3.69 K; measured in a magnetic field; in normal state.
57	1463	Van Dusen, M.S.	1922	C	313.2		Pure; specimen 3 cm long and 3 cm in dia; zinc used as comparative material.
58	969	Mikryukov, V.E. and Rabotnov, S.N.	1944	E	390-460		Single crystal; electrical resistivity reported as 14.45, 15.30, 15.80, 17.55, 18.03, and 18.94 μohm cm at 390.2, 404.4, 412.0, 439.5, 447.6, and 460.2 K, respectively.
59	475, 476	Garfinkel, M. and Lindenfeld, P.	1958	L	2.4-4.3	1	0.197 Bi; 4 mm dia rod; annealed for several months; electrical resistivity reported as 0.0721 and 11.69 μohm cm at 4.2 and 300 K, respectively; measured in a magnetic field of ~560 gauss; in normal state.
60	1598	Zavaritskii, N.V.	1957	L	2.1-4.0	Sn 1	99.9 pure; monocrystalline; 1.89 mm dia rod; polished; in superconducting state.
61*	1598	Zavaritskii, N.V.	1957	L	0.14-4.2	Sn 2	99.998 pure; monocrystalline; 1.72 mm dia rod with rough surface; angle between specimen axis and [001] direction = 30°; in superconducting state.
62	1598	Zavaritskii, N.V.	1957	L	2.3-3.7	Sn 2	The above specimen in normal state.
63	1598	Zavaritskii, N.V.	1957	L	0.12-1.4	Sn 3	99.998 pure; monocrystalline; 1.40 mm dia rod with rough surface; angle between specimen axis and [001] direction = 70°; in superconducting state.
64	1598	Zavaritskii, N.V.	1957	L	0.11-0.92	Sn 4	99.998 pure; monocrystalline; 1.81 mm dia rod with polished surface; angle between specimen axis and [001] direction = 45°; in superconducting state.
65*	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.47-0.64	Sn 2	99.997 pure; polycrystalline; effected by "frozen in" magnetic field; in superconducting state.
66*	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.57-0.71	Sn 2	99.997 pure; polycrystalline; in superconducting state.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
67*	935	Mendelssohn, K. and Renton, C.A.	1953	L	0.33-0.80	Sn 1	99.997 pure; single crystal; in superconducting state.
68	552	Grossmann, G.	1905	P	286.7		Chemically pure; specimen in ring form; cast and turned; density 7.31 g cm^{-3} at 14 C; electrical resistivity 11.82 μohm cm at 13.5 C; thermal conductivity value calculated from measured data of thermal diffusivity and specific heat.
69*	523	Graham, G. M.	1958	L	0.21-0.52	E 0	Spectroscopically pure; single crystal; 4.91 mm dia rod with specimen axis at 85 degrees to the tetrad axis; provided by Johnson, Matthey Co., Ltd; cast, crystallized, and electropolished to 0.05 μ in surface roughness; in superconducting state.
70*	523	Graham, G. M.	1958	L	0.21-0.52	E 1	The above specimen; 50% clouding etched by exposure to HCl fumes; surface roughness 0.3 μin.; in superconducting state.
71*	523	Graham, G. M.	1958	L	0.26-0.51	E 2	The above specimen lightly etched to 0.7 μ in surface roughness; in superconducting state.
72*	523	Graham, G. M.	1958	L	0.25-0.53	E 3	The above specimen lightly etched to 1.1 μ in surface roughness; in superconducting state.
73*	523	Graham, G. M.	1958	L	0.21-0.47	E 4	The above specimen electropolished to 0.05 μ in surface roughness and 4.75 mm in dia; in superconducting state.
74*	523	Graham, G. M.	1958	L	0.21-0.47	E 5	The above specimen 25% clouding etched by exposure to HCl fumes; surface roughness 0.12 μin.; in superconducting state.
75*	523	Graham, G. M.	1958	L	0.25-0.52	E 6	The above specimen electropolished to 0.10 μ in surface roughness and 3. 15 mm in dia; in superconducting state.
76*	523	Graham, G. M.	1958	L	0.24-0.53	E 7	The above specimen etched to 1.0 μ in surface roughness; in superconducting state.
77*	523	Graham, G. M.	1958	L	0.27-0.65	E 10	The above specimen electropolished, etched, annealed at 220 C, then again etched to 1.0 μ in surface roughness and 1.96 mm in dia; residual electrical resistivity 0.00377 μohm cm; in superconducting state.
78*	523	Graham, G. M.	1958	L	0.24-0.66	D 0	Spectroscopically pure; 2.82 mm dia rod consisted of 3 large crystals; as cast; surface roughness 0.10 μin.; residual electrical resistivity 0.0014 μohm cm; in superconducting state.
79*	523	Graham, G. M.	1958	L	0.26-0.63	D 1	The above specimen etched to 0.7 μ in surface roughness; in superconducting state.
80*	517	Goodman, B. B.	1953	L	0.18-0.67	Sn II	Spectroscopically pure; polycrystalline; 1.3 mm dia rod made up of crystals of the order of the dia; cast in tube; in superconducting state.
81*	517	Goodman, B. B.	1953	L	0.23-0.90	Sn III	Similar to the above specimen but with dia 0.7 mm; in superconducting state.
82	1603	Zavaritskii, N. V.	1960	L	0.13-4.0		0.002 impurity; single crystal; 0.175 cm in dia and ~50 mm long; cast in vacuo in thin-walled glass capillary in which crystallization took place immediately after casting; electrical resistivity ratio $\rho(293K)/\rho_0$ = 6250; in superconducting state.
83	1036	Nikol'skii, N. A., Kalakutskaya, N. A., Pchelkin, I. M., Klassen, T. V., and Veltishcheva, V. A.	1959	L	570-833		In molten state; melting point 231.9 C.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
84	1066, 1067	Pashaev, B. P.	1961	L	337-610		99.94 pure; in both solid and liquid states.
85	1233	Ruh, E.	1954	C	306-378	56 B-1	Specimen made from NBS freezing-point tin No. 42b (freezing point 231.9 C); 0.500 in. dia x 0.500 in. long; electrolytically deposited pure copper used as comparative material; reference data of copper taken from International Critical Tables (Vol. 5, McGraw-Hill Book Co., New York, 221, 1929).
86	869	Lussana, S.	1918	L	298.0		Specimen with radius of 0.7 cm furnished by the manufacturer Erba; measured at atmospheric pressure.
87	1065	Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L.	1961	P	295.2		Rectangular plate 1.9 x 1.9 x 0.306 cm; thermal conductivity values calculated from measured thermal diffusivity using values of density and specific heat taken from Smithsonian Physical Tables (9th ed., 1954).
88	1602	Zavaritskii, N. V.	1961	L	2.9-4.6	Sn-1	High purity; single crystal; 2.6 mm in dia; specimen axis in the [001] orientation; residual electrical resistivity $\rho_0 = (1 \pm 0.5) \times 10^{-4}$ μohm cm; superconducting transition point 3.72 K; measured in a longitudinal magnetic field; in normal state; data corrected to zero field.
89	1602	Zavaritskii, N. V.	1961	L	1.9-3.7	Sn-1	The above specimen in superconducting state.
90*	1602	Zavaritskii, N. V.	1961	L	2.6-4.4	Sn-2	Similar to the above specimen but 1.1 mm in dia and residual electrical resistivity $\rho_0 = 1.65 \pm 0.2 \times 10^{-4}$ μohm cm; measured in a longitudinal magnetic field; in normal state; data corrected to zero field.
91	1602	Zavaritskii, N. V.	1961	L	0.6-3.7	Sn-2	The above specimen in superconducting state.
92	1602	Zavaritskii, N. V.	1961	L	2.3-4.7	Sn-3	Similar to the above specimen but 1.5 mm in dia and residual electrical resistivity $\rho_0 = 6.1 \times 10^{-4}$ μohm cm; measured in a longitudinal magnetic field; in normal state; data corrected to zero field.
93	1602	Zavaritskii, N. V.	1961	L	2.0-3.7	Sn-3	The above specimen in superconducting state.
94	1602	Zavaritskii, N. V.	1961	L	2.8-4.5	Sn-4	High purity; single crystal; 2.1 mm in dia; specimen axis in the [110] orientation; residual electrical resistivity $\rho_0 = 1.2 \pm 0.5 \times 10^{-4}$ μohm cm; measured in a longitudinal magnetic field.
95	1602	Zavaritskii, N. V.	1961	L	2.5-3.7	Sn-4	The above specimen in superconducting state.
96	859	Lorenz, L.	1881	L	273, 373		Density 7.27 g cm^{-3}; electrical conductivity reported as 9.346 and 6.524 x 10^4 ohm^{-1} cm^{-1} at 0 and 100 C, respectively.
97	562	Guénault, A. M.	1961	L	2.7-4.3	Sn 1	High purity; single crystal; rod specimen about 14 cm long made from 2 mm dia extruded wire; nominal orientation [001]; rod along the tetrad axis; specimen crystallized by slow cooling, etched in concentrated HCl; electrical resistivity ratio $\rho(293K)/\rho_0 = 80000$; measured in a magnetic field; in normal state.
98*	562	Guénault, A. M.	1961	L	2.8-4.2	Sn 2	Similar to the above specimen but made from 5 parts of Johnson, Matthey Specpure and 8 parts of high purity tin from Vulcan De-tinning Co.; electrical resistivity ratio $\rho(293K)/\rho_0 = 23000$; measured in a magnetic field; in normal state.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
99*	562	Guénault, A. M.	1961	L	2.7–4.2	Sn 4	Similar to the above specimen but made from equal parts of Johnson, Matthey Specpure and Vulcan De-tinning Co. high purity tin; measured in a magnetic field; electrical resistivity ratio $\rho(293K)/\rho_0$ = 4500; in normal state.
100*	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.34–1.3		99.9998 pure; single crystal; specimen 2.2 mm in dia and 100 mm long with the tetragonal axis along the length; grown by Kapitza's method; residual electrical resistivity $\rho(4.2K) = 1.7 \times 10^{-10}$ ohm cm; in superconducting state.
101	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.48–1.3		The above specimen measured in a longitudinal magnetic field of 500 oersteds; in normal state.
102	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.45–1.2		The above specimen measured in a transverse magnetic field of 500 oersteds; in normal state.
103*	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.39–1.5		99.9998 pure; 1.5 mm dia x 100 mm long; prepared by rolling 0.05 mm tin foil into the rod shape; residual electrical resistivity 0.00017 μohm cm; in superconducting state.
104	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.42–2.0		The above specimen measured in a longitudinal magnetic field of 330 oersteds; in normal state.
105	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.36–1.7		Similar to the above specimen but the foil had been preliminarily etched; in superconducting state.
106	1081, 1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.43–1.4		The above specimen measured in a longitudinal magnetic field of 330 oersteds; in normal state.
107	1592	Yurchak, R. P. and Filippov, L. P.	1965	P	870–1230		Molten specimen filled in the space between 2 coaxial tantalum tubes of diameters 23.8 and 8 mm, each tube 0.12 mm thick; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat using data of density taken from M. P. Slavinskii ("Physicochemical Properties of Elements," Moscow, 1952).
108	434	Filippov, L. P.	1966	P	465–1365		Molten specimen filled in the space between two coaxial thin-walled tantalum tubes of 24 and 8 mm dia, respectively; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat.
109	383	Dutchak, Ya. I. and Panasyuk., P. V.	1967	C	429–773		Molten specimen held in a hole of 21 mm in dia drilled in an asbestos cement cylinder of 30 mm height; 1Kh18N9T steel used as comparative material.
110	1071	Pearson, G. J., Ulbrich, C. W., Gueths, J. E., Mitchell, M. A., and Reynolds, C. A.	1967	L	1.6–4.5	Sn 1	99.999 pure; supplied by Johnson-Matthey; extruded into 1.5 mm dia wire; electrical resistivity reported as 0.00213 and 13.06 μohm cm at 4.2 and 273 K, respectively; superconducting transition temp 3.720 K; below the transition temp, a longitudinal magnetic field was applied to the specimen; in normal state.
111*	1071	Pearson, G. J., et al.	1967	L	1.6–3.6	Sn 1	The above specimen measured with the magnetic field removed; in superconducting state.
112	1071	Pearson, G. J., et al.	1967	L	1.6–4.5	Pb 1	0.019 Pb; prepared by vacuum-melting appropriate amounts of Johnson, -Matthey 99.999 pure Sn and Pb, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.00564 and 12.71 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.716 K; measured in a longitudinal magnetic field; in normal state.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
113	1071	Pearson, G. J., Ulbrich, C. W., Gueths, J. E., Mitchell, M. A., and Reynolds, C. A.	1967	L	2.2-3.6	Pb 1	The above specimen measured without the magnetic field; in superconducting state.
114	1071	Pearson, G. J., et al.	1967	L	1.6-4.6	Pb 2	0.174 Pb; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Pb, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.0500 and 13.19 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.713 K; measured in a longitudinal magnetic field; in normal state.
115	1071	Pearson, G. J., et al.	1967	L	1.4-3.7	Pb 2	The above specimen measured without the magnetic field; in superconducting state.
116	1071	Pearson, G. J., et al.	1967	L	1.3-4.5	Bi 1	0.012 Bi; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Bi, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.00578 and 12.61 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.725 K; measured in a longitudinal magnetic field; in normal state.
117	1071	Pearson, G. J., et al.	1967	L	1.4-3.7	Bi 1	The above specimen measured without the magnetic field; in superconducting state.
118	1071	Pearson, G. J., et al.	1967	L	1.4-4.4	Bi 2	0.140 Bi; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Bi, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.0721 and 11.91 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.709 K; measured in a longitudinal magnetic field; in normal state.
119	1071	Pearson, G. J., et al.	1967	L	2.2-3.7	Bi 2	The above specimen measured without the magnetic field; in superconducting state.
120*	1071	Pearson, G. J., et al.	1967	L	1.6-4.7	Hg 1	0.018 Hg; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Hg, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.0203 and 12.87 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.718 K; measured in a longitudinal magnetic field; in normal state.
121	1071	Pearson, G. J., et al.	1967	L	1.7-3.7	Hg 1	The above specimen measured without the magnetic field; in superconducting state.
122	1071	Pearson, G. J., et al.	1967	L	1.4-4.0	Hg 2	0.168 Hg; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Hg, extruding into 1.5 mm dia wire; annealed at ~200 C for several days; electrical resistivity reported as 0.113 and 11.28 μohm cm at 4.2 and 273 K, respectively; superconducting transition point 3.686 K; measured in a longitudinal magnetic field; in normal state.
123	1071	Pearson, G. J., et al.	1967	L	1.4-3.6	Hg 2	The above specimen measured without the magnetic field; in superconducting state.
124*	191	Boxer, A. S.	1958	L	1.6-4.6	2	0.047 Hg; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Hg, casting into 1 mm dia x 12 cm long wire in a pyrex capillary; residual electrical resistivity 0.014 μohm cm; measured in a magnetic field; in normal state.
125*	191	Boxer, A. S.	1958	L	1.6-4.2	2	The above specimen measured without the magnetic field; in superconducting state.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
126*	191	Boxer, A. S.	1958	L	1.6–4.8	5	0.049 Bi; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Bi, casting into 1 mm dia x 12 cm long wire in a pyrex capillary; residual electrical resistivity 0.020 μohm cm; measured in a magnetic field; in normal state.
127*	191	Boxer, A. S.	1958	L	1.5–2.8	5	The above specimen measured without the magnetic field; in superconducting state.
128*	191	Boxer, A. S.	1958	L	1.6–4.9	8	0.040 Pb; prepared by vacuum-melting appropriate amounts of Johnson-Matthey 99.999 pure Sn and Pb, casting into 1 mm dia x 12 cm long wire in a pyrex capillary; residual electrical resistivity 0.010 μohm cm; measured in a magnetic field; in normal state.
129*	191	Boxer, A. S.	1958	L	1.6–2.8	8	The above specimen measured without the magnetic field; in superconducting state.
130*	1501	Walton, A. J.	1966	L	1.65	Sn 5.0	Polycrystalline; 2.25 mm dia x 10 cm long; supplied by Johnson-Matthey and Co.; specimen recrystallized in an alumina packing; annealed at a temp just below the melting point for several hrs; electrical resistivity ratio $\rho(290K)/\rho(4.2K)$ = 5000; measured in transverse static magnetic fields with strength ranging from 72 to 277 gauss.
131*	1501	Walton, A. J.	1966	L	1.65	Sn 5.0	The above specimen measured with the field rotated about the specimen axis 10 times at 5 sec rev^{-1} between points of measurement.
132	1501	Walton, A. J.	1966	L	1.80	Sn 47	Single crystal with tetrad axis at 3 degrees to the specimen axis; 2.15 mm dia x 10 cm long; same preparation procedure as the above specimen; electrical resistivity ratio $\rho(290K)/\rho(4.2K)$ = 47000; measured in transverse static magnetic fields with strength ranging from 76 to 227 gauss.
133*	1501	Walton, A. J.	1966	L	1.80	Sn 47	The above specimen measured with the field rotated about the specimen axis 5 times at 8 sec rev^{-1} between points of measurement.
134*	563	Gueths, J. E., Clark, N. N., Markowitz, D., Burckbuchler, F. V., and Reynolds, C. A.	1967	L	1.4–3.9	Sample 1	Spectroscopically pure (<0.001 at. % impurities); single crystal; residual electrical resistivity 0.00103 μohm cm; heat flow approximately perpendicular to tetrad axis; measured in vacuum at 5 x 10^{-6} torr; in normal state.
135	563	Gueths, J. E., et al.	1967	L	1.2–3.9	Sample 2	Spectroscopically pure (<0.001 at. % impurities); doped with 0.0044 Cd; single crystal; prepared by mixing in vacuum; grown in precision bore Pyrex tubing (I. D. = 2.00 ± 0.005 mm); after extraction from tubing, crystal annealed at 200 C for 72 hrs, slight etching in HCl; residual electrical resistivity 0.00658 μohm cm; heat flow approx perpendicular to tetrad axis; measured in vacuum at 5 x 10^{-6} torr; in normal state.
136	563	Gueths, J. E., et al.	1967	L	1.4–4.0	Sample 3	Similar to the above specimen except doped with 0,0087 Cd and residual electrical resistivity 0.0131 μohm cm.
137	563	Gueths, J. E., et al.	1967	L	1.6–3.8	Sample 4	Similar to the above specimen except doped with 0.0232 Cd and residual electrical resistivity 0.0360 μohm cm.
138	563	Gueths, J. E., et al.	1967	L	1.4–4.0	Sample 5	Similar to the above specimen except doped with 0.0294 Cd and residual electrical resistivity 0.0437 μohm cm.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
139	563	Gueths, J.E., Clark, N.N., Markowitz, D., Burckbuchler, F.V., and Reynolds, C.A.	1967	L	1.3-4.0	Sample 6	Similar to the above specimen except doped with 0.0370 Cd and residual electrical resistivity 0.0552 μohm cm.
140*	563	Gueths, J.E., et al.	1967	L	1.2-4.0	Sample 7	Similar to the above specimen except doped with 0.0399 Cd and residual electrical resistivity 0.0675 μohm cm.
141*	563	Gueths, J.E., et al.	1967	L	1.4-3.9	Sample 8	Similar to the above specimen except doped with 0.0460 Cd and residual electrical resistivity 0.0704 μohm cm.
142*	563	Gueths, J.E., et al.	1967	L	1.2-3.9	Sample 9	Similar to the above specimen except doped with 0.0598 Cd and residual electrical resistivity 0.0894 μohm cm.
143	563	Gueths, J.E., et al.	1967	L	1.2-4.0	Sample 10	Similar to the above specimen except doped with 0.116 Cd and residual electrical resistivity 0.173 μohm cm.
144	435	Filippov, L.P.	1968	P	472-1602		In both solid and liquid states; thermal conductivity values calculated from measured data of thermal diffusivity and specific heat.
145	1342	Solomon, P.R. and Otter, F.A., Jr.	1967	L	1.7-3.3		99.952 Sn and 0.048 In; specimen 1 cm wide, 3.5 cm long and 0.05 cm thick; prepared by rolling; annealed at 165 C for over 1 week; residual electrical resistivity 2.8×10^{-8} ohm cm; critical temp 3.66 K; measured in superconducting state.
146	1342	Solomon, P.R. and Otter, F.A., Jr.	1967	L	1.7-4.0		The above specimen measured in normal state.
147*	1591	Yurchak, R.P. And Filippov, L.P.	1964	P	463-1091		In solid and liquid states; electrical resistivity reported as 11.65, 15.05, 16.9, 20.7, 21.65, 49.1, 51.6, 53.2, 55.8, 57.6, 59.4, 61.1, and 62.5 μohm cm at 20, 108, 145, 212, 222, 241, 295, 404, 485, 565, 640, 700, and 750 C, respectively; thermal conductivity values calculated from measured thermal diffusivity data with specific heat data taken from Klinkhard, H. (Ann. Physik, 84, 167-200, 1927) and density data taken from Slavinskii, M. P. ("Physicochemical Properties of Elements," Moscow, 1952).
148	210	Bridgman, P.W.	1926	L	298.2		6 mm dia x 10 cm long; single crystal; crystal axis nearly perpendicular to specimen axis; electrical resistivity 9.92 μohm cm at room temp; reported values of thermal conductivity uncorrected for heat losses.
149*	210	Bridgman, P.W.	1926	L	298.2		Similar to above but electrical resistivity 10.38 μohm cm at room temp and the crystal axis inclined at a smaller angle to the specimen axis.
150	210	Bridgman, P.W.	1926	L	298.2		Similar to the above but electrical resistivity 10.71 μohm cm at room temp and the crystal axis inclination still smaller.
151	210	Bridgman, P.W.	1926	L	298.2		Similar to the above but electrical resistivity 11.14 μohm cm at room temp and the crystal axis inclination still smaller.
152	210	Bridgman, P.W.	1926	L	298.2		Similar to the above but electrical resistivity 13.20 μohm cm at room temp and the crystal axis inclination still smaller.
153	664	Jaeger, W. and Diesselhorst, W.	1900	E	291,373		<0.03 Pb; 1.8025 cm dia x 27.0 cm long; density 7.28 g cm^{-3} at 18 C; electrical conductivity 8.28 and 6.11×10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
154*	664	Jaeger, W. and Diesselhorst, W.	1900	E	291, 373		Drawn from a rod of the same material as the above specimen to give sample of higher density; electrical conductivity 8.82 and 6.53 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively, and thermal conductivity assumed to be proportionally increased.
155*	1604	Zavaritskii, N. V.	1965	L	0.13-0.32	0	99.9999 pure; single crystal; 2.6 mm dia cylindrical specimen; in superconducting state.
156*	1604	Zavaritskii, N. V.	1965	L	0.11-0.33	1	The above specimen measured in magnetic field with the fraction of the normal phase in the specimen η = 0.08.
157*	1604	Zavaritskii, N. V.	1965	L	0.10-0.34	2	The above specimen.
158*	1604	Zavaritskii, N. V.	1965	L	0.12-0.32	3	The above specimen with η = 0.15.
159*	1604	Zavaritskii, N. V.	1965	L	0.14-0.32	5	The above specimen with η = 0.45.
160*	1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.46		99.9998 pure; single crystal; 2.2 mm dia x 100 mm long with the tetragonal axis along the length; grown by Kapitza method; measured in transverse magnetic fields ranging from 0.144 to 7.67 kOe.
161*	1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.46		The above specimen measured in decreasing transverse magnetic fields ranging from 0.288 to 0.163 kOe.
162*	1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.60		The above specimen measured in transverse magnetic fields ranging from 0.316 to 8.67 kOe.
163*	1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.345		99.9998 pure; 1.5 mm dia x 100 mm long; preparedby rolling 0.05 mm tin foil into the rod shape; residual electrical resistivity 0.00017 μohm cm; measured in transverse magnetic fields ranging from 0.292 to 7.78 kOe.
164*	1082	Peshkov, V. P. and Parshin, A. Ya.	1965	L	0.83		The above specimen measured in transverse magnetic fields ranging from 0.312 to 7.83 kOe.
165	373	Detwiler, D. P.	1952	L	1.4-4.3	Sn-Bi III	The same specimen as used for curve No. 44.
166*	373	Detwiler, D. P.	1952	L	1.5-3.6	Sn-Bi III	The above specimen measured in transverse magnetic fields greater than the critical field ranging from 17 to 228 gauss.
167*	373	Detwiler, D. P.	1952	L	2.35	Sn-Bi III	The above specimen measured in increasing parallel magnetic field ranging from zero to 220 gauss.
168*	373	Detwiler, D. P.	1952	L	2.35	Sn-Bi III	The above specimen measured in decreasing parallel magnetic field ranging from 148 to zero gauss.
169*	373	Detwiler, D. P.	1952	L	3.62	Sn IV	The same specimen as used for curve No. 39; measured in decreasing magnetic fields parallel to the tetragonal axis ranging from 27.2 to zero gauss.
170*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in increasing magnetic fields parallel to the tetragonal axis ranging from zero to 190 gauss.
171*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in decreasing magnetic fields parallel to the tetragonal axis ranging from 177 to zero gauss.

* Not shown in figure.

TABLE 168. THERMAL CONDUCTIVITY OF TIN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
172*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in increasing magnetic fields perpendicular to the tetragonal axis ranging from 68 to 264 gauss; 1st cycle.
173*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in decreasing magnetic fields perpendicular to the tetragonal axis ranging from 190 to zero gauss; 1st cycle.
174*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in increasing magnetic fields perpendicular to the tetragonal axis ranging from 68 to 255 gauss; 2nd cycle.
175*	373	Detwiler, D. P.	1952	L	2.18	Sn IV	The above specimen measured in decreasing magnetic fields perpendicular to the tetragonal axis ranging from 184 to zero gauss; 2nd cycle.
176	1594	Yurchak, R. P. and Smirnov, B. P.	1968	E	514.2		In liquid state.
177	382	Dutchak, Ya. I., Osipenko, V. P., Panasyuk, P. V., and Stets'kiv, O. P.	1968	C	505-873		Liquid specimen contained in an asbestos cement ring; 1Kh18N9T steel used as comparative material.
178	716	Karamargin, M. C., Lipschultz, F. P., Reynolds, C. A., and Klemens, P. G.	1970	L	4.5-74	P-3	Single crystal; cylindrical specimen 10 cm long grown in precision bore Pyrex tubing from Johnson-Matthey 99.999 pure tin; the angle between the tetrad axis and the specimen axis $\theta = 72^{\circ}$; electrical resistivity 0.00090 μohm cm at 4.2 K.
179	716	Karamargin, M. C., et al.	1970	L	4.4-84	P-1	Similar to the above specimen but $\theta = 6^{\circ}$ and electrical resistivity 0.00115 μohm cm at 4.2 K.
180*	1025a	Neumann, F.	1862	P	298		Density 7.19 g cm^{-3}; measuring temperature not given and here assumed to be 25 C.

* Not shown in figure.

Titanium

The curve for polycrystalline titanium for which recommended values at low temperatures are tabulated is based on the experimental data (curve 12) of White and Woods [1554] for a 99.99 percent titanium sample that had been annealed at 800 C for 60 hours. The experimental data and the recommended values which were calculated by using $\beta = 69.5$ agree closely up to 40 K. This particular set of recommended values at low temperatures is applicable only to a sample having $\rho_0 = 1.90$ $\mu\Omega$ cm on account of the experimental Lorenz function $L = 2.74 \times 10^{-8}$ V^2 K^{-2} near 0 K found by White and Woods.

From just above T_m to the 293 K value (curve 19) of Powell and Tye [1135] for a sample of very high purity with $\rho_{293\ K} = 42.7$ $\mu\Omega$ cm, a smooth curve with a gradually decreasing slope has been drawn.

Over the temperature range from about 300 to 900 K the 11 sets of thermal conductivity data that are available cover a wide range, with the highest values some 50 percent greater than the lowest. With most metals, the purer the sample, the higher is the thermal conductivity. In the present instance, however, the two highest curves are those of Loewen [855] (curve 9) for a commercially pure titanium, for which no analysis is given, and of Mikryukov [693] (curve 5) for a sample of 99.6 percent purity. The situation is further complicated by the fact that Mikryukov reported at the same time values for a sample of 99.9 percent purity which are mainly some 6 to 12 percent lower. For the less pure sample Mikryukov's data indicate a higher Lorenz function and one that is increasing with increase in temperature, whereas the results for the purer sample are more in accord with the Lorenz functions found by Powell and Tye [1135] and Deem, Wood, and Lucks [331] (curve 7) which give mean values decreasing from 3.24×10^{-8} at 323 K to 3.06×10^{-8} V^2 K^{-2} at 773 K. Whilst admitting that complications might well be associated with the high phonon conductivity component of this metal, a tentative curve from room temperature upwards agreeing closely with the data of Kuprovskii and Gel'd [802] (curve 20) has been derived by assuming values of the Lorenz function of the order found by these three groups of workers. The Lorenz function has been assumed to continue to fall steadily to 2.44×10^{-8} V^2 K^{-2} at 1673 K, and in the uppermost range use has been made of the electrical resistivity data compiled in [1419]. A minimum thermal conductivity is indicated at about 650 K. Over the range 750 to 1400 K the suggested curve ignores the possibility of a discontinuity at the phase transition (1155 K) and lies some 30 to 3 percent above a curve deduced from the thermal diffusivity measurements made by Rudkin, Parker, and Jenkins [1230] (curve 27) on a sample of titanium for which no details were given. From 1417 to 1606 K similarly derived values lie on a reasonable continuation of the proposed curve. On the other hand the data derived by Zinov'ev, Krentsis, and Gel'd from thermal diffusivity data appear to be much too low.

The close-packed hexagonal crystalline form of this metal transforms into body-centered cubic form at about 1155 K. Any associated change in the thermal conductivity has yet to be experimentally investigated. The curve derived from the measurements of Rudkin, Parker, and Jenkins has a gradual drop of about 8 percent in this region, whereas according to the previously quoted electrical resistivity data [1419], the electrical conductivity increases by about 10 percent. Since these changes are about equal and opposite, no discontinuity has been introduced at this stage in the proposed curve. The Zinov'ev, et al. data showed no discontinuity when used with the specific heat values of Hultgren, et al. [644]; discontinuities in either direction were obtained when other specific heat data were used.

Quite apart from the importance of titanium in modern technology, facts such as the foregoing should encourage further investigation to be undertaken of the thermal and electrical conductivities of titanium in the transformation region and above.

The values given by the proposed curve are thought to be accurate to within ±10 percent of the true values at moderate temperatures, and ±15 percent at low and high temperatures. At temperatures below room temperature the values are, of course, only for a sample having $\rho_0 = 1.90$ $\mu\Omega$ cm.

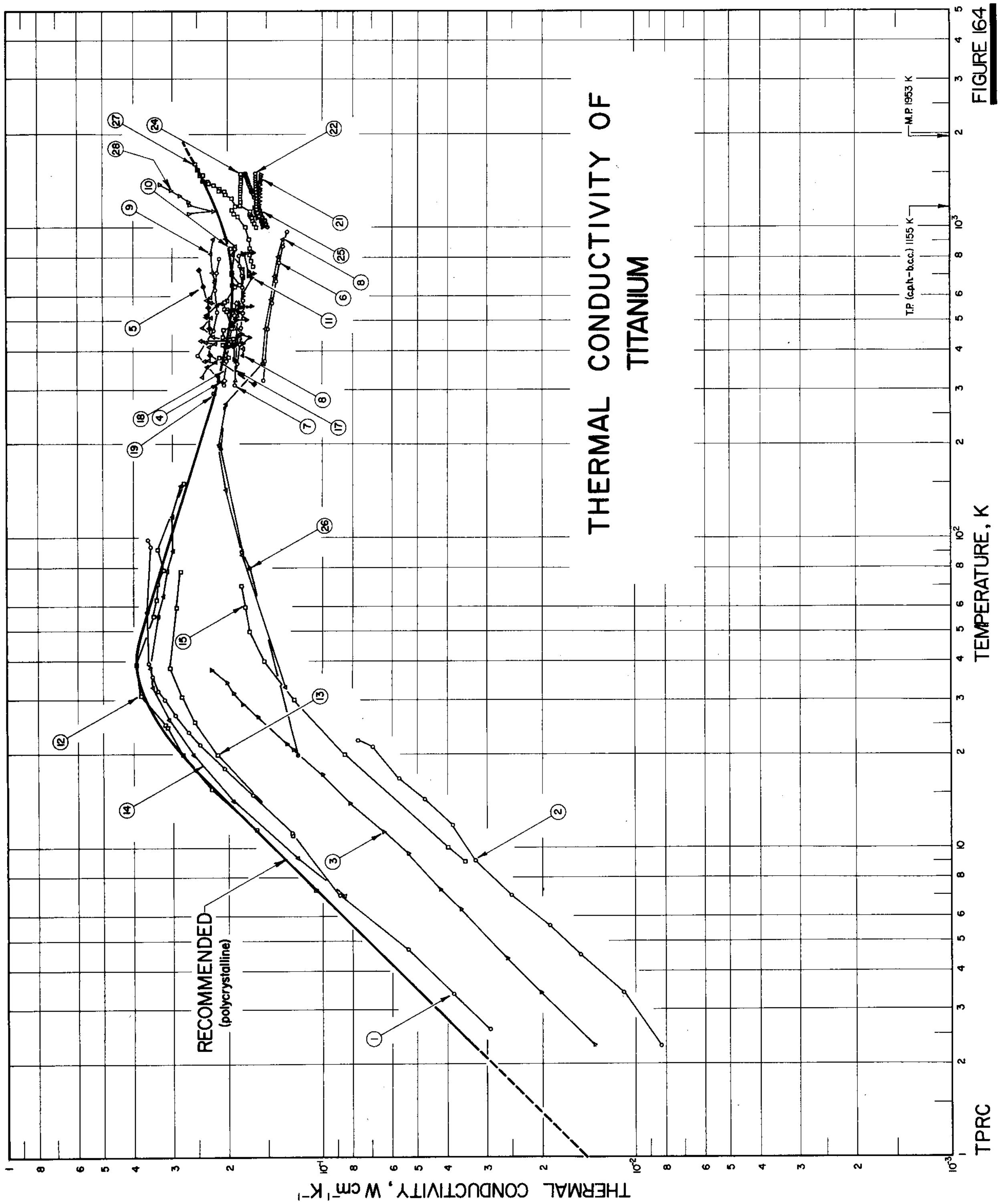
TABLE 169. Recommended thermal conductivity of titanium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	250	0.229
1	0.0144*	273.2	0.224
2	0.0288*	298.2	0.219
3	0.0432	300	0.219
4	0.0575	323.2	0.215
5	0.0719	350	0.210
6	0.0863	373.2	0.207
7	0.101	400	0.204
8	0.115	473.2	0.198
9	0.129	500	0.197
10	0.143	573.2	0.194
11	0.157	600	0.194
12	0.171	673.2	0.194
13	0.185	700	0.194
14	0.199	773.2	0.196
15	0.212	800	0.197
16	0.225	873.2	0.200
18	0.250	900	0.202
20	0.275	973.2	0.205
25	0.327	1000	0.207
30	0.365	1073.2	0.211
35	0.386	1100	0.213
40	0.390	1173.2	0.218
45	0.385	1200	0.220
50	0.374	1273.2	0.225
60	0.355	1300	0.228
70	0.340	1373.2	0.234
80	0.326	1400	0.236
90	0.315	1473.2	0.242
100	0.305	1500	0.245
123.2	0.286	1573.2	0.251
150	0.270	1600	0.253
173.2	0.257	1673.2	0.259*
200	0.245	1700	0.262*
223.2	0.237	1773.2	0.268*
		1800	0.270*
		1873.2	0.277*
		1900	0.279*
		1950	0.283*

†The recommended values are for well-annealed high-purity polycrystalline titanium, and those below room temperature are applicable only to a specimen having $\rho_o = 1.90$ $\mu\Omega$ cm.

*Extrapolated.


THERMAL CONDUCTIVITY OF
TITANIUM
FIGURE 164
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
RECOMMENDED
(polycrystalline)
T.P. (c.p.h.–b.c.c.) 1155 K
M.P. 1953 K
TPRC

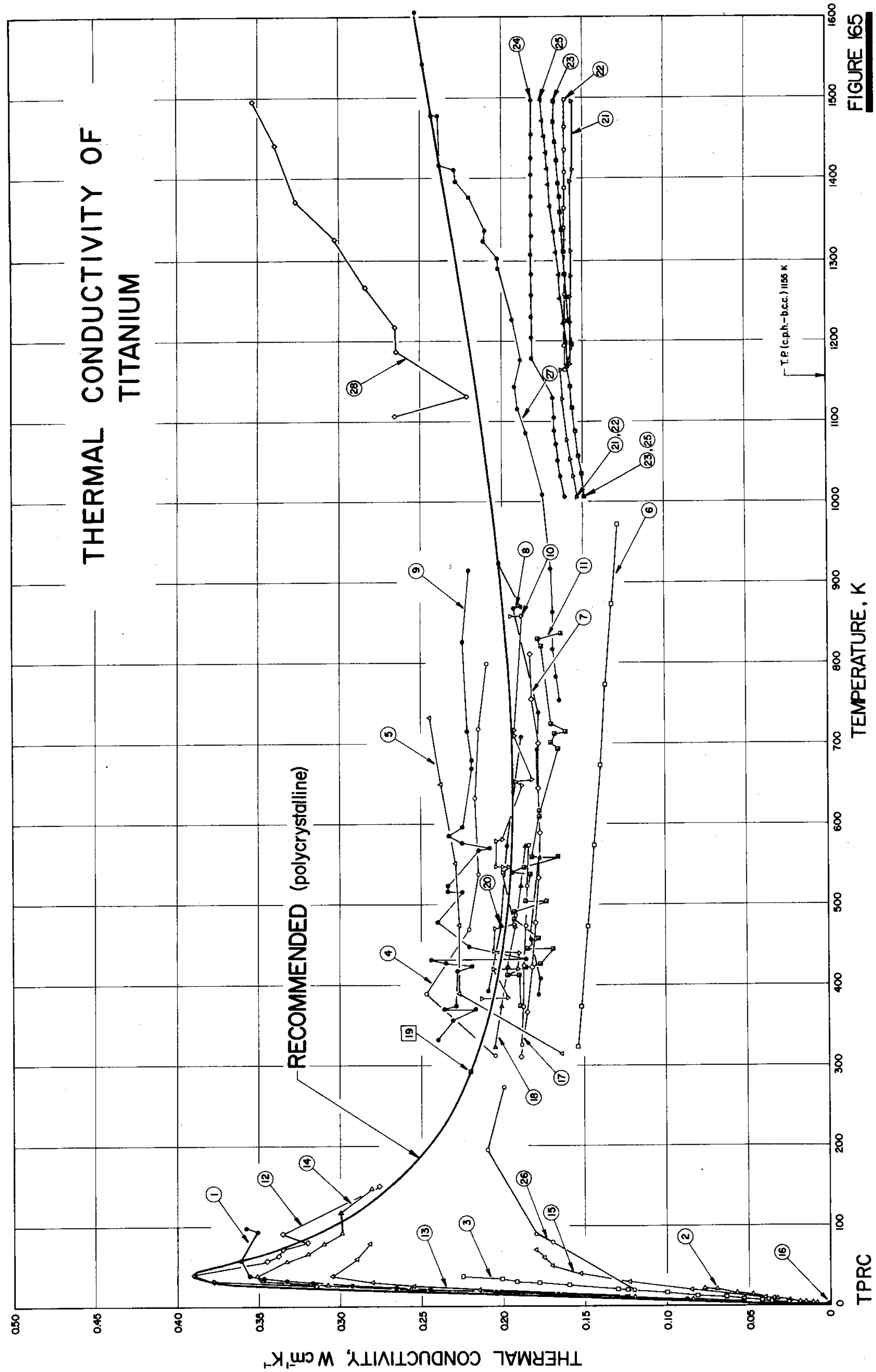

THERMAL CONDUCTIVITY OF TITANIUM
RECOMMENDED (polycrystalline)
T.P. (c.p.h.–b.c.c.) 1155 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm^{-1}K^{-1}
TPRC

FIGURE 165

TABLE 170. THERMAL CONDUCTIVITY OF TITANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1220	Rosenberg, H. M.	1955	L	2.6-99	Ti 3	99.99 pure; single crystal; 0.0306 cm^2 x 1.6 cm; prepared by method of A. T. Churchman (Nature, 171, 706, 1953); electrical resistivity 2.410, 2.428, 2.418, 2.435, 2.465, 2.577, 2.648, 2.748, and 2.880 μohm cm at 4.3, 10.1, 14.0, 16.9, 20.5, 28.6, 31.0, 34.1, and 37.2 K, respectively.
2	866, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-22	Ti 1	99.9 pure; polycrystalline; supplied by Associated Electrical Industries Research Laboratories; 0.246 cm dia x 3.07 cm long; prepared by Van Arkel process; $\rho(293K)/\rho(20K) = 6.32$.
3	866, 1220	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-38	Ti 2	99.99 pure; polycrystalline; same supplier and preparation method as above; 0.242 cm dia x 1.56 cm long; annealed in vacuo for 20 hrs; $\rho(293K)/\rho(25K) = 10.1$.
4	963	Mikryukov, V. E.	1957		312-799	Iodide Titanium	99.9 pure; annealed in vacuum at 700 C for 5 hrs; electrical resistivity reported as 53.8, 50.3, 67.2, 79.0, 90.0, 100.2, and 115.0 μohm cm at 38.9, 116.0, 196.0, 264.0, 359.3, 445.7, and 526.0 C, respectively.
5	963	Mikryukov, V. E.	1957		315-732		Forged titanium specimen 99.6 pure; annealed in vacuum at 700 C for 5 hrs; electrical resistivity reported as 65.8, 58.8, 73.5, 84.0, 98.2, and 107.5 μohm cm at 41.5, 116.6, 201.6, 278.3, 376.6, and 459.0 C, respectively.
6	1315	Silverman, L.	1953	C	323-973		0.1 Mn, 0.04 Fe, 0.035 C, and 0.01 Mg; annealed at 700 C; Advance (55 Cu - 45 Ni) used as comparative material.
7	331, 122a	Deem, H. W., Wood, W. D., and Lucks, C. F.	1958	C	311-811	A-55(RC-55)	Commercially pure; in a mill-annealed condition; electrical resistivity reported as 52, 63, 72, 83, 92, 101, 110, 118, 125, and 132 μohm cm at 311, 366, 422, 477, 533, 589, 644, 700, 755, and 811 K, respectively; measured in a vacuum of 5 x 10^{-5} mm Hg.
8	793	Krzhizhanovskii, R. E.	1964	E	388-923		99.6 pure (Russian commercial titanium); obtained from the Central Boiler and Turbine Institute; specimen 5 mm in dia and 100 mm long; experiment carried out in vacuum (10^{-4}-10^{-5} mm Hg); electrical resistivity reported as 47, 64, 82, 99, 117, 133, 143, and 145 μohm cm at 0, 100, 200, 300, 400, 500, 600, and 650 C, respectively.
9	855	Loewen, E. G.	1956	L	332-915	Ti 75 A(1)	Commercially pure; 0.75 in. dia rod.
10	855	Loewen, E. G.	1956	L	383-858	Ti 75 A(2)	99.75 Ti, 0.131 O, 0.07 Fe, 0.06 C, 0.048 N, and 0.0068 H; 0.75 in. dia rod.
11	855	Loewen, E. G.	1956	L	375-838	RC-55	99.64 Ti, 0.123 O, 0.12 Fe, 0.08 C, 0.028 N, and 0.0073 H; 0.75 in. dia rod.
12	1554	White, G. K. and Woods, S. B.	1959	L	7.3-150	Ti 3	99.99 pure; specimen cross section 3.1 x 1.6 mm; supplied by Winegard; annealed in vacuum for 60 hrs at 800 C; ideal electrical resistivity reported as 0.020, 0.075, 0.20, 0.65, 1.4, 2.3, 3.5, 4.85, 6.35, 7.9, 11.2, 14.8, 18.5, 22.1, 25.7, 29.3, 34.8, 39.0, and 43.1 μohm cm at 20, 25, 30, 40, 50, 60, 70, 80, 90, 100, 120, 140, 160, 180, 200, 220, 250, 273, and 295 K, respectively; electrical resistivity ratio $\rho(295K)/\rho_0 = 21.9$; Lorenz function 2.74 x 10^{-8} V^2 K^{-2} near 0 K.
13	1554	White, G. K. and Woods, S. B.	1959	L	11-78	Ti 4	99.99 pure; specimen cross section 3.1 x 1.6 mm; supplied by Winegard; as rolled; electrical resistivity ratio $\rho(295K)/\rho_0 = 16.4$; ideal electrical resistivity 43.8 μohm cm at 295 K; Lorenz function 2.81 x 10^{-8} V^2 K^{-2} near 0 K.

TABLE 170. THERMAL CONDUCTIVITY OF TITANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
14	1554	White, G.K. and Woods, S.B.	1959	L	7.0-147	Ti 5	99.99 pure; specimen cross section 4.9 x 3.1 mm; supplied by Winegard; annealed in vacuum for 60 hrs at 800 C; electrical resistivity ratio $\rho(295)/\rho_0 = 18.3$; ideal electrical resistivity 43.2 μohm cm at 295 K; Lorenz function 3.14 x 10^{-8} V^2 K^{-2} near 0 K.
15	494	Gladun, C. and Holzhäuser, W.	1964	P	9-70		99.9 pure; measured by a transient method; data taken from smoothed curve.
16	318	Davey, G. and Mendelssohn, K.	1963	L	0.3-0.9		Single crystal; electrical resistivity measured by Mendelssohn, K., et al. (Bull. Inst. Intern. Froid, Annexe, (2), 49-56, 1965) reported as 0.911 μohm cm in the range 0.44 to 1.19 K.
17	1135	Powell, R.W. and Tye, R.P.	1961	L, C	323-573	Sample A	Normal commercial grade; electrical resistivity reported as 56.0, 65.0, 73.5, 82.5, 90.5, and 98.5 μohm cm at 50, 100, 150, 200, 250, and 300 C, respectively; energy flow measured both calorimetrically and by using Armco iron as a comparative material.
18	1135	Powell, R.W. and Tye, R.P.	1961	L, C	323-573	Sample B	High purity grade; electrical resistivity reported as 51.8, 60.8, 70.0, 79.2, 88.4, and 97.5 μohm cm at 50, 100, 150, 200, 250, and 300 C, respectively; energy flow measured both calorimetrically and by using Armco iron as comparative material.
19	1135	Powell, R.W. and Tye, R.P.	1961	L, C	293.2	Sample C	Very high purity grade; DPN (Diamond Pyramid Hardness Number) 58-62; electrical resistivity 42.7 μohm cm at 20 C; energy flow measured both calorimetrically and by using Armco iron as a comparative material.
20	802	Kuprovskii, B.B. and Gel'd, P.V.	1961	R	393-708	2-Ti; VT-1D	~0.20 Fe, 0.09 Si, 0.06 C, 0.02 O, and 0.0048 H; 68 mm O.D. and 12 mm I.D.
21	1617, 1618	Zinov'ev, V.E., Krentsis, R.P., and Gel'd, P.V.	1968	P	1006-1498	Iodide titanium; 1	Specimen 8 x 8 x 0.110 mm; electrical resistivity ratio $\rho(298K)/\rho(4.2K) = 40$; α-β transition temp reported at 1156 K; measured in a vacuum of ~10^{-5} mm Hg; thermal conductivity values calculated from the measurement of thermal diffusivity, using specific heat data of Zaitseva, G.G. and Kraftmacher, Ya.A. (Prikl. Matem. Teov. Fiz., (3), 117, 1965), and density 4.5 g cm^{-3} at 20 K; taken from Eremenko, V.I. ("Titanium and its alloys," Izd-vo AN UKrSSR, 1960), and thermal expansion data from McCoy, H.E. (Trans. Amer. Soc. Metals, 57, 743, 1964); reported values extracted from smooth curve.
22	1617, 1618	Zinov'ev, V.E., et al.	1968	P	1006-1498	Iodide titanium; 2	Similar to above except using specific heat data of Eremenko, V.I. ("Titanium and its alloys," [in Russian], Izd. vo An UkrSSR, 1960).
23	1617, 1618	Zinov'ev, V.E., et al.	1968	P	1006-1497	Iodide titanium; 3	Similar to above except using specific heat data of Kohlhaas, R., Braun, M., and Vollmer, O. (Z. Naturforsch, 20a, 1077, 1965).
24	1617, 1618	Zinov'ev, V.E., et al.	1968	P	1006-1499	Iodide titanium; 4	Similar to above except using specific heat data of Serebrennikov, N.N. and Gel'd, P.V. (Izv. Vyssh. Uchebn. Zaved. Tsvet. Metallurgiya, 4, No. 4, 80, 1961).
25	1617, 1618	Zinov'ev, V.E., et al.	1968	P	1006-1499	Iodide titanium; 5	Similar to above except using specific heat data of Hultgren, R., Orr, R.L., Anderson, P.D., and Kelley, K.K. ("Selected values of thermodynamic properties of metals and alloys," New York-London, 1963).
26	1200	Rigney, C.J. and Bockstahler, L.I.	1951	L	20-273		Commercially pure; 8 mm dia x 72 mm long.

* Not shown in figure.

TABLE 170. THERMAL CONDUCTIVITY OF TITANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
27	1230	Rudkin, R. L., Parker, W. J., and Jenkins, R. J.	1963	P	753-1606		No details reported for the specimen; thermal conductivity values were not given in the paper but were calculated by TPRC using the reported thermal diffusivity data (measured by the flash method) and the selected values of specific heat by R. Hultgren, R. L. Orr, P. D. Anderson, and K. K. Kelley, "Selected values of thermodynamic properties of metals and alloys," John Wiley and Sons, Inc., 284-8, 1963, and using the room-temp density value of 4.50 g cm^{-3} from Metals Handbook, 8th ed., 1961, and the high-temp density values calculated from thermal expansion coefficient selected from literature.
28	1452	Unvala, B.A. and Goel, T.C.	1970	E	1106-1497		<0.05 Fe; 18 x 0.7 x 0.07 cm specimen prepared from I.M.I. Ltd. No. 125 tubing; ground to remove the surface oxide layer, then flattened in a hydraulic press, cut and polished; transition ($\alpha \rightarrow \beta$) temp 1155 K; electrical resistivity 177.2, 179.4, 173.1, 164.9, 166.6, 168.3, 170.0, and 171.7 μohm cm at 1076, 1137, 1155, 1179, 1258, 1339, 1418, and 1500 K, respectively; Lorenz function 4.41, 3.48, 3.60, 3.80, 3.96, and 4.13 x 10^{-8} V^2 K^{-2} at 1100, 1130, 1218, 1300, 1400, and 1500 K, respectively.

Tungsten

At low temperatures the recommended values for a sample having residual electrical resistivity $\rho_0 = 0.00170$ $\mu\Omega$ cm are calculated by using equation (7) and using the constants m, n, and α'' as listed in table 1 and the parameter $\beta = 0.0696$. This ρ_0 is for the sample of deHaas and deNobel [337] (curve 17), but their thermal conductivity data appear to be too high. Therefore the recommended curve does not follow their data.

In the temperature range 80 to 150 K, the data of van Witzenburg and Laubitz [1467] (curve 134) and Moore, McElroy, Barisoni, and Woodall [987] (curves 135 and 136) agree well and appear to relate to samples of high purity. The recommended curve in this region lies close to these data and is extended to higher temperatures to agree closely with the values of Tye [1437] (curve 83), Powell and Tye [1137] (curves 115–117), and Moore, Graves, Fulkerson, and McElroy [982] (curve 133) and has been smoothly continued from 1273 to 3500 K. Over this later range it lies within ±5 percent of measurements by Wheeler [1533] (curve 85), Osborn [1056] (curve 14), Gumenyuk and Lebedev [567] (curve 76), Timrot and Poletskii [1410] (curve 87), Taylor, Davis, Powell, and Kimbrough [1396] (curves 184–186), and the measurements of Platunov and Federov [1091] (curve 86) made above 2100 K.

The methods used by these workers included variants of the electrically heated wire method, an electron bombarded cylindrical rod method, and a variable state method employing a modulated electron beam technique. Thermal diffusivity was determined by Wheeler and the thermal conductivity was derived from it by using asumed values for the density and heat capacity.

It will be seen that the results obtained by some other workers in this high temperature range show quite large differences and their measurements have been disregarded as being less reliable.

Whereas for most of the metals the Lorenz function is considered to tend toward the theoretical value of 2.443×10^{-8} V^2 K^{-2} at high temperatures, for tungsten the high temperature values of thermal conductivity now recommended yield Lorenz functions which are fairly constant but almost 20 percent in excess of the theoretical value.

The recommended values are thought to be accurate to within ±3 percent of the true values at temperatures from 300 to 1500 K, ±5 percent from 100 to 300 K and 1500 to 3000 K, and ±10 percent below 100 K and above 3000 K. The values below 20 K are, of course, applicable only to tungsten having a residual electrical resistivity of 0.00170 $\mu\Omega$ cm.

No thermal conductivity measurements for molten tungsten have been published, but Grosse [546] (curve 191) has estimated values to the critical point (23 000 K) from derived values for the electrical conductivity and assuming the theoretical Lorenz number to hold throughout the range. These provisional values are very uncertain.

TABLE 171. Recommended thermal conductivity of tungsten†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid					
T	k	T	k	T	k
0	0	250	1.80	1800	1.03
1	14.4	273.2	1.77	1873.2	1.02
2	28.7	298.2	1.74	1900	1.01
3	42.8	300	1.74	1973.2	1.00
4	56.3	323.2	1.70	2000	1.00
5	68.7	350	1.66	2073.2	0.990
6	79.5	373.2	1.63	2100	0.988
7	88.0	400	1.59	2173.2	0.980
8	93.8	473.2	1.49	2200	0.977
9	96.8	500	1.46	2273.2	0.969
10	97.1	573.2	1.39	2300	0.966
11	95.0	600	1.37	2400	0.957
12	91.1	673.2	1.32	2473.2	0.951
13	86.0	700	1.30	2500	9.949
14	79.4	773.2	1.27	2600	0.941
15	72.0	800	1.25	2673.2	0.935
16	64.5	873.2	1.22	2700	0.933
18	51.2	900	1.21	2800	0.926
20	40.5	973.2	1.19	2873.2	0.921
25	23.2	1000	1.18	2900	0.920
30	14.4	1073.2	1.16	3000	0.914
35	9.61	1100	1.16	3073	0.911
40	6.92	1173.2	1.14	3100	0.910
45	5.29	1200	1.13	3200	0.906
50	4.28	1273.2	1.12	3273	0.904
60	3.13	1300	1.11	3300	0.903
70	2.57	1373.2	1.10	3400	0.900
80	2.27	1400	1.09	3500	0.898*
90	2.16	1473.2	1.08	3600	0.896*
100	2.08	1500	1.07	3660	0.895*
123.2	1.99	1573.2	1.06		
150	1.93	1600	1.06		
173.2	1.90	1673.2	1.05		
200	1.86	1700	1.04		
223.2	1.83	1773.2	1.03		

†The values are for well-annealed high-purity tungsten, and those below 200 K are applicable only to a specimen having residual electrical resistivity of 0.00170 $\mu\Omega$ cm.

*Extrapolated.

TABLE 171. Recommended thermal conductivity of tungsten—Continued

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Liquid

T	k	T	k
3660	0.705*	11000	0.732*
3673	0.704*	11273	0.721*
3800	0.723*	12000	0.693*
3873	0.721*	12273	0.681*
4000	0.730*	13000	0.646*
4073	0.735*	13273	0.632*
4273	0.748*	14000	0.594*
4500	0.761*	14273	0.579*
4773	0.780*	15000	0.538*
5000	0.785*	15273	0.521*
5273	0.795*	16000	0.478*
5500	0.801*	16273	0.461*
5773	0.809*	17000	0.416*
6000	0.811*	17273	0.398*
6273	0.817*	18000	0.352*
6773	0.818*	18273	0.334*
7000	0.819*	19000	0.286*
7273	0.819*	19273	0.267*
7500	0.819*	20000	0.217*
7773	0.818*	20273	0.198*
8000	0.816*	21000	0.146*
8273	0.813*	21273	0.127*
8500	0.810*	22000	0.0736*
8773	0.805*	22273	0.054*
9000	0.799*		
9273	0.791*		
9500	0.784*		
9773	0.776*		
10000	0.768*		
10273	0.758*		

†The values for molten tungsten are provisional.
*Estimated.

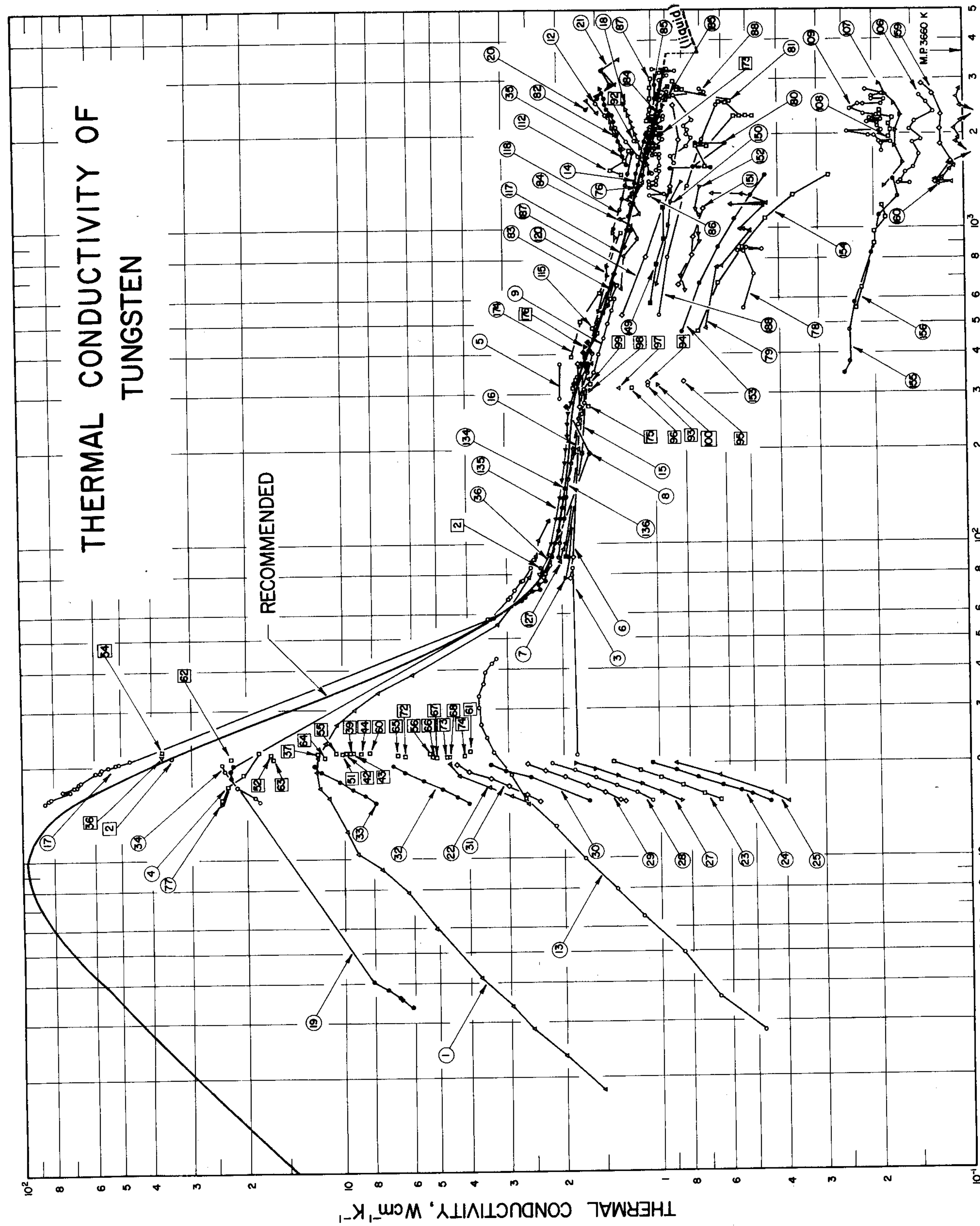

THERMAL CONDUCTIVITY OF TUNGSTEN
RECOMMENDED
M.P. 3660 K
liquid
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TEMPERATURE, K
TPRC

FIGURE 166

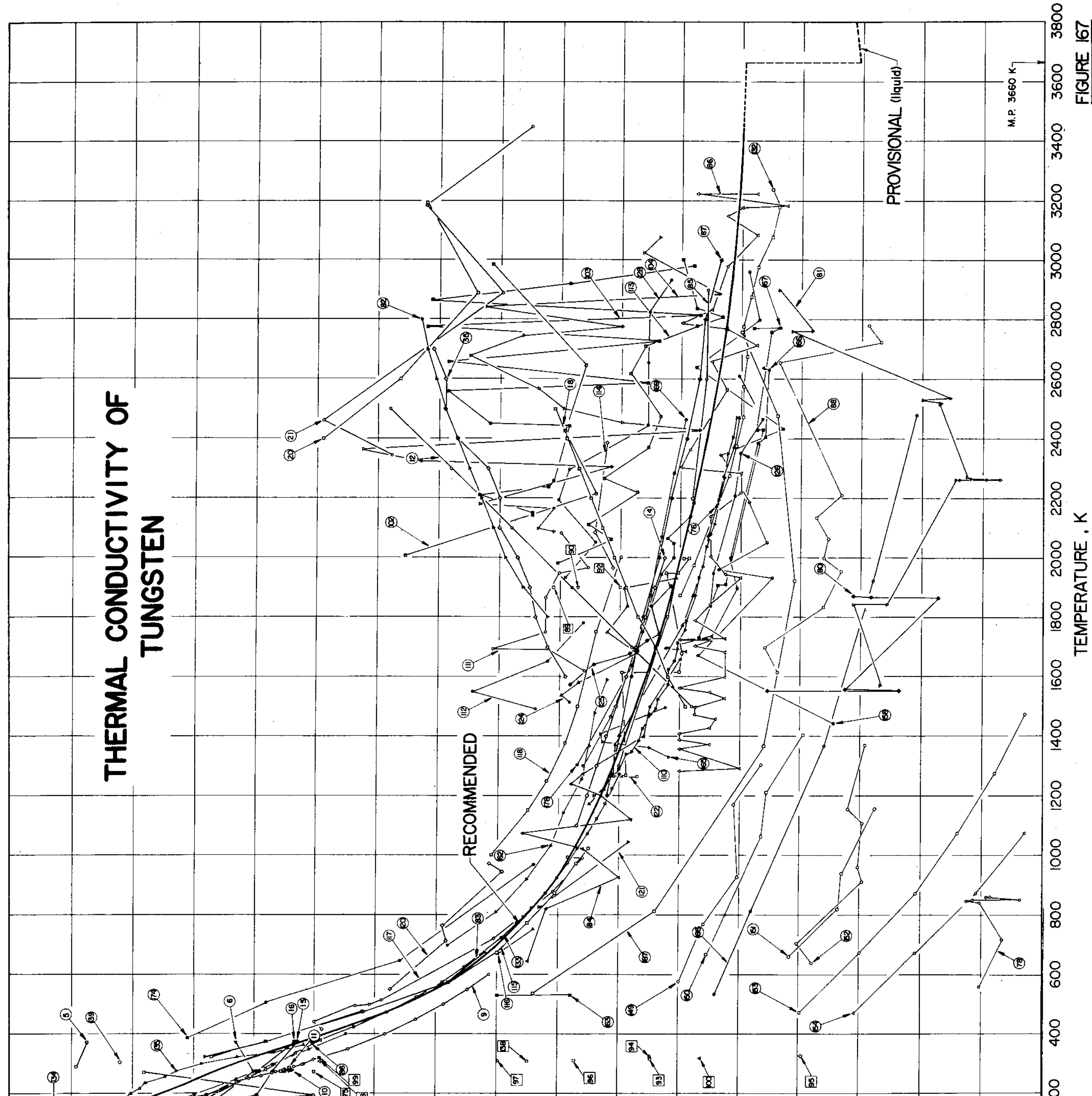

THERMAL CONDUCTIVITY OF TUNGSTEN
RECOMMENDED
PROVISIONAL (liquid)
M.P. 3660 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹K⁻¹
TPRC

FIGURE 167

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1547	White, G.K. and Woods, S.B.	1957	L	1.8-119	W 1b	0.01 Mo, traces of Fe, Si and Cu; 4 mm dia rod; annealed in vacuum at 1350 C; electrical resistivity ratio $\rho(295K)/\rho_0 = 169$; residual electrical resistivity 0.0315 μohm cm.
2	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	W 1	High purity; single crystal; electrical resistivity reported as 0.00589 and 0.681 μohm cm at -252 and -190 C, respectively.
3	559	Grüneisen, E. and Goens, E.	1927	L	21, 83	W 2	Less pure than the above specimen; single crystal; electrical resistivity reported as 0.266, 1.024, and 5.29 μohm cm at -252, -190, and 0 C, respectively.
4	201	Bremmer, H. and deHaas, W.J.	1936	L	16-22		Very pure; electrical resistivity ratio $\rho(273K)/\rho_0 = 2.18 \times 10^3$.
5	116, 117	Barratt, T. and Winter, R.M.	1914	F	290, 373	"Pladuram"	Pure; 0.0600 cm dia x 28.5 cm long; electrical resistivity reported as 5.206 and 7.562 μohm cm at 0 and 100 C, respectively.
6	302	Cox, M.	1943	E	77-373	2	High purity; 0.0250 cm dia x 40.85 cm long; drawn; aged at 2400 and 2600 C; electrical resistivity reported as 0.6736, 0.9132, 3.18, 5.034, and 7.392 μohm cm at 77.4, 90.2, 193, 273.2, and 372.8 K, respectively.
7	302	Cox, M.	1943	E	77-373	8	High purity; 0.0250 cm dia x 40.00 cm long; drawn; aged at 2300 C; electrical resistivity reported as 0.6135, 0.8558, 5.035, and 7.429 μohm cm at 77.36, 90.2, 273.2, and 373.1 K, respectively.
8	958	Michels, W.C. and Cox, M.	1936	E	78-273		Commercially pure; 0.00254 cm dia x 14.8 cm long; aged at white heat for several hrs in vacuum, etched; Lorenz function reported as 2.12, 2.68, and 3.48×10^{-8} $V^2 K^{-2}$ at 78, 194, and 273 K, respectively; measured in a vacuum of $<10^{-6}$ mm Hg.
9	809	Langmuir, I. and Taylor, J.B.	1936	E	240-600		Pure; 0.00499 cm dia wire; annealed at 2400 K; data taken from smoothed curve.
10	702	Kannuluik, W.G.	1931	E	276-280		Commercially pure; 0.1022 cm dia x 17.63 cm long; supplied by General Electric Co.; annealed at 220 C; electrical conductivity 16.7×10^4 $ohm^{-1} cm^{-1}$ at 273 K; measured in a vacuum of $<10^{-4}$ mm Hg.
11	702	Kannuluik, W.G.	1931	E	276-286		Commercially pure; 0.1022 cm dia x 19.96 cm long; supplied by General Electric Co.; annealed at 1300 C; electrical conductivity 17.7×10^4 $ohm^{-1} cm^{-1}$ at 273 K; measured in a vacuum of $<10^{-4}$ mm Hg.
12	1579	Worthing, A.G.	1914	E	1500-2500		Pure; 0.02090 cm dia filament; Lorenz function given as 1.183, 1.347, 1.513, 1.692, 1.882 and 2.100 $\times 10^{-8}$ $V^2 K^{-2}$ at 1500, 1700, 1900, 2100, 2300, and 2500 K, respectively; data taken from smoothed curve.
13	937, 1220	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.8-43	JM 2260; W 1	99.99 pure; polycrystalline; 0.401 cm dia x 2.96 cm long; annealed; electrical resistivity ratio $\rho(293K)/\rho(20K) = 38.0$.
14	1056	Osborn, R.H.	1941	E	1100-2000		Traces of metallic impurities; aged at 2700 K for 2 hrs; electrical resistivity reported as 30.0, 35.5, 42.3, 49.4, 58.2, and 66.6 μohm cm at 1180, 1350, 1570, 1800, 2050, and 2300 K, respectively; data taken from smoothed curve.
15	707	Kannuluik, W.G.	1933	E	90-373	W 1	99.96⁺ W, traces of Si, Ta, and V; single crystal; 7.846 cm long wire of rectangular section 0.01053 cm^2 with axis in the [100] plane; electrical resistivity reported as 0.892, 3.22, 4.98, and 7.35 μohm cm at -183.00, -78.50, 0, and 100 C, respectively.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
16	707	Kannuluik, W. G.	1933	E	90–373	W 2	99.96$^+$ W, traces of Si, Ta, and V; single crystal; wire of hexagonal section with specimen axis in the [111] plane; 7.940 cm x 0.01022 cm^2; electrical resistivity reported as 0.843, 3.17, 4.94, and 7.29 μohm cm at -183.00, -78.50, 0, and 100 C, respectively.
17	337	deHaas, W. J. and deNobel, J.	1938	L	15–88		High purity; single crystal; specimen axis in [111] direction; electrical resistivity reported as 0.00236, 0.00315, 0.00417, 0.00422, 0.1425, 0.3230, 0.3475, 0.3565, 0.3945, 0.4230, 0.4460, 0.4970, 0.5110, 0.5595, 0.6065, 0.7040, and 0.8070 μohm cm at 14.14, 17.55, 20.36, 20.42, 50.55, 63.50, 65.20, 65.80, 68.20, 69.80, 71.30, 74.30, 74.95, 77.40, 80.10, 85.05, and 90.15 K, respectively; heat flow 45 degrees to crystal axis; measured in a vacuum of $<5\times10^{-6}$ mm Hg.
18	452	Forsythe, W. E. and Worthing, A. G.	1925	E	1300–2500		Pure; density 19.3 g cm^{-3} at room temp; electrical resistivity reported as 5.64, 8.06, 13.54, 19.47, 25.70, 32.02, 38.52, 45.22, 52.08, 59.10, 66.25, 73.55, 81.0, 88.5, 96.2, 103.8, 111.7, and 115.7 μohm cm at 300, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200, 3400, and 3500 K, respectively.
19	347	deNobel, J.	1957	L	3.4–76	I-38	Pure single crystal; specimen axis in [100] direction; electrical resistivity reported as 0.0123, 0.0141, 0.2155, 0.3551, 0.4297, 0.5087, and 0.5921 μohm cm at 14.50, 20.42, 55.35, 63.95, 68.51, 72.97, and 77.35 K, respectively; heat flow parallel to (± 5°) the [100] crystal direction.
20	50	Allen, R. D., Glasier, L. F., Jr., and Jordan, P. L.	1960	E	2400–3194	1	0.04 Mo, 0.006 O, 0.005 Ti, 0.005 Ni, 0.004 Fe, and 0.027 others; prepared by pressing and sintering metal powder; hot-worked.
21	50	Allen, R. D., et al.	1960	E	2344–3451	2	99.95 W, 0.04 Mo, 0.002 Cu, and 0.008 others; prepared by pressing and sintering metal powder; hot-worked.
22	344	deNobel, J.	1949	L	15–20		High purity; single crystal; specimen axis in [111] direction; electrical resistivity reported as 0.319, 0.281, 0.236, and 0.187 μohm cm at 14.20, 15.98, 18.05, and 20.48 K, respectively; heat flow at 45 degrees to crystal axis; measured in a magnetic field of 10.3 kilooersteds perpendicular to specimen axis.
23	344	deNobel, J.	1949	L	15–20		As above but measured in a magnetic field of 26.39 kilooersteds, electrical resistivity reported as 1.932, 1.810, 1.677, 1.527, 1.382, 1.239, and 1.060 μohm cm at 14.21, 15.07, 15.96, 17.02, 18.06, 19.11, and 20.48 K, respectively.
24	344	deNobel, J.	1949	L	15–20		As above but measured in a magnetic field of 32.65 kilooersteds, electrical resistivity reported as 2.926, 2.737, 2.541, 2.317, 2.099, 1.882, and 1.594 μohm cm at 14.20, 51.07, 15.98, 17.02, 18.04, 19.08, and 20.51 K, respectively.
25	344	deNobel, J.	1949	L	15–20		As above but measured in a magnetic field of 36.27 kilooersteds, electrical resistivity reported as 3.572, 3.347, 3.106, 2.565, and 1.967 μohm cm at 14.21, 15.07, 15.99, 18.05, and 20.45 K, respectively.
26*	337	deHaas, W. J. and deNobel, J.	1938	L	15–20		High purity; single crystal; specimen axis parallel to (1,1,1) direction; measured in a transverse magnetic field of 25.85 kilogauss perpendicular to specimen axis.
27	337	deHaas, W. J. and deNobel, J.	1938	L	15–20		The above specimen measured in a transverse magnetic field of 21.83 kilogauss.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
28	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 18.96 kilogauss.
29	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 16.69 kilogauss.
30	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 13.82 kilogauss.
31	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 11.44 kilogauss.
32	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 8.18 kilogauss.
33	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 5.22 kilogauss.
34	337	deHaas, W. J. and deNobel, J.	1938	L	15-20		The above specimen measured in a transverse magnetic field of 2.61 kilogauss.
35	677	Jenkins, R. J., Parker, W. J., and Butler, C. P.	1959	E	1600-2700		Spectrographically pure; 0.010 in. dia; electrical resistivity reported as 46.4, 53.3, 63.3, 71.4, and 83.7 μohm cm at 1622, 1925, 2230, 2471, and 2965 K, respectively.
36	554	Grüneisen, E. and Adenstedt, H.	1937	L	22-91	W 1	7 cm x 0.106 cm^2; specimen axis at 8 degrees to the [110] direction; measured in a vacuum of 10^{-4}-10^{-6} mm Hg.
37	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.7	W 1	Measured at H (the transverse magnetic field strength) = 4850 oersteds and θ (the angle between the magnetic field direction and a line perpendicular to the rod axis) = -90° at which H parallel to [111] direction.
38*	554	Grüneisen, E. and Adenstedt, H.	1937	L	27.8	W 1	The above specimen measured at H = 6730 oersteds and θ = -90°.
39	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = -90°.
40*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.7	W 1	The above specimen measured at H = 6100 oersteds and θ = -60°.
41*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.7	W 1	The above specimen measured at H = 6100 oersteds and θ = -50°.
42	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.7	W 1	The above specimen measured at H = 6100 oersteds and θ = -40°.
43	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = -20°.
44	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = 0° at which H perpendicular to [111] direction.
45*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +20°.
46*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +40°.
47*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +60°.
48*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +70°.
49*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +80°.
50*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +90°.
51	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.7	W 1	The above specimen measured at H = 4850 oersteds and θ = +70°.
52	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.6	W 1	The above specimen measured at H = 2520 oersteds and θ = +70°.
53*	554	Grüneisen, E. and Adenstedt, H.	1937	L	21.5	W 1	The above specimen with the magnetic field removed.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
54	555	Grüneisen, E. and Adenstedt, H.	1938	L	22.2	W 1	Specimen axis in [110] direction; electrical resistivity 0.00463 μohm cm at -252.83 C; measured at H (the transverse magnetic field strength) = 0 and θ (the angle between the magnetic field direction and a line perpendicular to the rod axis) = -56° at which H parallel to [110] direction.
55	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.7	W 1	The above specimen measured at H = 6100 oersteds and θ = -56°.
56	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.5	W 1	The above specimen measured at H = 12200 oersteds and θ = -56°.
57*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.5	W 1	The above specimen measured at H = 0 oersteds and θ = +70° at which H perpendicular to [111] direction.
58*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.6	W 1	The above specimen measured at H = 2520 oersteds and θ = +70°.
59*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.7	W 1	The above specimen measured at H = 4850 oersteds and θ = +70°.
60	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.8	W 1	The above specimen measured at H = 6100 oersteds and θ = +70°.
61	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.8	W 1	The above specimen measured at H = 12200 oersteds and θ = +70°.
62	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	Specimen axis in [100] direction; electrical resistivity 0.01054 μohm cm at -252.82 C; measured at H (the transverse magnetic field strength) = 0 and θ (the angle between the magnetic field direction and a line perpendicular to the rod axis) = -5° at which H nearly parallel to [100] direction.
63	555	Grüneisen, E. and Adenstedt, H.	1938	L	20.8	W 13a	The above specimen measured at H = 2280 oersteds and θ = -5°; electrical resistivity 0.01980 μohm cm at -252.82 C.
64	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 4490 oersteds and θ = -5°; electrical resistivity 0.0346 μohm cm at -252.82 C.
65	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.4	W 13a	The above specimen measured at H = 8750 oersteds and θ = -5°; electrical resistivity 0.0760 μohm cm at -252.82 C.
66	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 10880 oersteds and θ = -5°; electrical resistivity 0.1044 μohm cm at -252.82 C.
67	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 11080 oersteds and θ = -5°.
68	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.1	W 13a	The above specimen measured at H = 12200 oersteds and θ = -5°; electrical resistivity 0.1241 μohm cm at -252.82 C.
69*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 0 oersteds and θ = -50° at which H parallel to [110] direction.
70*	555	Grüneisen, E. and Adenstedt, H.	1938	L	20.8	W 13a	The above specimen measured at H = 2280 oersteds and θ = -50°.
71*	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 4490 oersteds and θ = -50°.
72	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.1	W 13a	The above specimen measured at H = 8750 oersteds and θ = -50°.
73	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 10880 oersteds and θ = -50°.
74	555	Grüneisen, E. and Adenstedt, H.	1938	L	21.1	W 13a	The above specimen measured at H = 12200 oersteds and θ = -50°.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
75	1516	Weber, S.	1917	L	274.2		0.1 mm dia; tempered for 20 hrs at 225 C; electrical resistivity 0.204 μohm cm at 1 C; Lorenz function 2.88 x 10^{-8} V^2 K^{-2} at 1 C.
76	567	Gumenyuk, V. S. and Lebedev, V. V.	1961	L	1173-2473		Spectrally pure; two 2.2 mm dia wires used as the test materials; shaped and preliminarily annealed in a high vacuum at 1700 C for 1 hr; electrical resistivity reported as 29.8, 33.1, 38.4, 45.3, 52.0, 59.5, 67.3, and 76.7 μohm cm at 900, 1000, 1200, 1400, 1600, 1800, 2000, and 2200 C, respectively.
77	332	deHaas, W. J. and Biermasz, Th.	1936	L	16-22		No details reported.
78	1017, 1018	Neel, D. S., Pears, C. D., and Oglesby, S., Jr.	1962	R	559-860	C-54	0.003 Fe, 0.0026 Si, 0.0020 O, 0.0010 S, 0.0010 P, and Ni, Cu, H, and N; specimen 0.75 in. O.D., 0.25 in. I.D., and 0.75 in. long; arc-cast; maximum exposure temp 2255 C; density 18.87 g cm^{-3} (98.4% of theoretical).
79	1017, 1018	Neel, D. S., et al.	1962	R	484-1287	C-55	The above specimen; 2nd run.
80	1017, 1018	Neel, D. S., et al.	1962	R	1555-1872	C-85	Similar to the above specimen.
81	1017, 1018	Neel, D. S., et al.	1962	R	1571-2939	C-86	Similar to the above specimen; the specimen melted by 3038 K (probably because of carbon eutectic formation, the carbon might come from furnace vapor).
82	1625	Zwikker, C.	1925	E	1800-2800		Pure wire.
83	1437	Tye, R. P.	1961	L, C	323-673	JM 740	Spectrographically standardized tungsten; JM 740 of Johnson, Matthey and Co., Ltd; about 4 mm in dia and 10 cm in length; electrical resistivity reported as 5.45, 6.1, 7.3, 9.8, 12.45, 15.2, 18.1, 21.4, 24.6, 27.8, 30.9, 34.3, 37.7, 41.4, 45.1, 49.7, and 51.8 μohm cm at 20, 50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, and 1450 C, respectively; Armco iron used as comparative material; heat flow also measured calorimetrically.
84	310	Cutler, M. and Cheney, G. T.	1963	E	645-1660		Single crystal.
85	1533	Wheeler, M. J.	1965	P	1300-2900		99.5 pure, impurities: Fe, Mo and traces of other elements; 1.5 mm thick disc cut from a swaged rod; from General Electric Co. Osram Lamp Works; average grain size (after testing) 46 μ; density 19.3 g cm^{-3}; thermal conductivity values calculated from thermal diffusivity measurements using specific heat data of Kubaschewski, O. and Evans, L. L. (Metallurgical Thermochemistry, Pergamon, 1956).
86	1091	Platunov, E. S. and Fedorov, V. B.	1964	E	1283-3223		Short rod; electrical resistivity reported as 33.0, 36.0, 39.0, 42.0, 45.2, 48.6, 52.1, 56.0, 59.4, 63.2, 67.0, 71.0, 74.4, 78.0, 81.6, 85.2, 89.0, 92.6, 96.2, and 103.6 μohm cm at 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, 2500, 2600, 2700, 2800, and 3000 C, respectively.
87	1410	Timrot, D. L. and Poletskii, V. E.	1963	→	1200-3000		<0.1% impurities; cylindrical specimen; thermal conductivity values calculated from measured heat flow and specific radiation loss.
88	1229, 1231	Rudkin, R. L., Parker, W. J., Jenkins, R. J., and Westover, R. W.	1960	E	1615-2780		Spectrographically pure; 0.10 in. dia; electrical resistivity reported as 40.0, 50.0, 56.6, 66.6, and 80.6 μohm cm at 1545, 1812, 2087, 2353, and 2618 K, respectively; measured in a vacuum of <10^{-5} mm Hg.
89	437	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μ thick; wire rider of 0.2 mm in dia placed on that part of the foil where temp was constant; circular diaphragms used in optical pyrometer system.
90	437	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μthick; rider dia 0.3 mm, circular diaphragms in system.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
91	437	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μ thick; rider dia 0.2 mm, slit diaphragms in system.
92	437	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Wire of 0.2 mm in dia; rider dia 0.2 mm, slit diaphragms in system.
93	798	Kulcinski, G. L., Wagner, P., and Cowder, L. R.	1964	L	317.2	LASL; set No. 1, Sample 1	An oxide layer on the surface and <0.0050 oxide inside the specimen; porous right cylinder prepared from tungsten powder; material obtained from Powder Metallurgical Group of Los Alamos Scientific Laboratory; material hydrostatically pressed in a plastic sack with 30 000 psi initial pressure, machined, and sintered at 1500 C for 2 hrs in a hydrogen reducing atm; particle size 0.8 micron; 72.3% theo. density; electrical resistivity 10.4 μohm cm at 20 C.
94	798	Kulcinski, G. L., et al.	1964	L	323.2	LASL; set No. 1, Sample 2	Similar to the above specimen except 72.1% theo density, and 10.6 μohm cm electrical resistivity at 20 C.
95	798	Kulcinski, G. L., et al.	1964	L	326.2	LASL; set No. 1, Sample 3	Similar to the above specimen except 1350 C sintering temp, 63.2% theo. density, and 13.3 μohm cm electrical resistivity at 20 C.
96	798	Kulcinski, G. L., et al.	1964	L	311.2	LASL; set No. 1, Sample 6	Similar to the above specimen except 1575 C sintering temp, 78.1% theo density, and 9.1 μohm cm electrical resistivity at 20 C.
97	798	Kulcinski, G. L., et al.	1964	L	311.2	LASL; set No. 1, Sample 7	Similar to the above specimen except 1625 C sintering temp, 83.6% theo. density, and 8.2 μohm cm electrical resistivity at 20 C.
98	798	Kulcinski, G. L., et al.	1964	L	308.2	LASL; set No. 1, Sample 11	Similar to the above specimen except sintered at 1700 C for 9 hrs, 95.3% theo density, 6.2 μohm cm electrical resistivity at 20 C, and the ratio of isolated pores to total pores ≈0.9.
99	798	Kulcinski, G. L., et al.	1964	L	320.2	LASL; set No. 1, Sample 12	Similar to the above specimen except 95.5% theo density, and 6.3 μohm cm electrical resistivity at 20 C.
100	798	Kulcinski, G. L., et al.	1964	L	319.2	LASL; set No. II, Sample 2	Similar to the above specimen except sintered at 1700 C for 3 hrs, particle size 2-4.5 microns, 74.4% theo density, and 10.5 μohm cm electrical resistivity at 20 C.
101	660	Israel, S. L., Hawkins, T. D., and Hyman, S. C.	1966	→	1930-2933	S 1	99.8^+ pure; cylindrical specimen 1.52 in. in dia, 0.502 in. thick; polished; specimen heated inductively in vacuum; thermal conductivity determined by equating the axial heat flux within the specimen to the radiation flux at the center of the top surface.
102*	660	Israel, S. L., et al.	1966	→	2005-2983	S 2	Similar to above except dimensions 1.006 in. dia, 0.504 in. thick.
103*	660	Israel, S. L., et al.	1966	→	2138-2978	S 3	Similar to above except dimensions 1.0066 in. dia, 0.356 in. thick.
104	660	Israel, S. L., et al.	1966	→	2086-3075	S 4	Similar to above except dimensions 0.804 in. dia, 0.284 in. thick.
105*	660	Israel, S. L., et al.	1966	→	1506-2150	P 1	Unknown purity; cylindrical specimen; 1.52 in. dia, 0.538 in. thick; fabricated by gravity sintering tungsten particles 0.006 to 0.01 in. in size; fired for a long duration at >2478 K; porosity 55%; thermal conductivity data determined by the same method as above.
106	660	Israel, S. L., et al.	1966	→	1384-2569	P 2	Similar to above except dimensions 1.45 in. dia, 0.507 in. thick, and 45% porosity.
107	660	Israel, S. L., et al.	1966	→	1366-2894	P 3	Similar to above except dimensions 0.975 in. dia, 0.379 in. thick, and 46% porosity.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
108	660	Israel, S.L., Hawkins, T.D., and Hyman, S.C.	1966	→	1958-2366	P 4	Similar to above except dimensions 1.03 in. dia, 0.302 in. thick, and 42% porosity.
109	660	Israel, S.L., et al.	1966	→	1755-2753	P 5	Similar to above except dimensions 0.80 in. dia, 0.25 in. thick, and 42% porosity.
110	566	Gumenyuk, V.S., Ivanov, V.E., and Lebedev, V.V.	1962	E	1173-2473		1 mm in dia, 30 mm long; electrical resistivity reported as 0.205, 0.23, 0.258, and 0.293 μohm cm at 1000, 1400, 1800, and 2200 C, respectively.
111	1317	Simonova, Yu.N. and Filippov, L.P.	1965	E	1618-2081	Sample No. 1	Foil strip; 2 mm x 60 μ x 20 mm.
112	1317	Simonova, Yu.N. and Filippov, L.P.	1965	E	1490-1779	Sample No. 2	Foil strip; 3 mm x 60 μ x 20 mm.
113	1317	Simonova, Yu.N. and Filippov, L.P.	1965	E	1979-2999	Sample No. 3	Specimen 0.3 mm in dia and 20 mm long.
114	1317	Simonova, Yu.N. and Filippov, L.P.	1965	E	1963-2384	Sample No. 4	Specimen 0.2 mm in dia and 20 mm long.
115	1137	Powell, R.W. and Tye, R.P.	1967	L	313-664	I	99.99 W, 0.01 Mo, trace Si and Cu; 0.4 cm dia x 10 cm long; supplied by Johnson-Matthey and Co., Ltd; measured in the intermediate-temp apparatus.
116	1137	Powell, R.W. and Tye, R.P.	1967	C	451-751	I	The above specimen measured in the high-temp apparatus; Armco iron used as comparative material.
117	1137	Powell, R.W. and Tye, R.P.	1967	C	405-992	II	The specimen for curve No. 83 measured in the high-temp apparatus.
118	1086	Pigal'skaya, L.A., Filippov, L.P., and Borisov, V.D.	1966	P	1000-2000		99.95 W and 0.035 Mo; forged rod specimen 10 mm in dia and 80 mm long; density 19.17 g cm^{-3}; thermal conductivity values calculated from measured data of thermal diffusivity using specific heat data taken from Hoch, M. and Johnston, H.L. (J. Phys. Chem., 65, 855, 1961).
119*	1345	Southern Research Institute	1966	C	285-500	1	0.026 O, 0.010 Mo, <0.005 Si, 0.001 each of Cu and Ag, <0.001 each of Al, Ca, Fe, Mg, Mn, and Ni, and <0.0005 N; tungsten sheets ~0.060 in. thick supplied by Fansteel Metallurgical Corp; specimen dimensions 1.000 in. dia x 1.250 in. long; squares cut from the sheets clamped together to form cubes, single welds perpendicular to the sheets made at opposite ends with an inert-gas arc welder, machined to size with the sheets parallel to the cylinder axis; thermocouple holes drilled at 75 degrees to the sheets; density 19.21 g cm^{-3} at 26.3 C; Armco iron used as comparative material; measured in a helium atm with diatomaceous earth insulation.
120	1345	Southern Research Institute	1966	C	549-972	1	Second run of the above specimen with thermatomic carbon insulation.
121	1345	Southern Research Institute	1966	C	823-1042	1	Same as above, third run.
122	1345	Southern Research Institute	1966	R	1266-1997	2	Prepared from the same material as the above specimen; consisted of 32 one-in. dia discs with 0.25 in. holes in their centers, the central 16 discs used as test specimen.
123*	1345	Southern Research Institute	1966	R	1451-2033	2	Second run of the above specimen.
124	699	Jun, C.K. and Hoch, M.	1966	→	1513-1930	No. 1	0.0007 C, <0.0005 each of N and O, and <0.00005 H; specimen 2.5339 cm in dia and 0.2994 cm thick; density 18.89 g cm^{-3}; thermal conductivity derived from the temp distribution on the flat surface of the cylindrical disc specimen heated in high vacuum (10^{-5} mm Hg) by high frequency induction.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
125	699	Jun, C.K. and Hoch, M.	1966	→	1572-1905	No. 2	Similar to above except specimen 2.4785 cm in dia and 0.2714 cm thick with density 19.03 g cm^{-3}.
126	699	Jun, C.K. and Hoch, M.	1966	→	1836-2608	No. 3	Similar to above except specimen 2.0801 cm in dia and 0.27 cm thick with avg. grain size 0.035 mm dia and density 19.23 g cm^{-3}.
127	102	Bäcklund, N. G.	1967	L	87-377		Spectroscopically standardized; 4 mm dia x 10 cm long; supplied by Johnson, Matthey and Co., Ltd; electrical resistivity reported as 0.24, 0.83, 1.08, 3.32, 5.61, and 7.33 μohm cm at 5, 78, 91, 195, 298, and 374 K, respectively. (Tabulated data received from author.)
128*	1299	Sharma, J. K. N.	1967	L	0.54-0.97		Polycrystalline; wire specimen obtained from Lamp and Metals; form factor $(\ell/a) = 7.38 \times 10^2$ cm^{-1}; electrical resistivity 1.76×10^{-7} ohm cm at 1.5 K; electrical resistivity ratio $\rho(293K)/\rho(1.5K) = 30$; run No. 41.
129*	1299	Sharma, J. K. N.	1967	L	0.61-0.88		The above specimen run No. 42.
130*	1299	Sharma, J. K. N.	1967	L	0.53-0.98		The above specimen run No. 43.
131*	186	Bourdeau, R. G.	1962		298.2		Single crystal; obtained from High Temperature Materials, Inc.; density 19.3 g cm^{-3}; melting point 3655 K; electrical resistivity 5.4 μohm cm at room temp; preliminary result. (Measuring temp assumed 25 C.)
132	783	Kraev, O.A. and Stel'makh, A.A.	1966	P	1873-3233		Thermal conductivity values calculated from measured thermal diffusivity data with density data taken from Chirkin, V.C. (Teploprovodnost Promizhlennich Materialov, M., Mazhgiz, 1962) and specific heat data taken from Kraftmakher, Ya.A. (Zh. Prikl. Mekhan. i Tekhn. Fiz., (5), 176-80, 1962).
133	465, 982	Fulkerson, W., Moore, J. P., and Graves, R. S.	1965	R	373-1273		Specimen machined from wrought material derived from extrusions of pressed and sintered billets; electrical resistivity ratio $\rho(300K)/\rho(4.2K) = 35$; electrical resistivity reported as 4.05, 7.33, 9.80, 12.42, 15.16, 18.01, 20.93, 23.93, 27.01, 30.09, 33.25, 36.49, 39.71, 42.99, and 46.40 μohm cm at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, and 1400 C, respectively; density 99.8% of theoretical value.
134	1467	van Witzenburg, W. and Laubitz, M. J.	1968	L	80-150		99.95 pure; 1.6 mm dia wire supplied by United Min. Chem. Corp; annealed in a vacuum of 10^{-6} mm Hg at 1620 K for 2 hrs; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 46.65$; residual electrical resistivity 0.11 μohm cm; reported thermal conductivity values calculated from measurements of the two (electrical and thermal) relative magnetoresistances and the two normal resistances.
135	987, 1576	Moore, J. P., McElroy, D. L., Barisoni, M., and Woodall, N. D.	1966	L	80-360		High purity; cylindrical specimen prepared by electron-beam melting in ORNL Metals and Ceramics Div; density 19.29 g cm^{-3}; electrical resistivity 0.60, 1.04, 1.48, 1.92, 2.36, 2.80, 3.24, 3.68, 4.12, 4.56, 5.00, 5.44, 5.88, 6.32, and 6.76 μohm cm at 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, and 360 K, respectively; $\rho(273K)/\rho(4.2K) > 400$.
136	987, 1576	Moore, J. P., et al.	1966	L	90-400	"radial"	99.98 pure; cylindrical specimen; density 19.077 g cm^{-3}; electrical resistivity 0.76, 1.20, 1.64, 2.08, 2.52, 2.96, 3.40, 3.84, 4.27, 4.71, 5.16, 5.60, 6.04, 6.48, and 6.92 μohm cm at 80, 100, 120, 140, 160, 180, 200, 220, 240, 260, 280, 300, 320, 340, and 360 K, respectively; $\rho(273K)/\rho(4.2K) = 31.4$. (Revised thermal conductivity data obtained from the authors in a private communication.)

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
137*	1520	Wechsler, A. E.	1967	C	311.5	41 A	Specimen 0.75 in. in dia and 0.57 in. thick; supplied by Fansteel Metallurgical Corp, Chicago, Ill.; pressed and sintered; density 19.22 g cm^{-3}; measured in a vacuum of ~1 x 10^{-4} torr; Armco iron used as comparative material; preliminary result.
138	1520	Wechsler, A. E.	1967	C	311.8	47 B	Similar to the above specimen; another run.
139	1520	Wechsler, A. E.	1967	C	310.8	59 A	Similar to the above specimen except heated at 2040C for 10 hrs; electrical resistivity 0.822 and 5.58 μohm cm at 77 and 293.2 K, respectively.
140*	1520	Wechsler, A. E.	1967	C	311.0	62 B	Similar to the above specimen.
141*	1520	Wechsler, A. E.	1967	C	310.5	82 A	Similar to the above specimen except heated at 2040 C for 20 hrs; electrical resistivity 0.810 and 5.51 μohm cm at 77 and 293.2 K, respectively.
142*	1520	Wechsler, A. E.	1967	C	310.4	83 B	Similar to the above specimen.
143*	1520	Wechsler, A. E.	1967	C	312.7	48 A	0.0023 Mo, 0.002 Si, 0.0008 N, <0.0006 Fe, 0.0005 C, 0.0003 O, and <0.0001 each of Ni, Ti, and H; specimen 0.56 in. in dia and 0.57 in. thick; supplied by Universal-Cyclops, Bridgeville, Pa.; density 19.22 g cm^{-3}; arc cast; measured in a vacuum of ~1 x 10^{-4} torr; Armco iron used as comparative material; preliminary result.
144*	1520	Wechsler, A. E.	1967	C	312.4	49 B	Similar to the above specimen.
145*	1520	Wechsler, A. E.	1967	C	311.4	60 A	Similar to the above specimen excpept heated at 2040 C for 10 hrs; electrical resistivity 0.588 and 5.29 μohm cm at 77 and 293.2 K, respectively.
146*	1520	Wechsler, A. E.	1967	C	310.6	61 B	Similar to the above specimen.
147*	1520	Wechsler, A. E.	1967	C	310.6	80 A	Similar to the above specimen except heated at 2040 C for 20 hrs; electrical resistivity 0.586 and 5.29 μohm cm at 77 and 293.2 K, respectively.
148*	1520	Wechsler, A. E.	1967	C	310.4	81 B	Similar to the above specimen.
149	871	L'vov, S. M., Mal'ko, P. I., Nevskaya, L. V., and Nemchenko, V. F.	1966	L	581-1304		Porous specimen prepared by mixing 99.8 pure tungsten powder with a paraffin-in-benzine solution, compacted hydrostatically into a small bar, sintered in a hydrogen atm at 2100 C; porosity 20%, electrical resistivity 8.1, 13.9, 23.6, 33.0, 44.3, 55.2, 67.8, and 75.8 μohm cm at 16, 178, 378, 579, 779, 931, 1089, and 1183 C, respectively; measured in a vacuum of 10^{-4}-10^{-5} mm Hg.
150	871	L'vov, S. M., et al.	1966	L	669-1405		Similar to above.
151	871	L'vov, S. M., et al.	1966	L	662-1156		Similar to above but porosity 30% and electrical resistivity 11.9, 19.0, 26.6, 33.9, 47.3, 57.9, 71.3, and 82.6 μohm cm at 44, 200, 349, 454, 656, 800, 979, and 1115 C, respectively.
152	871	L'vov, S. M., et al.	1966	L	639-1368		Similar to above.
153	871	L'vov, S. M., et al.	1966	L	473-1473		Same materials and fabrication method as above; porosity 35%; thermal conductivity values taken from smoothed curve; measured in a vacuum of 10^{-4}-10^{-5} mm Hg.
154	871	L'vov, S. M., et al.	1966	L	473-1473		Similar to above but porosity 40%.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
155	871	L'vov, S. M., Mal'ko, P. I., Nevskaya, L. V., and Nemchenko, V. F.	1966	L	345-1425		Same materials and fabrication method as above; porosity 55%; electrical resistivity 54, 94, 136, 205, 251, 314, and 391 μohm cm at 30, 182, 355, 612, 778, 974, and 1200 C, respectively; measured in a vacuum of 10^{-4}-10^{-5} mm Hg.
156	871	L'vov, S. M., et al.	1966	L	555-1175		Similar to above.
157*	871	L'vov, S. M., et al.	1966	L	496-1404		Similar to above.
158	661	Israel, S. L., Hawkins, T. D., Salter, R. T., and Hyman, S. C.	1964	→	1442-2957		99.8 pure; 1.5 in. dia x 0.5 in. thick; obtained from Wah Chang Corp; 99.5% dense; specimen heated by high frequency induction current in a thin layer at the outer cylindrical surface; thermal conductivity values calculated from the temp distribution on the upper end surface and the total hemispherical emittance of the specimen.
159	661	Israel, S. L., et al.	1964	→	1392-2869		Obtained from Wah Chang Corp; 1 in. dia x 0.5 in. thick; fabricated by sintering tungsten powder at 3033 K; porosity 42%; same measuring method as above.
160	661	Israel, S. L., et al.	1964	→	1374-2751		Similar to above but specimen 1.5 in. in dia.
161*	661	Israel, S. L., et al.	1964	→	1243-2066		Similar to above but specimen porosity 55%.
162	218	Brown, R. M.	1962	R	701-1590		Pure; 2.75 in. O. D., 0.375 in. I. D., and 5 in. long; sintered, machined; porosity 7.5%; measured in a vacuum of 10^{-6} torr; reported values taken from smoothed curve after correcting for porosity.
163	1347	Sparrell, J. K., Coumou, K. G., and Plunkett, J. D.	1963	L	533		Specimen 12 x 12 x 1.5 in. consisted of nine 4 x 4 x 1.5 in. blocks; measured in argon atm; preliminary results.
164*	1347	Sparrell, J. K., et al.	1963	L	928		The above specimen measured in the same apparatus with another set of thermocouples; preliminary results.
165	423	Feith, A. D. (compiled by Wechsler, A. E.)	1969	R	1328-1499	100W 7611-1 Bar III	99.87$^+$ W, 0.1 Mo, 0.005 C, 0.003 Fe, <0.003 N, <0.003 O, <0.002 each of Al, Pb, Si, and Sn, 0.001 Ni, <0.001 each of Co, Cu, Cr, Mg, Mn, Ti, and V; specimen 1.933 in. dia and 0.5 in. thick; supplied by Climax Molybdenum Corp; arc cast; extruded; stress relieved and recrystallized at 3000 F; density 19.263 g cm^{-3}; measured in argon atm.
166	423	Feith, A. D. (compiled by Wechsler, A. E.)	1969	R	1685-2634	100W 7611-1 Bar III	The above specimen measured in hydrogen atm.
167	423	Feith, A. D. (compiled by Wechsler, A. E.)	1969	R	1728-2767	100W 7851-9 Bar I	Similar to the above specimen except density 19.262 g cm^{-3}.
168*	423	Feith, A. D. (compiled by Wechsler)	1969	R	1500	100 W 7851-9	The above specimen measured in argon atm.
169	597	Hedge, J. C. (compiled by Wechsler, A. E.)	1969	R	1299-2461	Specimen 10	Similar to the above except specimen 0.795 cm I. D., 5.08 cm O. D., and 1.27 cm thick.
170*	597	Hedge, J. C. (compiled by Wechsler)	1969	R	1389-2149	Specimen 10	The above specimen measured at decreasing temps.
171*	597	Hedge, J. C. (compiled by Wechsler)	1969	R	1243-2450	Specimen 18	Similar to the above except measured at increasing temps.
172*	597	Hedge, J. C. (compiled by Wechsler)	1969	R	1396-2014	Specimen 18	The above specimen measured at decreasing temps.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
173	1045	Null, M.R. and Lozier, W.W.	1969	P	2000		Specimen 12.7 mm in dia and 10.6 mm thick; electrical resistivity 5.61 μohm cm at room temp; thermal conductivity value calculated from the measurement of thermal diffusivity, using specific heat data of Spence, G. B., WADD Tech. Rept. 61-72, Vol. XLI, Nov. 1963, and density 19.3 g cm^{-3} at room temp.
174	1020	Neimark, B.E. and Voronin, L.K.	1968	E	391-973	Specimen No. 1	99.85 pure; rod specimen 4 mm in dia and 140 to 160 mm long; electrical resistivity reported as 5.5, 6.2, 6.9, 7.4, 8.0, 8.8, 9.2, 10.0, 11.7, 12.7, 13.4, 14.0, 15.7, 16.4, 18.0, 19.7, 20.9, 22.5, 23.2, 25.4, 27.0, 28.2, and 29.5 μohm cm at 19, 49, 73, 99, 121, 150, 176, 205, 260, 301, 327, 358, 422, 450, 492, 551, 614, 663, 686, 761, 809, 840, and 897 C, respectively; Lorenz function reported as 3.58, 3.54, 3.23, and 3.00 x 10^{-8} V^2 deg^{-2} at 108, 221, 349, and 700 C, respectively.
175*	1020	Neimark, B.E. and Voronin, L.K.	1968	E	1318-2437	Specimen No. 2	99.95 pure; specimen 2 mm in dia and 140 to 160 mm long; annealed at 2200 C for 1 hr; electrical resistivity reported as 34.3, 39.9, 40.8, 40.8, 45.4, 46.4, 49.7, 54.6, 58.3, 62.3, 66.6, and 73.0 μohm cm at 1039, 1222, 1237, 1281, 1379, 1400, 1505, 1645, 1758, 1879, 1999, and 2163 C, respectively; Lorenz function reported as 2.94, 3.09, 3.00, 3.00, 2.99, 2.92, 2.92, and 2.96 x 10^{-8} V^2 K^{-2} at 1007, 1231, 1371, 1496, 1636, 1771, 2003, and 2158 C, respectively.
176	320	Davis, M., Densem, C.E., and Rendall, J.H.	1955	→	423.2	Grade R. P. X.	99.99 pure; supplied by the British Thomson-Houston Co., Ltd, Rugby; density 19.3 g cm^{-3}; electrical resistivity reported as 5.6, 27, and 33 μohm cm at 20, 800, and 1000 C, respectively; thermal conductivity value calculated from the electrical resistivity value by the method of Fine, M. E. (Trans. Amer. Inst. Min. Met. Eng., 188, 951, 1950).
177*	262	Chechovskoy, V.Ya. and Vertogradskii, V.A.	1970	E	1300-2500		99.9 W, 0.1 Mo; wire specimen 0.2 mm in dia and about 150 mm long; density 19.26 g cm^{-3}; annealed; Lorenz function reported as 3.08, 3.04, 3.00, 2.96, 2.93, 2.89, and 2.87 x 10^{-8} V^2 K^{-2} at 1300, 1500, 1700, 1900, 2100, 2300, and 2500 K, respectively; measured in vacuum.
178	1075	Peletskii, V.E., Sobol', Ya.G. and Drujinin, V.P.	1970	E	1300-2186		99.98 W, 0.001-0.002 C, <0.001 N, and <0.001 O; single crystal; specimen 8 mm in dia and about 70 mm long; prepared by zone-melting method (two passage); grown in crystallographic direction [111], a deviation of the axis of the specimen ~18°; electrical resistivity reported as 5.28, 30.2, 37.05, 43.95, 50.85, 57.75, and 64.65 μohm cm at 293, 1200, 1400, 1600, 1800, 2000, and 2200 K, respectively; Lorenz function reported as 2.90, 2.98, 3.03, 3.05, 3.03, and 3.03 x 10^{-8} $V^2 K^{-2}$ at 1200, 1400, 1600, 1800, 2000, and 2200 K, respectively; measured in a vacuum of <10^{-5} torr.
179*	1075	Peletskii, V.E., et al.	1970	E	1290-2027		Similar to the above specimen.
180*	1075	Peletskii, V.E., et al.	1970	E	1365-2125		Similar to the above specimen.
181*	1075	Peletskii, V.E., et al.	1970	E	1444-1839		Similar to the above specimen.
182*	1075	Peletskii, V.E., et al.	1970	E	1476-2003		Similar to the above specimen.
183*	1075	Peletskii, V.E., et al.	1970	E	2095-2471		Simflar to the above specimen.

* Not shown in figure.

TABLE 172. THERMAL CONDUCTIVITY OF TUNGSTEN - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
184	1396	Taylor, R. E., Davis, F. E., Powell, R. W., and Kimbrough, W. D.	1969	E	1849-2352	Sample 1	99.87⁺ W, 0.1 Mo, and various gaseous and metallic impurities in the ppm range; purchased from A. D. Little, Inc. (manufactured by Climax Molybdenum Corp.); arc cast; extruded; stress relieved and recrystallized at 1925 K; aged in vacuum at 2750 K for several hrs; density 19.23 g cm^{-3}; electrical resistivity reported as 12.7, 19.4, 25.9, 46.3, 48.5, 51.6, 53.0, 56.9, 58.8, 61.2, 66.2, 70.2, 70.5, 72.3, 74.3, 76.3, and 79.1 μohm cm at 619, 850, 1049, 1675, 1747, 1815, 1884, 2007, 2064, 2129, 2274, 2384, 2407, 2456, 2509, 2565, and 2641 K, respectively.
185	1396	Taylor, R. E., et al.	1969	E	1748-2801	Sample 2-1	Similar to the above except aged in vacuum at 2980 K for several hrs; electrical resistivity reported as 33.7, 36.9, 38.9, 42.6, 45.2, 50.0, 51.5, 56.9, 59.6, 61.5, 66.7, 67.9, 71.9, 74.0, 78.2, 80.9, and 84.8 μohm cm at 1284, 1384, 1446, 1563, 1658, 1798, 1855, 2006, 2085, 2145, 2286, 2320, 2443, 2501, 2616, 2703, and 2806 K, respectively; Lorenz function reported as 2.758, 2.755, 2.750, 2.744, 2.737, 2.728, 2.718, 2.708, 2.696, 2.684, 2.670, and 2.656 x 10^{-8} V^2 deg^{-2} at 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400, 2500, 2600, 2700, and 2800 K, respectively.
186*	1396	Taylor, R. E., et al.	1969	E	1700-2672	Sample 2-2	The above specimen measured after a noticeable vaporization occurred (heated to 3087 K); electrical resistivity reported as 13.0, 23.1, 28.5, 30.5, 35.5, 39.7, 44.4, 47.7, 50.7, 54.6, 58.2, 60.0, 61.5, 61.8, 64.1, 65.8, 69.4, 73.3, 77.7, and 83.2 μohm cm at 642, 991, 1127, 1199, 1347, 1476. 1620, 1734, 1828, 1942, 2054, 2102, 2148, 2276, 2379, 2493, 2620, and 2766 K, respectively.
187	1068	Pears, C. D.	1965	C, R	533-2755		Hot-pressed polycrystalline disc of 1 in. in dia and 1 in. in thickness; no macrocracks; 90% theoretical density; measured with comparative method to 1366 K and with radial inflow method to 2755 K; specimen equally guarded.
188	1069	Pears, C. D. and Neel, D. S.	1962	R	533-2477		99.3 W (by difference), 0.2 Si, 0.2 V, 0.1 Cu, and 0.2 Nb; hot-pressed polycrystalline disc of 0.75 in. in dia and 0.75 in. in thickness produced by Carborundum Co.; 97% theoretical density; measured with radial inflow method with specimen equally guarded; macrocracks found in specimens after measurements.
189*	1520	Wechsler, A. E.	1969	P	1272-2441	WB-1	0.376 in. dia x 0.985 in. long; density 19.3 g cm^{-3}; thermal conductivity values calculated from the thermal diffusivity measurements of Nakata, M. M. using specific heat data of Kirillin, V. A., et al. (Teploenerg., 9 (2), 63-6, 1962).
190*	1520	Wechsler, A. E.	1969	P	1757-1825	WA-1-1	0.259 in. dia x 1.025 in. long; density 19.3 g cm^{-3}; thermal conductivity values calculated from the thermal diffusivity measurements of Springer, J. R., et al. using specific heat data of Kirillin, V. A., et al. (Teploenerg., 9 (2), 63-6, 1962).
191*	546	Grosse, A. V.	1965	→	3653-23000		In liquid state; thermal conductivity values calculated from electrical conductivity data of Cusack, N. E. (Repts. of Progress in Physics, 26, 361-409, 1963), and electrical conductivity values over the whole liquid range derived from the hyperbola relationship; theoretical Lorenz number used in the calculation.

* Not shown in figure.

Uranium

Many determinations have been reported for the thermal conductivity of uranium over the temperature range 300 to 1000 K. The values at 300 K mainly range from about 0.22 to 0.28 W cm^{-1} K^{-1} and, with increase in temperature, rise at a gradually increasing rate to about cover the range 0.35 to 0.45 W cm^{-1} K^{-1} at 1000 K.

At low temperature the available data are much sparser, and are limited to five sets of measurements. Mendelssohn and Rosenberg [937] (curve 22) for the range 2.1 to 21 K, Rosenberg [1220] (curve 10) from 2.5 to 94 K, Haen and Weil [575] (curves 114, 115) for two sets of measurements from 3.8 to 43 K, and Tyler, Wilson, and Wolga [1444] (curve 5) from 23 to 278 K. The sample used by Rosenberg was stated to have $\rho_{293\ K}/\rho_{20\ K} = 10.6$ whereas the corresponding ratio for the sample of Tyler, et al. would appear to be of the order of 7.6. This would indicate Rosenberg's sample to be of higher purity and could help to explain some of the higher thermal conductivity values which he obtained but not those above 60 K. The curve of more rapidly increasing thermal conductivity indicated by Rosenberg's values at 63 K and above is out of line with the general trend of values in the normal temperature region. The higher temperature points of Tyler, et al., however, conform much better and give no evidence for a maximum in the range 100 to 300 K such as Rosenberg's curve would suggest.

The thermal conductivity of polycrystalline uranium has been represented by a smooth curve drawn to fit the data of Mendelssohn and Rosenberg and of Rosenberg up to about 60 K. It then approximately agrees with the data of Tyler, et al. as it continues to rise smoothly through a value of 0.276 W cm^{-1} K^{-1} at 300 K and on to 0.49 W cm^{-1} K^{-1} at 1200 K.

Determinations made in the region of the phase transformations which occur at 938 and 1049 K have, for the most part, failed to reveal any marked change in thermal conductivity so no discontinuity has been shown in the proposed curve. This however is not true for some other properties including the electrical conductivity, so the present smooth curve should be regarded as provisional in these regions.

The curve due to Erez and Even [397] (curve 109), which did show a small discontinuity above 900 K, had been based on values calculated from the thermal diffusivity and using measured values for the specific heat, both showing marked transitions. This curve, which has a minimum near 500 K and rises much more steeply to higher temperatures, and which appears to be strongly at variance with all other curves, has been ignored.

Uranium is another metal for which the characteristic low temperature maximum in the thermal conductivity has not yet been reported, and it will be interesting to see whether the purity of this metal is eventually increased sufficiently for a maximum to be obtained. A suggestion by Fisher and Dever [440] may have a bearing on this and should be noted. These workers consider from observations of hysteresis in the elastic moduli of single crystals of α–U that uranium undergoes a structural phase transformation $\alpha \rightarrow \alpha_0$ at some temperature between 35 and 43 K and that owing to the close similarity of the two phases they can co-exist over a wide temperature range. They also suggest that both the filamentary superconductivity at $T < 2$ K and an excess electrical resistance at 4 K are produced when the α–phase is retained after fast cooling. Pulse heating to temperatures below 22.5 K was found to gradually anneal out this excess resistance. Thermal conductivity determinations on similarly treated samples would be of considerable interest.

The recommended values are thought to be accurate to within ±10 percent of the true values at temperatures from room temperature to 900 K and ±15 percent below room temperature. Above 900 K the values are provisional and are probably good to ±20 percent. Values below room temperature are applicable only to a sample having a residual electrical resistivity of 2.14 $\mu\Omega$ cm.

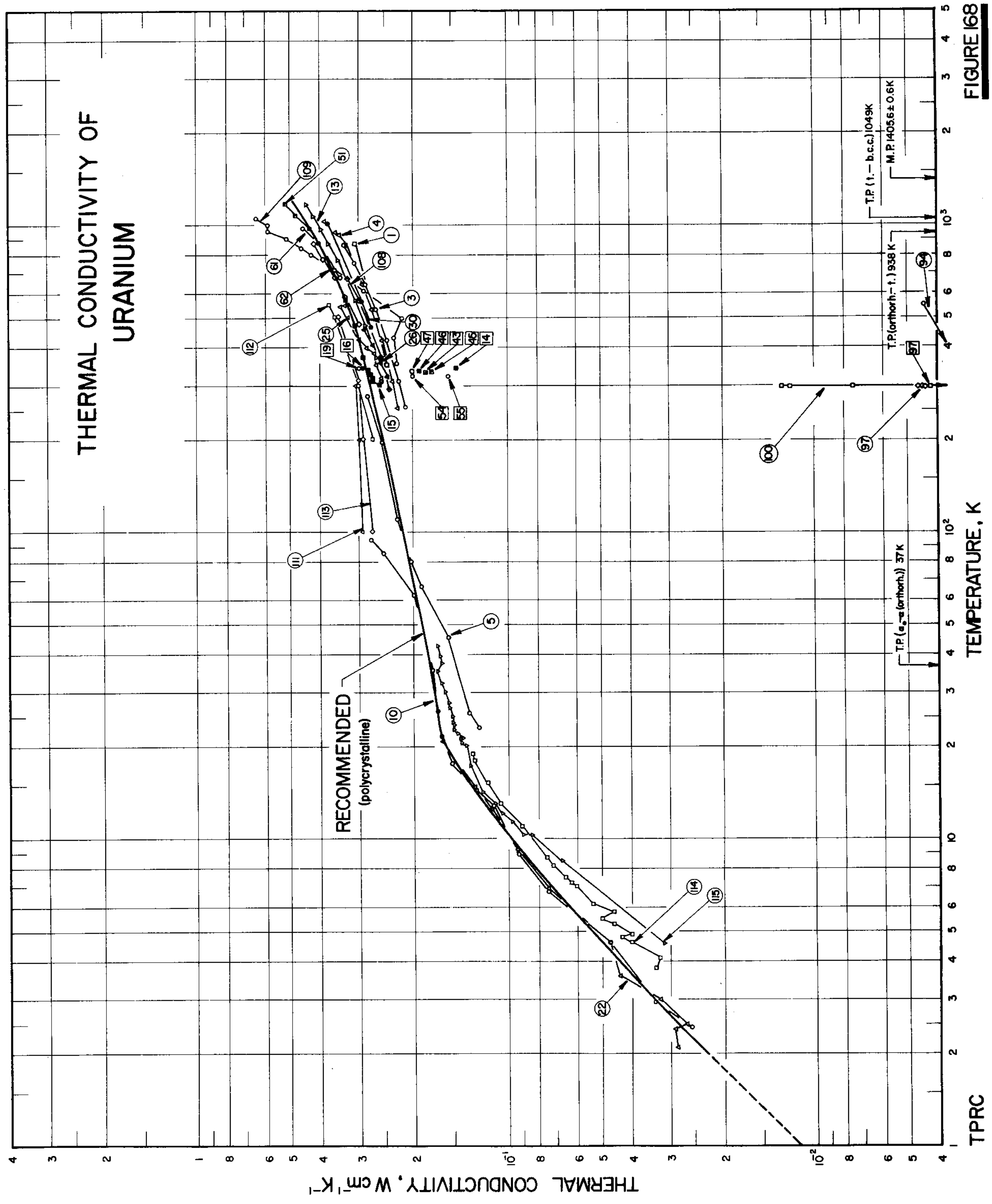
TABLE 173. Recommended thermal conductivity of uranium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	123.2	0.226
1	0.0114*	150	0.236
2	0.0228*	173.2	0.243
3	0.0338	200	0.251
4	0.0442	223.2	0.257
5	0.0541	250	0.264
6	0.0638	273.2	0.270
7	0.0731	298.2	0.275
8	0.0818	300	0.276
9	0.0898	323.2	0.281
10	0.0980	350	0.286
11	0.106	373.2	0.291
12	0.113	400	0.296
13	0.120	473.2	0.311
14	0.126	500	0.317
15	0.132	573.2	0.334
16	0.138	600	0.340
18	0.149	673.2	0.357
20	0.158	700	0.364
25	0.167	773.2	0.381
30	0.173	800	0.388
35	0.178	873.2	0.405
40	0.182	900	0.413
45	0.186	973.2	0.431
50	0.189	1000	0.439
60	0.196	1073.2	0.456
70	0.202	1100	0.463
80	0.208	1173.2	0.483
90	0.212	1200	0.490*
100	0.217		

†The recommended values are for well-annealed high-purity uranium, and those below room temperature are applicable only to a specimen having $\rho_0 = 2.14\ \mu\Omega$ cm. The values above 900 K are provisional.

*Extrapolated.


THERMAL CONDUCTIVITY OF
URANIUM
RECOMMENDED
(polycrystalline)
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
T.P. (orthorh.–t.) 938 K
T.P. (t.–b.c.c.) 1049 K
M.P. 1405.6 ± 0.6 K
T.P. (α₀–α (orthorh.)) 37 K
TPRC
FIGURE 168

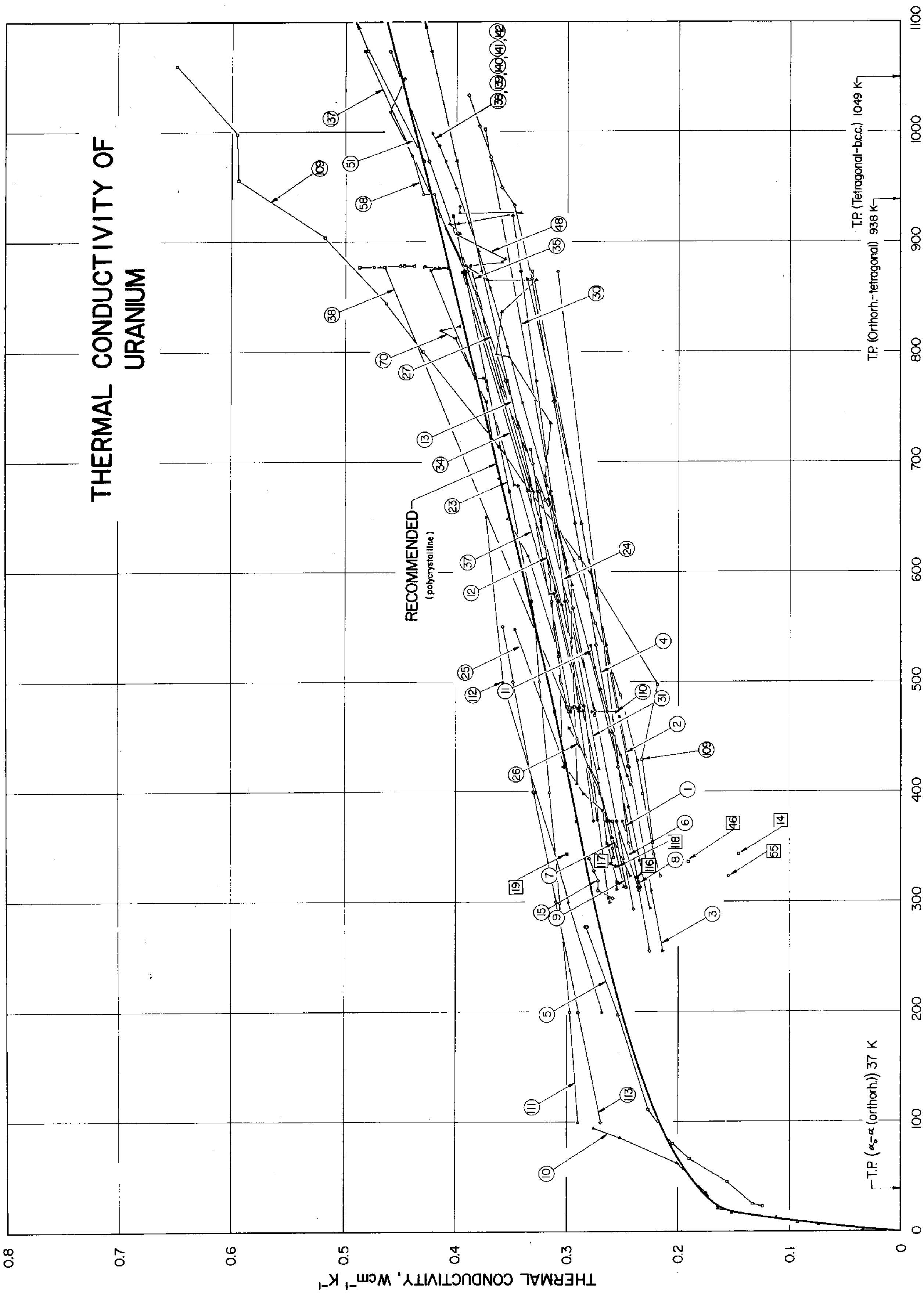

THERMAL CONDUCTIVITY OF URANIUM
THERMAL CONDUCTIVITY, Wcm⁻¹ K⁻¹
TEMPERATURE, K
RECOMMENDED
(polycrystalline)
T.P. (Tetragonal-b.c.c.) 1049 K
T.P. (Orthorh.-tetragonal) 938 K
T.P. (α₀-α (orthorh.)) 37 K
TPRC

FIGURE 169

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Authors(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	453	Francis, E. L. (compiler)	1958		353, 873		Mg-reduced.
2	453	Francis, E. L. (compiler)	1958		423, 873		Ca-reduced.
3	370	Droher, J.J. and Domingo, F.A.	1954	R	255-867		Pure; cylindrical disc specimen; rolled in the α-phase; as received; data taken from smoothed curve.
4	370	Droher, J.J. and Domingo, F.A.	1954	R	255-1033		Pure; cylindrical disc specimen; rolled in the α-phase; heated to 750 C for 10 min in the β-phase, then water quenched; data taken from smoothed curve.
5	1444	Tyler, W.W., Wilson, A.C., Jr., and Wolga, G.J.	1952	L	23-278		Approx 99.8 pure; specimen in a rod form 0.5 in. in dia and 2.5 in. long; heated at 700 C in a lead bath for 10 min then quenched in water at 50 C; electrical resistivity reported as 4.07, 9.79, 10.4, 9.96, 9.72, 13.3, 13.4, 13.2, 21.6, 21.6, and 28.4 μohm cm at 21.14, 77.60, 77.61, 77.61, 77.61, 109.7, 109.7, 109.7, 194.5, 194.5, and 277.2 K, respectively.
6	329	Deem, H.W. and Nelson, H.R.	1952	C	313, 373	695	Pure; 1.445 in. dia x 2.008 in. long; supplied by Sylvania Electric Products Corp; prepared by hot-pressing uranium powder; density 18.86 g cm^{-3}; Armco iron used as comparative material.
7	329	Deem, H.W. and Nelson, H.R.	1952	C	313, 373	BMI	Pure; rolled from 1.625 in. to 0.875 in. in dia at 500 C, heat treated at 725 C for 0.5 hr, water quenched from 725 C, and α-phase annealed at 525 C for 1 hr; density 18.86 g cm^{-3}; Armco iron used as comparative material.
8	329	Deem, H.W. and Nelson, H.R.	1952	C	313, 373	688	Pure; 1.449 in. dia x 1.98 in. long; supplied by Sylvania Electric Products Corp; powder-compact prepared by decomposition of UH_3 under hot pressing; grain size 0.25-0.50 mm in dia; density 18.84 g cm^{-3}; Armco iron used as comparative material.
9	329	Deem, H.W. and Nelson, H.R.	1952	C	313, 373	690	Pure; 1.445 in. dia x 2.06 in. long; supplied by Sylvania Electric Products Corp; powder-compact specimen prepared by decomposition of UH_3 under hot pressing; fine grained; density 18.905 g cm^{-3}; Armco iron used as comparative material.
10	1220	Rosenberg, H.M.	1955	L	2.5-94		Highly pure; specimen 2.95 cm long and 0.203 cm in dia; supplied by Atomic Energy Research Establishment; electrical resistivity reported as 2.2, 2.4, 2.5, 2.7, 3.0, 4.2, 6.7, 9.4, and 11.1 μohm cm at 9.4, 13.5, 17.8, 20.6, 26.1, 35.1, 56.3, 79.5, and 90.0 K, respectively; $\rho(293K)/\rho(20K) = 10.6$.
11	788	Kratz, H.R. and Raeth, C.H.	1945	C	407-534	U1	0.068 C, 0.004 Si, 0.0035 Fe, 0.002 Ni, 0.00009 N, 0.0002 Cr, 0.0002 Ag, and 0.00014 B; 1 in. dia x 10.75 in. long; extruded; thermal conductivity measured in the direction of extrusion; brass used as comparative material.
12	788	Kratz, H.R. and Raeth, C.H.	1945	C	340-711	U2	0.0720 C, 0.0150 Fe, 0.0100 Ag, 0.0028 N, 0.0020 Ni, 0.00175 Si, 0.0005 Cu, 0.0003 Cr, and 0.00012 B; 1 in. dia x 10.75 in. long; extruded; thermal conductivity measured in the direction of extrusion; brass used as comparative material.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
13	399	Eriksen, N.O. and Hälg, W.	1955	E	371-1105		Pure; 0.86 cm dia x 14 cm long; density 18.6 g cm^{-3}; electrical resistivity reported as 39.6, 41.6, 41.8, 43.4, 43.9, 45.4, 46.3, 47.2, 48.8, 50.9, 51.2, 52.4, 54.1, 56.5, 56.1, 57.8, 58.2, 56.9, 57.8, 58.4, 57.9, 59.5, 59.3, 58.9, 57.7, 58.5, 56.0, 50.5, 50.4, 54.3, and 54.3 μohm cm at 97, 137, 137, 185, 188, 192, 234, 236, 277, 316, 323, 353, 366, 432, 440, 458, 463, 466, 475, 532, 532, 597, 623, 640, 645, 652, 696, 711, 720, 829, and 835 C, respectively; thermal conductivity data show no discontinuous change at the transition points, whereas the electrical resistivity data show sudden changes.
14	1524 1525	Weeks, J.L. and Seifert, R.L.	1952	C	343		Pure; specimen 0.1875 x 0.1875 x 1.75 in.; density 18.8 g cm^{-3}; Armco iron used as comparative material.
15	1261	Schlegel, R.	1945	L	304-339	C-241-7B	From an "as rolled" rod, heated 2 hrs at 850 C and water quenched.
16	1522	Weeks, J.L.	1955	C	343.2	1 B 2	0.03 C; supplied by Argonne National Laboratory; as-rolled; Armco iron used as comparative material.
17*	1522	Weeks, J.L.	1955	C	343.2	2 B 3	0.08 C; supplied by Argonne National Laboratory; as-rolled; Armco iron used as comparative material.
18*	1522	Weeks, J.L.	1955	C	343.2	A-6	High purity; supplied by Argonne National Laboratory; quenched from 1000 C; Armco iron used as comparative material.
19	1522	Weeks, J.L.	1955	C	343.2	A-8	High purity; supplied by Argonne National Laboratory; quenched from 900 C; Armco iron used as comparative material.
20*	1522	Weeks, J.L.	1955	C	343.2	35	Supplied by Argonne National Laboratory; prepared from hot-pressed UH_3; Armco iron used as comparative material.
21*	1522	Weeks, J.L.	1955	C	343.2	5 A 3	0.1 Cr; supplied by Argonne National Laboratory; as-rolled; Armco iron used as comparative material.
22	937	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.1-21	U 1	Supplied by Atomic Energy Research Establishment.
23	128	Bell, I.P. and Makin, S.M.	1954	L	373-923	U 1	Bar specimen; cast.
24	128	Bell, I.P. and Makin, S.M.	1954	L	373-923	U 2	The above specimen heated to 690 C, maintained for several hrs in the β-phase then cooled to room temp at a rate of 4.2 C per min to change from β to α-phase.
25	121	Bates, J.C.	1953	E	311-548		Cylindrical bar specimen; cast.
26	121	Bates, J.C.	1953	E	323-458		Cylindrical bar specimen; cast; irradiated to 190 MWD/Te (Megawatt Day/Tonne of uranium) at 300 C; "cooling time" > 1 yr.
27	327, 864	Lucks, C.F. and Deem, H.W.	1958	C	293-1073		Measured in vacuum; Zircaloy-2 was used as comparative material.
28*	99	Babbitt, J.D., Dauphinee, T.M., Armstrong, L.D., and Peria, W.	1949	L	293-473	Canadian extruded No. 1	0.026 Si, 0.0188 Fe, 0.0036 Ni, 0.0030 Mn, 0.001 Cu, 0.0009 Cr, 0.0001 Co, and 0.00005 Ag; specimen approx 2.5 cm in dia and 8.0 cm in length; taken from a bar of metal refined in Canada, extruded in the γ-phase at 800 C to 900 C by Bureau of Mines; heated at 250 C for an hr for tinning; measured in vacuum.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
29*	99	Babbitt, J.D., Dauphinee, T.M., Armstrong, L.D., and Peria, W.	1949	L	291-422	Canadian extruded No. 1	The above specimen measured in a hotter furnace with different temp gradient in guard sleeve.
30	99	Babbitt, J.D., et al.	1949	L	470-1003	Canadian extruded No. 1	The above specimen heated at 800 C for 0.5 hr before measurement.
31	99	Babbitt, J.D., et al.	1949	L	420, 667	Canadian extruded No. 1	The above specimen heated to 400 C three times before measurement.
32*	99	Babbitt, J.D., et al.	1949	L	470, 572	Canadian extruded No. 1	The above specimen heated to 500 C; measured by a new main heater.
33*	99	Babbitt, J.D., et al.	1949	L	573.9	Canadian extruded No. 1	The above specimen heated to 400 C for 40 min prior to measurement.
34	99	Babbitt, J.D., et al.	1949	L	574-872	Canadian extruded No. 1	The above specimen tempered for 6 hrs at 600 C during the measurement.
35	99	Babbitt, J.D., et al.	1949	L	304-878	Canadian extruded No. 1	The above specimen completely remounted and heated to 600 C to set bonds.
36*	99	Babbitt, J.D., et al.	1949	L	477-877	Canadian extruded No. 1	The above specimen heated to 600 C for 3 hrs and cooled down before measurement.
37	99	Babbitt, J.D., et al.	1949	L	299-878	Canadian extruded No. 1	The above specimen heated for 1.5 hrs at 700 C.
38	99	Babbitt, J.D., et al.	1949	L	477-878	Canadian extruded No. 1	The above specimen heated for 2 hrs at 700 C.
39*	99	Babbitt, J.D., et al.	1949	L	475-878	Canadian extruded No. 1	The above specimen heated for 2.5 hrs at 600 C.
40*	786, 787	Kratz, H.R. and Raeth, C.H.	1943	C	323-573		Natural uranium; 1 in. in dia; extruded; measured along the direction of extrusion; brass used as comparative material (assumed thermal conductivity 0.23 cal $sec^{-1} cm^{-1} C^{-1}$).
41*	126	Bell, I.P.	1955	L	489-884		Cast uranium; specimen heated from α-phase to β-phase and cooled again to α-phase; electrical resistivity reported as 44.7, 46.2, 54.2, 56.3, and 58.1 μohm cm at 202, 296, 405, 509, and 599 C, respectively.
42*	1092	Plott, R.F. and Raeth, C.H.	1942	L	333.2	Tuballoy	Sintered; density 14.79 g cm^{-3} at about 25 C; the sintered uranium specimen contained possibly some uranium carbide.
43	1092	Plott, R.F. and Raeth, C.H.	1942	L	333.2	Tuballoy	Sintered and cold-pressed with 200 tons; density 17.22 g cm^{-3} at about 25 C; the sintered uranium specimen contained possibly some uranium carbide.
44*	1092	Plott, R.F. and Raeth, C.H.	1942	L	334.2	Tuballoy	Pure; sintered; density 16.29 g cm^{-3} at about 25 C.
45	1092	Plott, R.F. and Raeth, C.H.	1942	L	334.2	Tuballoy	Pure; sintered; density 15.72 g cm^{-3} at about 25 C.
46	1092	Plott, R.F. and Raeth, C.H.	1942	L	336.2	Tuballoy	Fused; density 18.06 g cm^{-3} at about 25 C.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
47	1092	Plott, R. F. and Raeth, C. H.	1942	L	335.2	Tuballoy	Fused; density 18.52 g cm^{-3} at about 25 C.
48	1070	Pearson, G. J., Davey, P. O., and Danielson, G. C.	1957	C	407-932		Pure; measured in a vacuum of 10^{-6} mm Hg; Armco iron used as comparative material.
49*	1607	Zegler, S. T. and Nevitt, M. V.	1961	C	423-1023	Casting No. 747	<0.005 each of K, P, Ti and Zn, 0.002 Si, <0.002 each of Ca and Mo, 0.001-0.002 C, <0.001 each of As and Na, 0.0003-0.0005 Fe, <0.0005 each of Al, Be, Co, Ni, and Sn, 0.0004 Sb, 0.0003 Mg, 0.0001 Cu, <0.0001 each of Ag, Bi, Cr, Li, and Pb, and <0.00001 B; specimen 2 cm in dia and 15 cm long; machined from cast ingot; Armco iron used as comparative material.
50*	122	B. M. I.	1945		398-573		Pure; extruded in γ-phase; measured in argon.
51	1531	Westphal, R. C.	1954		293-1173		Average values for two specimens measured.
52*	290	Compton, A. H. (Project Director)	1943	R	357-514		Hollow cylinder; extruded; measurements made by Raeth and King.
53*	1340	Snyder, T. M. and Kamm, R. L.	1955	P	323.2		Specimen in the shape of a sphere; cast by Westinghouse Co.; thermal conductivity value calculated from measured thermal diffusivity using the specific heat value of 0.026 cal g^{-1} C^{-1} and the density 18.6 g cm^{-3}.
54	1340	Snyder, T. M. and Kamm, R. L.	1955	C	323.2		Specimen 2 in. in dia and 1.31 in. long; cast by Westinghouse Co.; cold rolled iron used as comparative material (reference value 0.12 cal cm^{-1} sec^{-1} C^{-1}).
55	1340	Snyder, T. M. and Kamm, R. L.	1955	L, C	323.2		Porous specimen 2.5 cm x 2.8 cm x 2.05 cm; prepared from sintered metal powder by Metal Hydrides Corp; copper used as comparative material (reference value 0.91 cal cm^{-1} sec^{-1} C^{-1}).
56*	1236	Saller, H. A., Dickerson, R. F., Bauer, A. A., and Daniel, N. E.	1956	L	293-973		Pure; measured in a vacuum of about 1 x 10^{-5} mm Hg.
57*	127	Bell, I. P.	1954	L	334-873		In α-phase; cast; electrical resistivity reported as 34.48, 38.62, 42.76, 46.90, 51.04, 55.18, 59.32, 61.39, and 56.74 μohm cm at 0, 100, 200, 300, 400, 500, 600, 650, and 690 C, respectively.
58	316	Danielson, G. C. (editors, Chiotti, P. and Carlson, O. N.)	1954	P	323-1048		Specimen 0.125 in. in dia; Ames uranium; thermal conductivity values calculated from measured data of thermal diffusivity using a constant density 18.7 g cm^{-3} with the specific heat values taken from Katz, J. J. and Rabinowitch, E. ("The Chemistry of Uranium," McGraw Hill, N. Y., p. 147, 1951).
59*	99	Babbitt, J. D., Dauphinee, T. M., Armstrong, L. D., and Peria, W.	1956	L	285-776	Canadian extruded No. 2	0.026 Si, 0.0188 Fe, 0.0036 Ni, 0.0030 Mn, 0.0010 Cu, 0.0009 Cr, 0.0001 Co, and 0.00005 Ag; prepared from a bar of metal refined in Canada and extruded in the γ-phase at a temp between 800 and 900 C for Bureau of Mines; specimen approx 2.5 cm in dia and 8.0 cm in length; ends plated with Ni and Cu, tinned to the main heater and the heat sink at approx 250 C for 1 hr, then cooled to room temp; heated to 600 C and held for 45 min for bonding; measured in vacuum.
60*	99	Babbitt, J. D., et al.	1956	L	471.2	Canadian extruded No. 2	The above specimen remounted and heated to 750 C for 15 min to set bonds.
61	99	Babbitt, J. D., et al.	1956	L	677-979	Canadian extruded No. 2	The above specimen heated to 700 C and cooled to room temp prior to the measurement; measured with decreasing temps.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
62	99	Babbitt, J.D., et al.	1956	L	480-875	Canadian extruded No. 2	The above specimen heated to 300 C and cooled to room temp prior to the measurement.
63*	99	Babbitt, J.D., et al.	1956	L	293-781	Chalk River No. 1	Specimen approx 2.5 cm in dia and 8.0 cm in length; ends-plated with Ni and Cu, tinned to the main heater and heat sink at approx 250 C for 1 hr, then cooled to room temp; measured in vacuum.
64*	99	Babbitt, J.D., et al.	1956	L	432-687	Chalk River No. 2	Similar to above.
65*	99	Babbitt, J.D., et al.	1956	L	497-738	Chalk River No. 2	The above specimen remounted.
66*	99	Babbitt, J.D., et al.	1956	L	298-683	Chalk River No. 3	Similar to the above specimen.
67*	99	Babbitt, J.D., et al.	1956	L	474-726	Chalk River No. 3	The above specimen remounted.
68*	1093	Plott, R.F. and Raeth, C.H.	1945	L	301-333	C-241-7A	Pure; prepared from a rolled rod; heated 2 hrs at 850 C and water quenched.
69*	1093	Plott, R.F. and Raeth, C.H.	1945	L	304-333	C-245-1	Pure; prepared from a rolled rod.
70	639	Howl, D.A.	1966	C	422-819	13	Specimen 2.5 cm in dia and 17.7 cm long; Springfield uranium; β-quenched and α-annealed; Armco iron used as comparative material.
71*	314	Danielson, G.C. (real author) (Chiotti, P. and Carlson, O.N., the article authors)	1953	P	337-588		Specimen 0.125 in. in dia and 30 cm long; swaged from a Hanford uranium slug and annealed; thermal conductivity values calculated from the measured data of thermal diffusivity using the density and specific heat data of Katz, J.J. and Rabinowitch, E. ("The Chemistry of Uranium", McGraw-Hill, N.Y., pp. 144-8, 158, 1951).
72*	314	Danielson, G.C. (real author) (Chiotti, P. and Carlson, O.N., the article authors)	1953	P	481-693		Another run of the above specimen.
73*	478	Garlick, A. and Shaw, D.	1965	C	333.2		0.05-0.12 Al, 0.1 C, 0.02-0.05 Fe, 0.01 total of N, O and Si; Springfields standard adjusted uranium; specimen 2.9 cm in dia and 7.5 cm long; cast; heat treated by traverse water quenching in the beta phase (666-760 C) followed by an anneal for 1 hr at 550 C; Armco iron used as comparative material.
74*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
75*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
76*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
77*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
78*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
79*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
80*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
81*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen except annealed at 450 C for 3000 hrs.
82*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
83*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
84*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen except annealed at 450 C for 10000 hrs.
85*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
86*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
87*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen.
88*	478	Garlick, A. and Shaw, D.	1965	C	333.2		0.05–0.12 Al, 0.1 C, 0.02–0.05 Fe, 0.01 total of N, O and Si; irradiated Springfields standard adjusted uranium; specimens 2.9 cm in dia and 7.5 cm long; cast; heat treated by traverse water quenching in the beta phase (666–760 C) followed by an anneal for 1 hr at 550 C; irradiated in the Calder Hall reactors at an estimated mean temp of 250 C with doses ranging from 1152 to 1932 MWD/te; Armco iron used as comparative material.
89*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimens except irradiated at an estimated mean temp of 320 C with doses ranging from 3000 to 3298 MWD/te.
90*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimen except irradiated at an estimated mean temp of 370 C with doses ranging from 659 to 1750 MWD/te.
91*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimens except irradiated at an estimated mean temp of 395 to 415 C with doses ranging from 55 to 4660 MWD/te.
92*	478	Garlick, A. and Shaw, D.	1965	C	333.2		Similar to the above specimens except irradiated at estimated mean temp 420 to 450 C with doses ranging from 985 to 3157 MWD/te.
93*	1382	Swift, D. L.	1966	→	297.7		0.05 Fe, 0.01 Mg, 0.008 Mo, 0.005 Si, <0.005 P, <0.005 K, <0.005 Ti, <0.005 Zn, <0.002 Ca, <0.001 As, <0.001 Na, 0.0005 Ni, <0.0005 Al, <0.0005 Co, <0.0005 Sn, 0.0004 Mn, 0.0002 Cu, 0.0001 Pb, traces of Sb, Be, Bi, B, Cr, Li, and Ag; spherical powder obtained from National Lead Co.; contained in a 0.75 in. dia x 2 in. long stainless steel cylindrical cell; mesh size -16+20; grain size 1000 μ; thermal conductivity measured by the transient line source method; measured in nitrogen at atmospheric pressure.
94	1382	Swift, D. L.	1966	→	297-553		Same impurities, source, and measuring method as above; mesh size -70+80; grain size 190 μ; measured in nitrogen at atmospheric pressure.
95*	1382	Swift, D. L.	1966	→	297-553		Same impurities, source, and measuring method as above; mesh size -230+325; grain size 50 μ; measured in nitrogen at atmospheric pressure.
96*	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -16+20; average grain size 1000 μ; measured in nitrogen under pressures ranging from 2.85×10^{-5} to 8.71×10^{2} mm Hg.
97	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -40+50; average grain size 350 μ; measured in nitrogen under pressures ranging from 5.13×10^{-5} to 6.166×10^{3} mm Hg.
98*	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -70+80; measured in nitrogen at 1 atm.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
99*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in nitrogen under pressures ranging from 10^{-2} to 5.495×10^3 mm Hg.
100	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in helium under pressures ranging from 10^{-2} to 3.589×10^3 mm Hg.
101*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in methane under pressures ranging from 10^{-2} to 3.715×10^3 mm Hg.
102*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in argon under pressures ranging from 10^{-2} to 5.370×10^3 mm Hg.
103*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in nitrogen under pressures ranging from 2.92×10^{-5} to 5.188×10^3 mm Hg.
104*	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -170+200; average grain size 80 μ; measured in nitrogen under pressures ranging from 2.34×10^{-5} to 4.955×10^3 mm Hg.
105*	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -230+325; average grain size 53 μ; measured in nitrogen under pressures ranging from 1.05×10^{-2} to 2.483×10^3 mm Hg.
106*	1382	Swift, D. L.	1966	→	298.2		Same impurities, source, and measuring method as above; mesh size -230+325; measured in nitrogen at 1 atm.
107*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in nitrogen under pressures ranging from 0.01 to 3890 mm Hg.
108	327	Deem, H. W. and Lucks, C. F.	1959	C	293-973		Specimen 0.5 in. in dia and 5.625 in. long; unirradiated, unclad natural uranium; measured in a vacuum of 2×10^{-5} mm Hg; Armco iron used as comparative material; data reported here are ten times lower than the original data, which are believed to be wrong as the results of typographical error.
109	397	Erez, G. and Even, U.	1966	→	354-1059		Total impurity content <0.03; melted and cast in an alumina-coated graphite crucible; cooled and machined to desired dimensions; grain size ~0.25 mm; electrical resistivity reported as 33.8, 38.3, 44.3, 48.9, 53.8, 55.9, 57.5, 58.2, 56.0, 56.0, and 54.5 μohm cm at 81, 156, 234, 339, 440, 526, 570, 630, 682, 724, and 786 C, respectively; Lorenz function reported as 2.17, 1.93, 2.82, 3.44, 3.51, 3.24, 3.37, and 3.30×10^{-8} $V^2 K^{-2}$ at 96, 251, 467, 668, 670, 768, 773, and 801 C, respectively; thermal conductivity values orginally used by the authors when deriving these Lorenz function values had been calculated from their measured data for specific heat and thermal diffusivity, present thermal conductivity values calculated (by TPRC) from reported electrical resistivity data and Lorenz function values.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
110	330	Deem, H.W., Pobereskin, M., Lusk, E.C., Lucks, C.F., and Calkins, G.D.	1955	P, C	473.2		0.125 in. dia x 0.75 in. long; 347 stainless steel, K monel, and SAE 1010 steel used as comparative materials; measured by a heat-wave method.
111	595	Heal, T.J. and McIntosh, A.B.	1958		100-550	Mg-reduced U	~0.11 C; final average grain size 1.5 mm.
112	595	Heal, T.J. and McIntosh, A.B.	1958		200-550	U-0.5 a/o Mo	0.19 Mo and 0.13 C; Mg-reduced U; initial grain size 0.27 mm.
113	595	Heal, T.J. and McIntosh, A.B.	1958		100-550	U-0.5 a/o Cr	0.12 Cr and 0.08 C; Mg-reduced U; initial grain size 0.05 mm.
114	575	Haen, P. and Weil, L.	1964	L	3.8-19		α-uranium; cylindrical specimen supplied by C.E.A.; electrical resistivity 3.4 and 32 μohm cm at 20.4 and 290 K, respectively.
115	575	Haen, P. and Weil, L.	1964	L	4.6-43		The above specimen measured by another apparatus.
116	1324	Smart, D.	1960	P	323.2		Natural uranium; 2.9 cm dia x 9.1 cm long; measured by a transient method.
117	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		1.15 in. dia x 3 in. long; cut from fuel rod irradiated in a Calder-type reactor by a dose of 57 MWD/te; Armco iron used as comparative material.
118	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 657 MWD/te.
119*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 663 MWD/te.
120*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 933 MWD/te.
121*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 971 MWD/te.
122*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1067 MWD/te.
123*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1319 MWD/te.
124*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1663 MWD/te.
125*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1746 MWD/te.
126*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1892 MWD/te.
127*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 1896 MWD/te.
128*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 2803 MWD/te.
129*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3012 MWD/te.
130*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3059 MWD/te.
131*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3150 MWD/te.
132*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3289 MWD/te.
133*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3303 MWD/te.
134*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3338 MWD/te.
135*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 3567 MWD/te.
136*	477	Garlick, A. (Shaw, D. editor)	1963	C	333.2		Similar to above but irradiation dose 4655 MWD/te.

* Not shown in figure.

TABLE 174. THERMAL CONDUCTIVITY OF URANIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
137	734, 735	Kelman, L. R., Dunworth, R. J., Savage, H., and Rhude, H. V.	1964	C	473-1073		Density 19.07 g cm^{-3} at 25 C.
138	1237	Saller, H. A., Rough, F. A., and Chubb, W.	1956	C	295-998		0.08 Ti, 0.0200 C, 0.0010 H, and 0.0010 N; prepared by arc-melting into ingot, forged to 1.5 in. dia, hot-rolled from salt bath at 620 C; heat-treated in a lead bath at 730 C for 15 min, water quenched; grain size 0.07 mm; smoothed values reported.
139	1231	Saller, H. A., et al.	1956	C	295-998		0.17 Si, 0.0100 C, 0.0050 N, and 0.0002 H; same fabrication method and heat-treatment as the above specimen; grain size 0.04 mm; smoothed values reported.
140	1231	Saller, H. A., et al.	1956	C	295-998		0.05 Cr, 0.0300 C, 0.0040 N, and 0.0005 H; same fabrication method as the above specimen; heat-treated in a lead bath at 730 C for 15 min and in another lead bath at 550 C for 20 min, water quenched; grain size 0.07 mm; smoothed values reported.
141	1231	Saller, H. A., et al.	1956	C	295-998		0.0050 C, 0.0040 N, and 0.0004 H; same fabrication method as the above specimen; heat-treated in a lead bath at 730 C for 15 min, water quenched; grain size 0.10 mm; smoothed values reported.
142	1231	Saller, H. A., et al.	1956	C	295-998		0.0600 C, 0.0050 N, and 0.0001 H; prepared by induction melting into ingot, forged to 1.5 in. dia, hot-rolled from salt bath at 620 C; same heat-treatment as the above specimen; grain size 0.05 mm; electrical resistivity 28.9, 35.1, 41.5, 46.6, 50.8, 54.2, 56.3, and 56.6 μohm cm at 15, 100, 200, 300, 400, 500, 600, and 622 C, respectively; smoothed values reported.
143*	1111	Powell, R. W.	1945		293-473	Metal X	Bar specimen; electrical resistivity 34, 39.5, and 45.7 μohm cm at 20, 100, and 200 C, respectively, and Lorenz function 0.7, 0.63, and 0.5 x 10^{-8} V^2 K^{-2} at the respective temperatures.

* Not shown in figure.

Vanadium

Since vanadium is a superconductor below 5.3 K, the majority of the earlier thermal conductivity determinations on this metal have been restricted to this cryogenic temperature region. Only White and Woods [1548] (curve 3) and Rosenberg [1220] (curve 2) have extended their liquid-helium-temperature determinations to higher temperatures. White and Woods covered the wider temperature range of 4.3 to 90 K over which their values increased continuously with temperature and showed no maximum, presumably because of the low sample purity. The electrical resistance ratio between room and liquid-helium temperatures of this sample was only 5.1; that of Rosenberg's was lower. No other low temperature workers have included electrical resistivity data. The highest low-temperature thermal conductivity data are by Mendelssohn [930] (curve 6) and Chaudhuri, Mendelssohn, and Thompson [261] (curve 23). These two sets of data conform closely to the same linear curve over their respective temperature ranges of 0.18 to 4.4 K and 1.4 to 3.2 K. This straight line serves as the low-temperature end of the recommended curve for a sample in the normal state having $\rho_0 = 1.72$ $\mu\Omega$ cm, and at about 20 K it commences to bend over toward a maximum value located at about 60 K. Owing to the dearth of information on vanadium, the position of this maximum has been tentatively determined in terms of those of tantalum, niobium, and chromium and of their reported Debye temperatures.

The above-normal-temperature thermal conductivity measurements on vanadium which cover a wide range of temperatures are those of Fieldhouse and Lang [431] (curve 18) for the range 423 to 1876 K and of Heubner [601] (curve 25) for the range 296 to 937 K. Hoch and Nitti [611] (curves 12–17) have reported values for a few temperatures around 1700 K, for which Vardi and Lemlich [1468] (curve 24) have since proposed some revised evaluations, and Zinov'ev, Krentsis, and Gel'd [1622] for the range 905 to 1511 K have derived two sets of thermal conductivity values (curves 26, 27) from determinations of thermal diffusivity. These two sets, which were obtained by using different specific heat data, differ by about 2 percent at 905 K and 4 percent at 1500 K. The lower values are some 10 percent above those of Fieldhouse and Lang at 900 K, but agree well at the higher temperatures, whereas the corrected value of Vardi and Nitti at 1736 K is less than half those of the other workers. The proposed curve for vanadium spans the intervening temperature region as a smooth curve having a minimum at about 300 K and then rising to a mean position between the data of Fieldhouse and Lang and of Heubner. It then continues to increase smoothly to reach the highest point of Fieldhouse and Lang.

This curve between 30 K and 250 K must be regarded as rather tentative, and the tabulated values for this range are provisional and very uncertain. Above 250 K the probable accuracy is of the order of ± 10 percent, and below 30 K the values should be good to within ± 15 percent. The values of temperatures below 200 K are applicable only to a sample in the normal state having $\rho_0 =$ 1.72 $\mu\Omega$ cm.

No information is available for either the thermal or electrical conductivity of liquid vanadium.

TABLE 175. Recommended thermal conductivity of vanadium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid			
T	k	T	k
0	0	350	0.309
1	0.0142	373.2	0.310
2	0.0282	400	0.313
3	0.0422	473.2	0.319
4	0.0561	500	0.322
5	0.0697	573.2	0.330
6	0.0835	600	0.333
7	0.0971	673.2	0.342
8	0.111	700	0.345
9	0.125	773.2	0.354
10	0.138	800	0.357
11	0.151	873.2	0.366
12	0.165	900	0.369
13	0.177	973.2	0.379
14	0.190	1000	0.382
15	0.202	1073.2	0.392
16	0.214	1100	0.395
18	0.237	1173.2	0.405
20	0.258	1200	0.408
25	0.305	1273.2	0.417
30	0.342	1300	0.421
35	0.369	1373.2	0.430
40	0.389	1400	0.434
45	0.401	1473.2	0.443
50	0.405	1500	0.446
60	0.406	1573.2	0.455
70	0.402	1600	0.459
80	0.390	1673.2	0.468
90	0.373	1700	0.472
100	0.358*	1773.2	0.481
123.2	0.336*	1800	0.484
150	0.324*	1873.2	0.494
173.2	0.318*	1900	0.497*
200	0.313*	1973.2	0.506*
223.2	0.310*	2000	0.509*
250	0.308*		
273.2	0.307*		
298.2	0.307		
300	0.307		
323.2	0.308		

†The recommended values are for well-annealed high-purity vanadium, and those below 200 K are applicable only to a specimen having $\rho_0 = 1.72$ $\mu\Omega$ cm. The values from 30 to 250K are provisional.
*Extrapolated or interpolated.

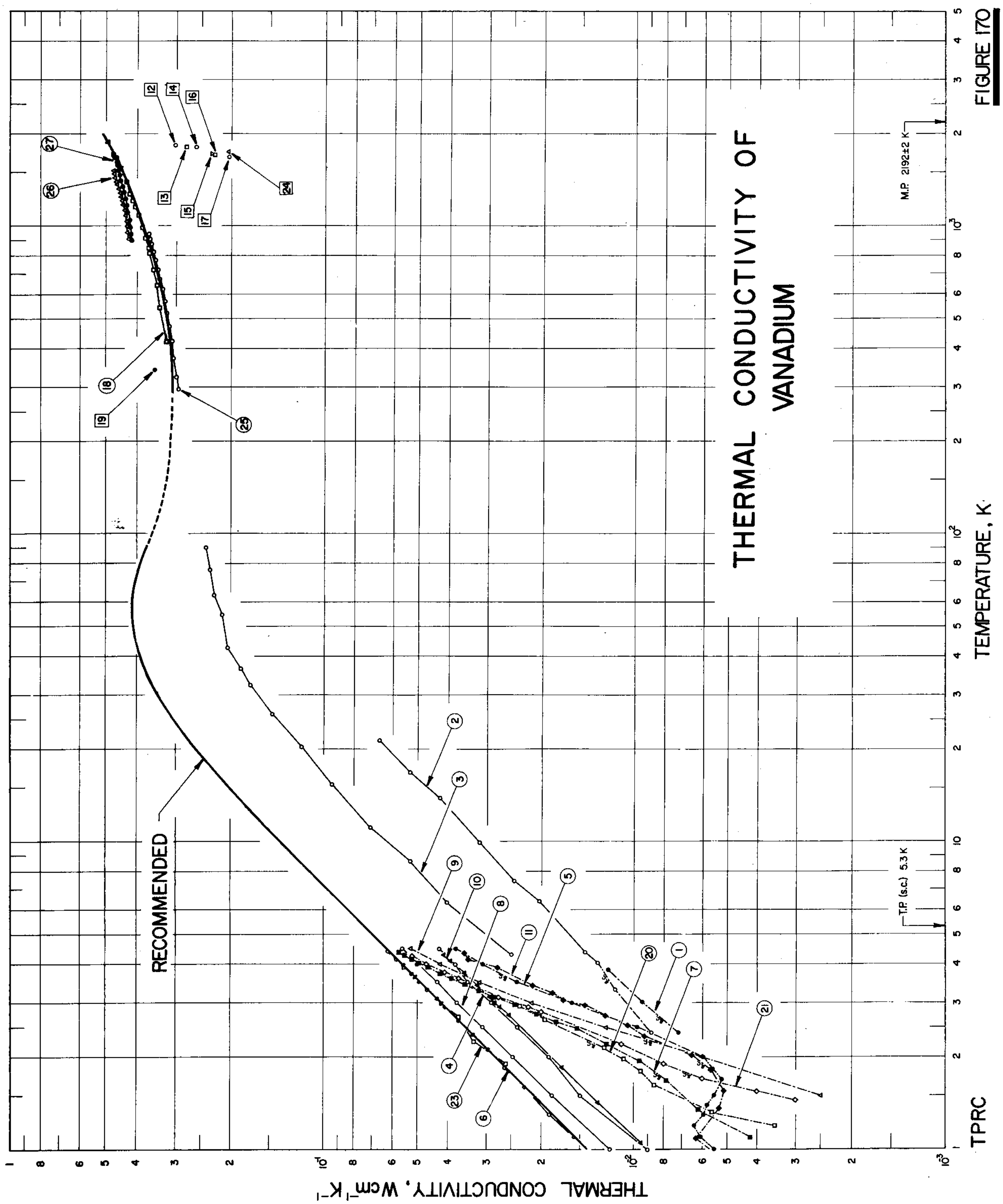

THERMAL CONDUCTIVITY OF VANADIUM
FIGURE 170
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
RECOMMENDED
M.P. 2192±2 K
T.P. (s.c.) 5.3 K
TPRC

TABLE 176. THERMAL CONDUCTIVITY OF VANADIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	1220	Rosenberg, H.M.	1955	L	2.4-3.84	V 1	Polycrystalline; specimen 0.725 cm long, 0.0995 cm in dia; made from spectrographically standardized metal from Johnson, Matthey and Co.; in superconducting state; electrical resistivity ratio $\rho(293K)/\rho(20K)$ = 3.22.
2	1220	Rosenberg, H.M.	1955	L	2.4-21	V 1	The above specimen measured in a magnetic field; in normal state.
3	1548	White, G.K. and Woods, S.B.	1957	L	4.3-90	V 4	Approx 99.9 pure; obtained from Electrometallurgical Co.; specimen 3.55 mm in dia; annealed in vacuo at 1300 C; residual electrical resistivity ρ_0 = 4.83 μohm cm; ideal electrical resistivity reported as 0.014, 0.038, 0.14, 0.38, 0.74, 2.3, 4.25, 8.7, 12.95, 16.65, 18.3, and 19.9 μohm cm at 15, 20, 30, 40, 50, 75, 100, 150, 200, 250, 273, and 295 K, respectively.
4	930	Mendelssohn, K.	1958	L	0.5-4.5	V I	Single crystal; in normal state.
5	930	Mendelssohn, K.	1958	L	1.0-4.5	V I	The above specimen in superconducting state.
6	930	Mendelssohn, K.	1958	L	0.18-4.4	V II	Single crystal; in normal state.
7	930	Mendelssohn, K.	1958	L	1.1-4.4	V II	The above specimen in superconducting state.
8	930	Mendelssohn, K.	1958	L	0.2-4.5		Polycrystalline; in normal state.
9	930	Mendelssohn, K.	1958	L	1.5-4.5		The above specimen in superconducting state.
10	233	Calverley, A., Mendelssohn, K., and Rowell, P.M.	1961	L	1.1-4.3	V II	0.05 Fe, 0.01 Si, 0.005 Mo, 0.0005 Mn, and 0.0003 Cu; single crystal; specimen obtained by floating-zone melting of polycrystalline rod; measured in magnetic field of 6200 oersteds; in normal state.
11	233	Calverley, A., Mendelssohn, K., and Rowell, P.M.	1961	L	0.92-4.3	V II	The above specimen measured with the magnetic field removed; in superconducting state.
12	611	Hoch, M. and Nitti, D.A.	1961	→	1840		Specimen 0.50 in. in dia and 0.442 in. thick; heated in high vacuum (10^{-5} mm Hg) by high-frequency induction to 1000-3000 C; localized heating within 0.003 in. of the surface at current frequency of 500000 cps; heat lost only by radiation, cylindrical surface assumed isothermal, and the temperature gradient along the radius analytically correlated to the thermal conductivity, run No. 1.
13	611	Hoch, M. and Nitti, D.A.	1961	→	1807.5		The above specimen, run No. 3.
14	611	Hoch, M. and Nitti, D.A.	1961	→	1801.5		The above specimen, run No. 4.
15	611	Hoch, M. and Nitti, D.A.	1961	→	1729		The above specimen, run No. 6.
16	611	Hoch, M. and Nitti, D.A.	1961	→	1707.5		The above specimen, run No. 7.
17	611	Hoch, M. and Nitti, D.A.	1961	→	1674.5		The above specimen, run No. 8.
18	431	Fieldhouse, I.B. and Lang, J.I.	1961	R	423-1876		99.74 V, 0.073 O, 0.048 Fe, 0.043 N, and 0.042 C; specimen composed of 5 one-inch dia disks; hot rolled and annealed; density 6.05 g cm^{-3}.
19	1526, 1527	Weeks, J.L. and Smith, K.F.	1955	C	343		99.6^+ pure, calcium-reduced vanadium from the Electrometallurgical Co.; Armco iron used as comparative material.

TABLE 176. THERMAL CONDUCTIVITY OF VANADIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight, percent), Specifications and Remarks
20	261	Chaudhuri, K.D., Mendelssohn, K., and Thompson, M.W.	1960	L	1.2-4.4		Single crystal; ~ 50 mm long, 4 mm in dia; prepared by 'floating zone' technique; in superconducting state.
21	261	Chaudhuri, K.D., Mendelssohn, K., and Thompson, M.W.	1960	L	1.5-4.3		The above specimen irradiated to a dose of 10^{18} fast neutrons cm^{-2}; in superconducting state.
22*	261	Chaudhuri, K.D., Mendelssohn, K., and Thompson, M.W.	1960	L	1.4-3.2		The above specimen measured before irradiation; in normal state.
23	261	Chaudhuri, K.D., Mendelssohn, K., and Thompson, M.W.	1960	L	1.9-4.4		The above specimen measured after irradiated to a dose of 10^{18} fast neutrons cm^{-2}; in normal state.
24	1468	Vardi, J. and Nitti, D.A.	1968		1746		Recalculation of the experimental data of Hoch, M. and Nitti, D.A. (see curve No. 12-17) based on a new theory of the high frequency electromagnetic induction heating method.
25	601	Heubner, U.	1969	L, C	296-937		0.08 O, 0.046 N, and 0.044 C; specimen 8 mm in dia; electrical conductivity reported as 4.29, 2.86, 2.30, 1.93, 1.67, and 1.47 x 10^4 ohm^{-1} cm^{-1} at 25, 200, 350, 500, 650, and 800 K, respectively; measured in a vacuum of $<10^{-6}$ torr.
26	1622	Zinov'ev, V.E., Krentsis, R.P., and Gel'd, P.V.	1969	P	905-1511	1	0.05 total impurities; specimen 0.249 mm thick; heated for a short time to 1800 K in the vacuum chamber of the apparatus; electrical resistivity ratio $\rho(298K)/\rho(4.2K) = 15$; thermal conductivity values calculated from the measured data of thermal diffusivity, using specific heat data from Neimark, B. E. (editor, "Handbook of Physical Properties of Steels and Alloys Applied in Power Engineering," Izd. Energiya, Moscow and Leningrad, 1967), and density of Neimark, B.E. et al. (Tez. Dokl. An AzSSR, Baku, 1968); smoothed values reported.
27	1622	Zinov'ev, V.E., et al.	1969	P	901-1679	2	The above specimen, thermal conductivity values calculated by using specific heat data of Kohlhaas, R., Braun, M., and Vellmer, O. (Z. Naturforsch., 20a, 1077, 1965); smoothed values reported.

* Not shown in figure.

Xenon

The thermal conductivity of xenon in each of the physical states is discussed separately below.

Solid

For a considerable period, the only information available for the thermal conductivity of solid xenon was a set of calculated values of Julian [696] from 3.8 to 152 K. As noted in that source, and evident from the graphs there presented, severe disagreement exists between theory and experiment at sufficiently low temperatures, where the theory of Julian does not predict a maximum in the thermal conductivity to occur. The tabulated values, obtained from a plot of the Julian values, have thus been restricted to temperature of 50 K and above, where this difficulty should not arise. However, even for such temperatures a comparison of theory and experiment for the other substances considered by Julian indicates that errors of twenty percent are quite possible in the calculated values for xenon.

The measurements of Krupskii [791, 792] show considerable disagreement with the Julian values. The supposition of Krupskii that other experimenters failed to sufficiently purify their materials may be correct in part, as the trend to higher values at the lower temperatures certainly parallels this conclusion. However, other factors are considered possible as producing some of the disagreement and a new, highly detailed, experimental investigation of the thermal conductivity of the inert gas solids is strongly suggested.

Saturated Liquid

In studying the thermal conductivity of saturated liquid xenon, the experimental data of Keyes [748] and of Ikenberry and Rice [654] were compared with the correlation of Owens and Thodos [1058]. Where necessary, the experimental values of [654] were extrapolated to saturation conditions. The result of the intercomparison was to indicate that the two sets of experimental data agreed to within a few percent. Above 210 K the correlated values appeared too high and the recommended values were derived from a smooth curve which passed through the mean of the two sets of available data at the lowest temperatures, through the Ikenberry and Rice data above 200 K and which passed through a critical point value about five percent lower than the Owens and Thodos value. The maximum difference between the present values and those of the correlation was about nine percent at 260 K.

The recommended values should be accurate to within about five percent for the entire tabulated range, except possibly in the immediate vicinity of the critical point.

Saturated Vapor

No experimental data were located for the thermal conductivity of saturated xenon vapor. The provisional values were derived from a correlation of Owens and Thodos [1058] and must be regarded as of uncertain accuracy until experimental measurements are available. Based upon a comparison of such values with atmospheric pressure values at low temperatures a few percent uncertainty below 250 K would appear reasonable, the uncertainty then gradually increasing to the critical temperature, at which a magnitude of about twenty-five percent seems a reasonable estimate. Due to the absence of experimental data no departure plot is given.

Gas

At the time of compilation of the earlier tables [843, 1420, 608, 844], the only experimental investigations located which extended over any temperature range were those of Kannuluik and Carman [705] and Keyes [748]. Covering the range 150–579 K, these measurements enabled recommended values to be generated to 750 K with an estimated uncertainty of five percent or less.

Subsequent to these tables, further experimental values, due to Saxena and Saxena [1251] from 350 to 1500 K using the column method, Zaitseva [571] from 306 to 794 K, von Ubisch [1490a, 1490] at 302 and 790 K, and some values to nearly 1200 K [1474] which are only presently available as departures from tabulated values, became available. A further experimental study over a lower temperature range (303–363 K) was located [472] and various other values were examined, including those of Hanley to 1000 K, using the Lennard–Jones 24–6 potential [585], Landolt–Bornstein to 800 K [1147], Amdur and Mason [55], Svehla [1381] and the recent standards publication by Vargaftik, et al. [1474]. The newer information shows that the older tables were low at the highest temperatures. However, the newer experimental information [1490a, 1251, 472, 571] is in disagreement with theoretical estimates at the higher temperatures, being consistently larger. Some of this may be due to errors in viscosity values, but it appears that either the conclusion of Kestin [743] (that the claims for accuracy made in viscosity and thermal conductivity measurements do not check with the theory) is correct or the generally accepted theory may be in error by up to five percent or so.

In the present work, no detailed examination of viscosities were made. Plotting the various experimental values revealed that the trend of the Saxena, et al. [1251] data more nearly resembled the theoretical trend than the recent Russian standards values [1474]. Analysis of the Saxena data showed that these could be represented by absolute temperature raised to the 0.76 power. This was used to generate recommended values above 1000 K. Values below this were generated from graphically determined values which were faired into the original tables at 250 K.

Analysis of the departure plots reveals that a systematic difference of about five percent exists between the curve 8 [1251] data and the curves 12 and 14 [55, 1381] calculations, from about 500 to 1000 K. If, however, the present values are adjusted to make the trend of these curves temperature independent, much poorer agreement exists with the Russian values. Furthermore, the present selection of recommended values does result in the same general trend of the agreement with temperature with the column-method and with the values of Vargaftik, et al., as noted for some other fluids. Further highly accurate experimentation is obviously needed for gaseous xenon to resolve the difficulties noted above. Pending this, the present values are considered accurate to a few percent below 500 K, the uncertainty then increasing to at least five percent at 1000 K and ten percent at 1500 K.

TABLE 177. Recommended thermal conductivity of xenon†

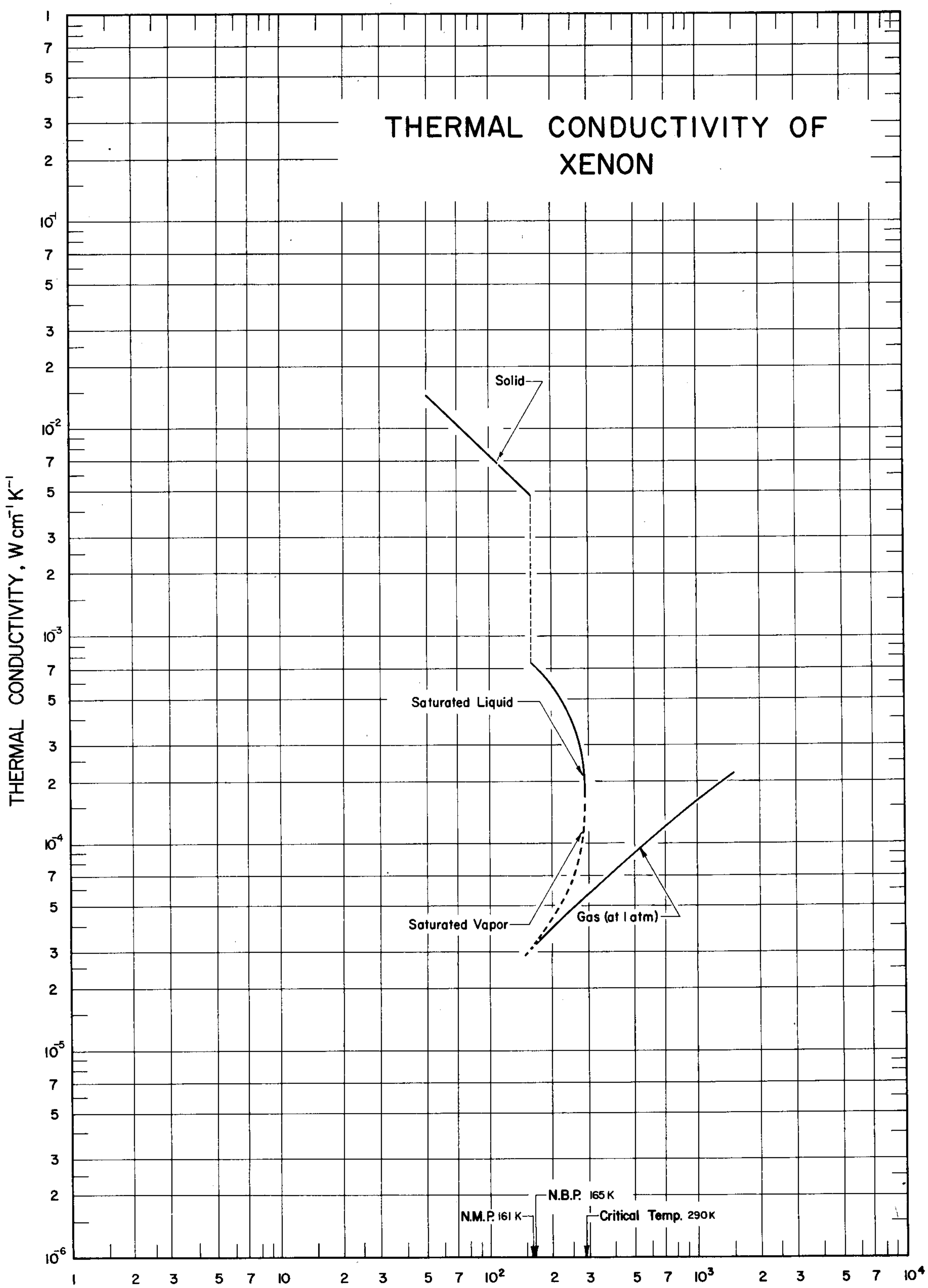
(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid		Saturated liquid		Saturated vapor	
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
50	14.4	161	0.74	165	0.032*
60	12.0	170	0.70	170	0.034*
70	10.5	180	0.66	180	0.037*
80	9.2	190	0.62	190	0.041*
90	8.2				
		200	0.58	200	0.044*
100	7.5	210	0.54	210	0.048*
110	6.8	220	0.50	220	0.051*
120	6.3	230	0.46	230	0.055*
130	5.8	240	0.42	240	0.060*
140	5.4				
		250	0.38	250	0.066*
150	5.1	260	0.34	260	0.073*
160	4.8	270	0.31	270	0.084*
161	4.8	280	0.27	280	0.098*
		290	0.16*‡	290	0.16*‡

Gas
(At 1 atm)

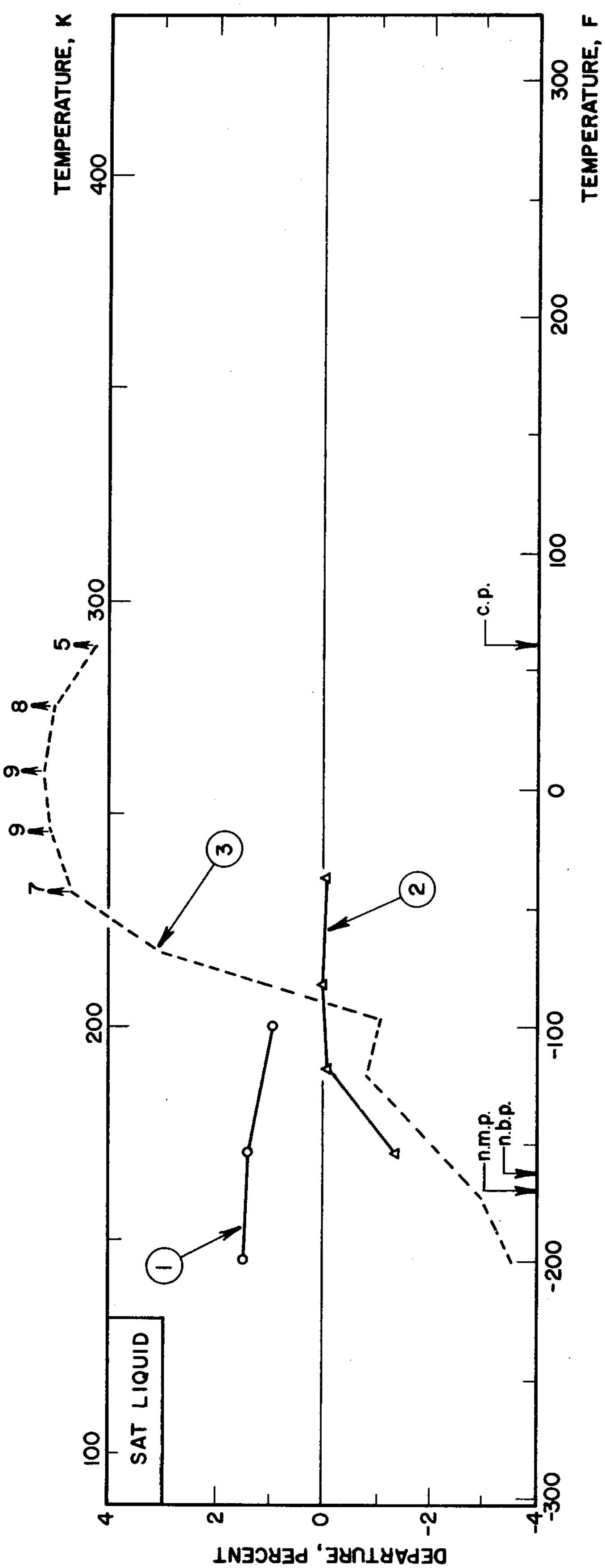
T	$k\times10^3$	T	$k\times10^3$	T	$k\times10^3$
		500	0.0905	850	0.142
165	0.0325	510	0.0920	860	0.143
170	0.0334	520	0.0935	870	0.145
180	0.0352	530	0.0950	880	0.146
190	0.0370	540	0.0965	890	0.147
200	0.0388	550	0.0980	900	0.149
210	0.0406	560	0.0995	910	0.150
220	0.0424	570	0.1010	920	0.151
230	0.0442	580	0.1025	930	0.152
240	0.0460	590	0.1040	940	0.154
250	0.0478	600	0.1055	950	0.155
260	0.0496	610	0.1070	960	0.156
270	0.0514	620	0.1085	970	0.157
280	0.0532	630	0.1100	980	0.159
290	0.0550	640	0.1115	990	0.160
300	0.0569	650	0.1130	1000	0.161
310	0.0587	660	0.1145	1050	0.167
320	0.0605	670	0.1160	1100	0.173
330	0.0623	680	0.1175	1150	0.179
340	0.0641	690	0.1190	1200	0.185
350	0.0659	700	0.1205	1250	0.190
360	0.0677	710	0.1220	1300	0.196
370	0.0695	720	0.1234	1350	0.202
380	0.0713	730	0.1249	1400	0.208
390	0.0731	740	0.1263	1450	0.213
400	0.0745	750	0.1278	1500	0.219
410	0.0761	760	0.129		
420	0.0777	770	0.131		
430	0.0793	780	0.132		
440	0.0809	790	0.134		
450	0.0825	800	0.135		
460	0.0841	810	0.136		
470	0.0857	820	0.138		
480	0.0873	830	0.139		
490	0.0889	840	0.140		

†Values for the solid and saturated vapor are provisional.
*Estimated or extrapolated.
‡Pseudo-critical value.



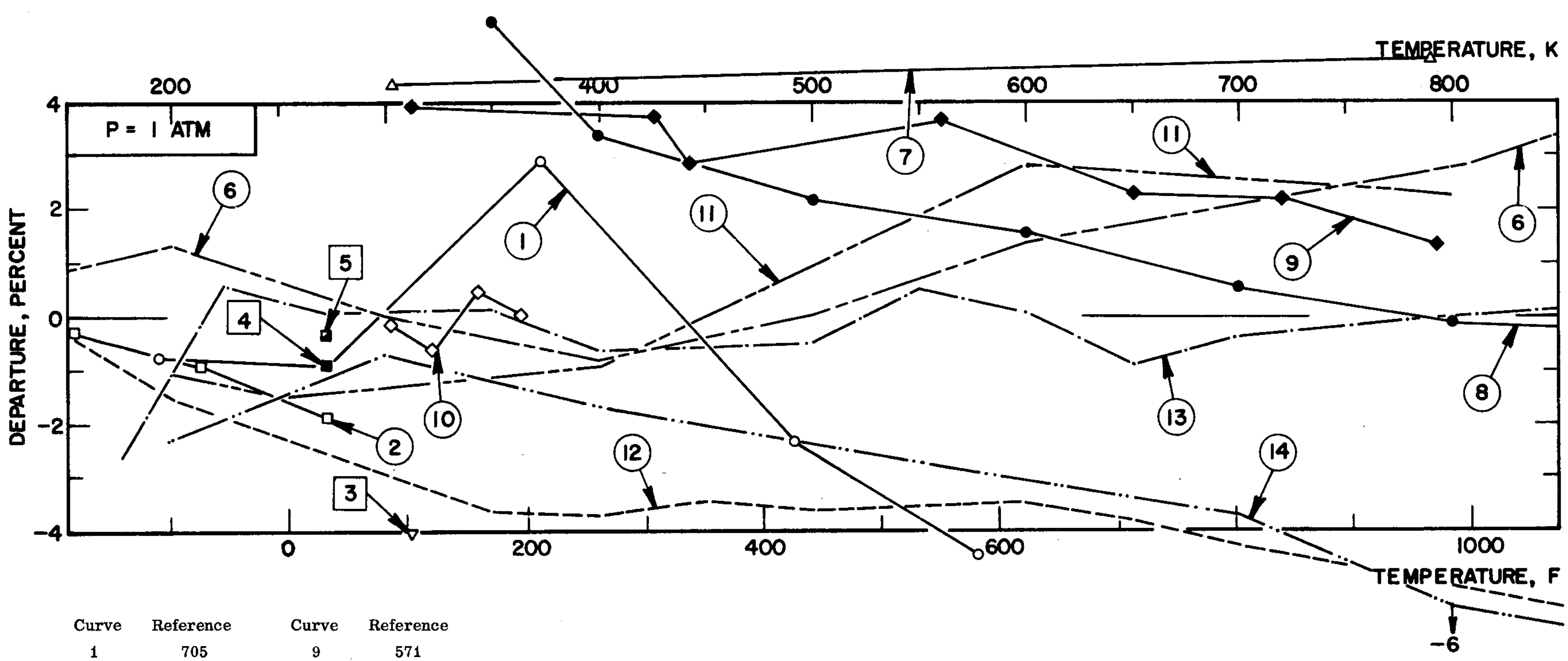
TPRC FIGURE 171

FIGURE 172. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF SATURATED LIQUID XENON



Curve	Reference
1	748
2	654
3	1058

FIGURE 173. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS XENON



Curve	Reference	Curve	Reference
1	705	9	571
2	748	10	472
3	1250	11	1417
4	305	12	585
5	72	13	1474
6	1473	14	1381
7	1490a	15	55
8	1251		

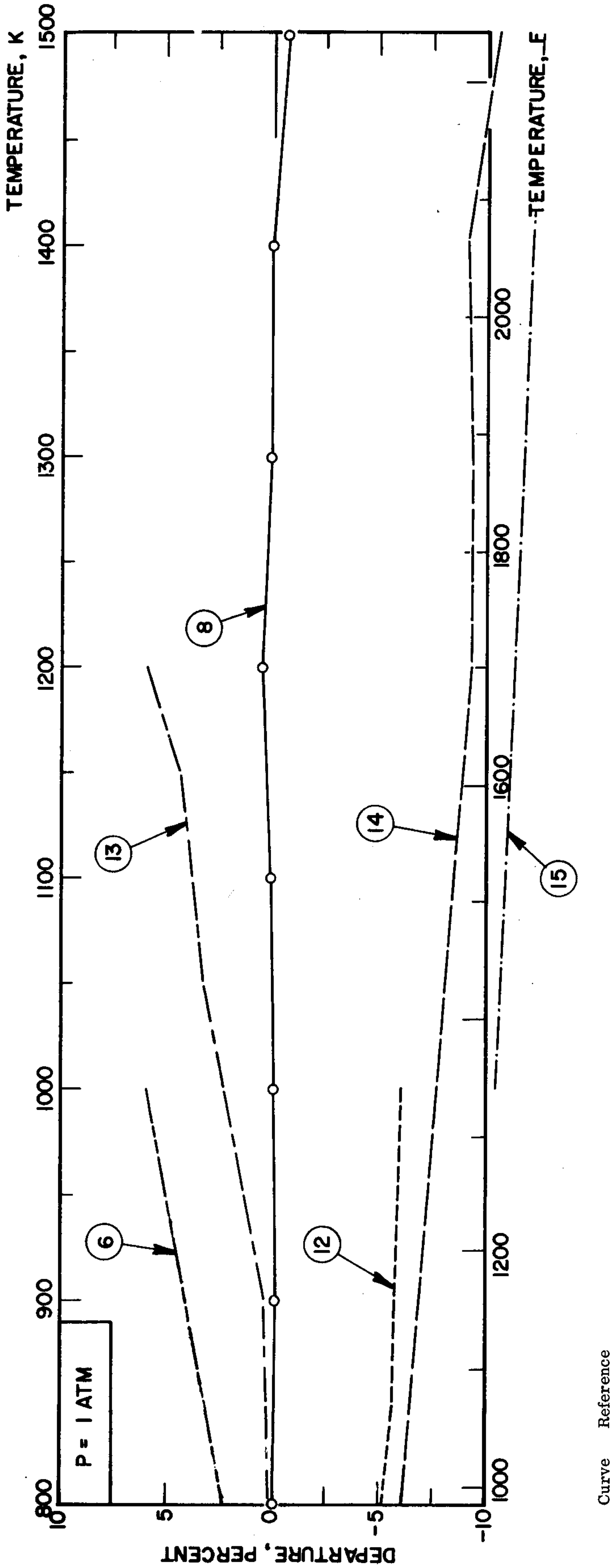


FIGURE 173. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS XENON (continued)

Curve	Reference
6	1473
8	1251
12	585
13	1474
14	1381
15	55

Ytterbium

The only reported measurements for the thermal conductivity of ytterbium are those of Aliev and Volkenshtein [46] (curve 1) for the temperature range from 2.1 to 79 K, of Rao [1170] (curve 3) from 1.2 to 4.2 K, and of Ratnalingam [1181] (curve 4) from 0.5 to 4.0 K. Ratnalingam and Rao appeared to have used the same specimen and measured in the same Laboratory, but their results are very different. The sample [46] was stated to be 99.99 percent pure, but the electrical resistivities at 4.2 K and 293 K were, respectively, 5.56 and 27 $\mu\Omega$ cm, yielding a resistivity ratio $\rho_{293}/\rho_{4.2}$ of only 4.86, whereas the corresponding figures for Rao's sample were 15.2 and 35.5 $\mu\Omega$ cm, and a ratio of 2.338. At 4.2 K Aliev and Volkenshtein obtained a Lorenz function of 3.17 $\times$ 10^{-8} V^2 K^2, Ratnalingam 2.30 $\times$ 10^{-8} V^2 K^{-2}, and Rao 3.345 $\times$ 10^{-8} V^2 K^{-2}.

Aliev and Volkenshtein covered the range from 2.1 to 79 K and their data would offer no choice but to accept them as the basis of the most probable values for the low-temperature range. It should however be noted that this curve presents difficulties at both ends. The initial slope is much greater than that obtained for most metals. The thermal conductivity in the liquid-helium range is indicated to be approximately proportional to $T^{2.3}$ rather than to T. This is certainly an unusual feature that demands further investigation.

Some further information regarding the thermal conductivity of ytterbium comes from the room-temperature electrical resistivity. For this quantity three sets of observers, Spedding, Hanak, and Daane [1348], Curry, Legvold, and Spedding [308], and Aliev and Volkenshtein agree in obtaining values of 27 or 28 $\mu\Omega$ cm. That of Rao was some 30 percent greater. Jolliffe, Tye, and Powell [690], from a plot of their derived values for the Lorenz function at 291 K against the atomic number for atomic numbers 57 to 71 deduce that for ytterbium, of atomic number 70, the Lorenz function is likely to be about 3.3 $\times$ 10^{-8} V^2 K^{-2}. From this value for the Lorenz function and a resistivity of 27.5 $\mu\Omega$ cm, they estimated that the thermal conductivity of ytterbium is likely to be 0.35 W cm^{-1} K^{-1} at 291 K.

The question which then arises is how to proceed from the experimental curve of Aliev and Volkenshtein to this much higher estimated value.

The straight-forward extrapolation of the curve of Aliev and Volkenshtein would have led to a room-temperature thermal conductivity of the order of 0.094 W cm^{-1} K^{-1} and a Lorenz function of 0.86 $\times$ 10^{-8} V^2 K^{-2}. The characteristic Debye temperature of ytterbium is 118 K, by which temperature the Lorenz function would be expected to be not less than the theoretical value. Hence it seems reasonable to assume that at temperatures above 118 K the thermal conductivity of ytterbium will be equal to the sum of an electronic component, 2.443 $\times$ 10^{-8} T ρ^{-1}, and a lattice component 26.4 T^{-1}, this last numerical coefficient being required to satisfy the estimated value of Jolliffe, et al. at 291 K. Approximate values for ρ over the range 118 to 500 K were derived by assuming the residual resistance value of Aliev and Volkenshtein to have been reached at 20 K and a linear increase to hold from 20 to 293 K and on to 500 K. On the basis of the foregoing assumptions regarding the electronic and lattice components, the curve drawn as a short-dashed line was derived for the range 118 to 500 K.

These considerations serve to emphasize the present uncertainty regarding the thermal conductivity of ytterbium. That a four-fold increase in value should occur between 80 and 120 K seems most unlikely. Yet unless an increase of this order does occur by room temperature the difference between the extrapolated experimental curve and the derived curve seems too great to be explained by compositional differences, particularly in view of the close agreement of the reported electrical resistivity values. Ytterbium is a metal for which further thermal conductivity determinations are required before any firm recommendations can be made. Very tentatively, points read from the short-dashed line are proposed for the range 123 to 500 K, but no values are at present recommended at lower temperatures. These provisional values are probably good to $\pm$20 percent near room temperature and $\pm$30 percent at other temperatures.

TABLE 178. Provisional thermal conductivity of ytterbium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid	
T	k
123.2	0.456*
150	0.423*
173.2	0.402*
200	0.384*
223.2	0.372*
250	0.361*
273.2	0.354*
298.2	0.349*
300	0.349*
323.2	0.347*
350	0.345*
373.2	0.343*
400	0.341*
473.2	0.338*
500	0.337*

†The provisional values are for high-purity ytterbium.
*Estimated.

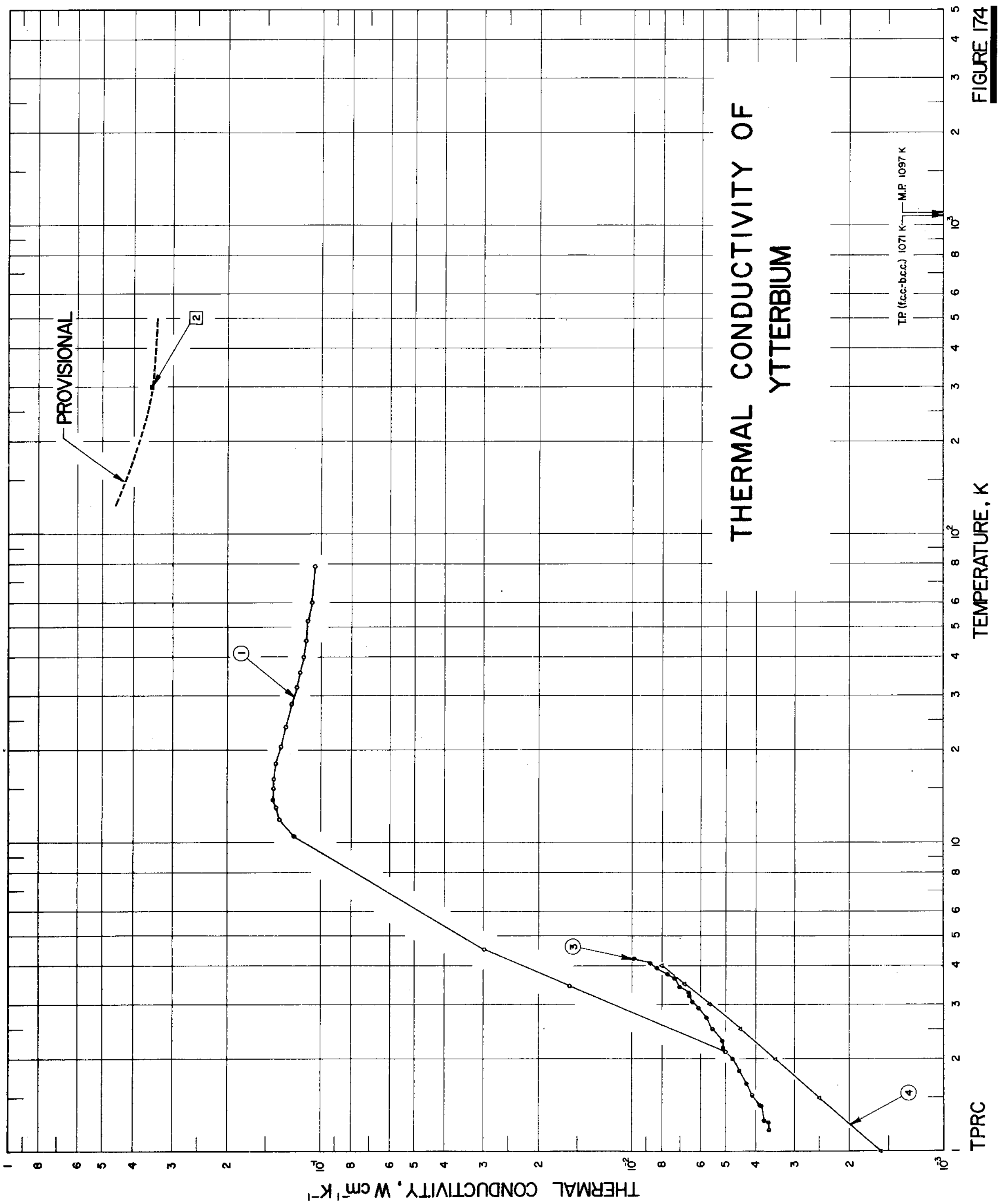

THERMAL CONDUCTIVITY OF YTTERBIUM
FIGURE 174
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
PROVISIONAL
TPRC
T.P. (f.c.c.-b.c.c.) 1071 K
M.P. 1097 K

TABLE 179. THERMAL CONDUCTIVITY OF YTTERBIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	46	Aliev, N.G. and Volkenshtein, N.V.	1965	L	2.1-79		99.99 pure; polycrystalline; strip specimen 0.25 mm thick; annealed in helium vapor at 450 C for 2.5 hrs; electrical resistivity reported as 5.56 and 27 μohm cm at 4.2 and 293 K, respectively; Lorenz function in the residual resistance region found to be 3.17 x 10^{-8} V^2 K^{-2}; data taken from smoothed curve.
2	690	Jolliffe, B.W., Tye, R.P., and Powell, R.W.	1966	→	300		Predicted value-calculated from electrical resistivity value averaged from data of Spedding, F.H., et al. (Trans. AIME, 212, 379, 1958) and Curry, M.A., et al. (Phys. Rev., 117, 953, 1960), using the Lorenz number 3.36 x 10^{-8} V^2 K^{-2} based on the smoothed curve of Lorenz number vs atomic number given by the authors.
3	1170	Rao, K.V.	1967	L	1.2-4.2		0.02 other base metals and <0.1 other rare-earth metals; polycrystalline; specimen 1.5 mm in dia and 5 cm long; specific gravity 6.997 at 20 C; electrical resistivity ratio $\rho(298.2K)/\rho_0$ = 2.338; residual electrical resistivity 15.2 μohm cm; Lorenz function 3.345 x 10^{-8} V^2 K^{-2} at 4.2 K.
4	1181	Ratnalingam, R.	1970	L	0.5-4.0		Electrical resistivity 35.1 μohm cm at 295 K; residual electrical resistivity 15.76 μohm cm; electrical resistivity ratio $\rho(295K)/\rho_0$ = 2.23; thermal conductivity values calculated from the formula k = 1.46 T + 0.138 T^2 (mW cm^{-1} K^{-1}) given by author.

Yttrium

Although the data available for the thermal conductivity of yttrium cover a wide range of temperatures, some of the reported values appear to be unsatisfactory and others to relate to rather impure materials. A strong need therefore exists for further determinations to be made on pure samples of yttrium over a wide temperature range, even though the availability of the recent data of Tamarin, Chuprikov, and Shalyt [1387] (curves 7, 8) on two single crystal samples over the range from 2.6 to 161 K has slightly improved the situation [608].

At low temperatures, in the order of high to low conductivity, the data for $k_{\parallel}$ of Tamarin, et al. (curve 7), the data of Mamiya, Fukuroi, and Tanuma [878] (curves 2, 3), the data for $k_{\perp}$ of Tamarin, et al. (curve 8), and the data of Aliev and Volkenshtein [47] (curve 5) when plotted logarithmically lie on four well separated parallel straight lines. The respective electrical resistivity ratios, $\rho_{293\ K}/\rho_{4.2\ K}$, were 14.5, 13.0, 8.9, and 7.3, while the respective Lorenz functions around 4 or 5 K were 3.01, 2.65, 4.36, and 3.00 $\times$ 10^{-8} V^2 K^{-2}. This would suggest that the data of Mamiya, et al. are low and those for $k_{\perp}$ of Tamarin, et al. are high if the correct Lorenz function for all should be around 3.0 $\times$ 10^{-8} V^2 K^{-2}. The values of the anisotropy ratio, $k_{\parallel}/k_{\perp}$, of Tamarin, et al. are about 2.82 at 3 K, 2.42 at 20 K, 1.88 at 100 K, and 1.86 at 160 K. For the time being their data have been accepted as provisional values for single crystal yttrium up to 160 K. The provisional values for polycrystalline yttrium have been derived from the single-crystal values for $k_{\parallel}$ and $k_{\perp}$ assuming the value for the crystalline sample to be the mean of those given by equation (11) and equation (12).

At room temperature, the data of Legvold and Spedding [831] (curve 4) and of Jolliffe, Tye, and Powell [690] (curve 6) agree to within 10 percent. At higher temperatures the available data come from two sources and show considerable differences. A report by Lundin and Klodt [868] (curve 1), that attributes the thermophysical properties measurements to R. D. Seibel, contains thermal conductivity determinations on yttrium for the range 653 to 1153 K but gives no details of either the sample or test method. The Rare Metals Handbook, edited by Hampel [584], contains a table for the thermal conductivity of yttrium that covers the temperature range 225 to 811 K. These data are attributed to the General Electric Aircraft Nuclear Propulsion Department and the Battelle Memorial Institute Laboratories, and a source reference is given, but was not found to contain the original data.

The room temperature value quoted by Hampel is 64 percent below that of Jolliffe, et al. and presumably relates to a sample of much lower purity. This sample shows a much greater increase in thermal conductivity with increase in temperature than does that of Lundin and Klodt. At 811 K, its upper limit, the value is greater by 34 percent, and, since an increasing difference in thermal conductivity at high temperatures usually results from experimental error, an attempt has been made to assess the relaibility of these two sets of data. Jolliffe, et al. had reported an electrical resistivity of 53 $\mu\Omega$ cm and a Lorenz function of 2.9 $\times$ 10^{-8} V^2 K^{-2}. From these measurements the thermal conductivity can be regarded as the sum of an electronic component given by 2.443 $\times$ 10^{-8} T ρ^{-1} and a lattice component of 7.3 T^{-1}. Since no values have been located for the electrical resistivity of yttrium to high temperature, the temperature variation has been assumed to approximately parallel the curves of lanthanum and praesodymium as given by Kaye and Laby [723]. At 580 K, where the curves of Lundin and Klodt and of Hampel intersect, a value of 113 $\mu\Omega$ cm is derived for ρ, and the approximately parallel resistivity curve is drawn through this point. The value so derived at 293 K is 86 $\mu\Omega$ cm, which yields a total calculated thermal conductivity of 0.108 W cm^{-1} K^{-1}, which is only 7 percent above Hampel's tabulated value. This confirms the data of Hampel below 580 K to have approximately the expected temperature variation, but to apply to a rather impure sample. Above 580 K, similar checks indicate the Hampel curve to become increasingly too high and the Lundin and Klodt values also to apply to an impure sample and to err still more on the low side. By adopting the same method of calculation, but adjusting the electrical resistivity curve to pass through the value of 33.0 $\mu\Omega$ cm at 160 K which would yield a value for the thermal conductivity at 160 K same as that derived from $k_{\parallel}$ and $k_{\perp}$, the provisional curve for polycrystalline yttrium from 160 K to 1200 K has been obtained.

The provisional values are probably good to $\pm$10 percent near room temperature and $\pm$20 percent at other temperatures. The values below 100 K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having residual electrical resistivities of 2.30, 8.70, and 5.54 $\mu\Omega$ cm, respectively.

Table 180. Provisional thermal conductivity of yttrium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid						
	‖ to c-axis	⊥ to c-axis	Polycrystalline			
T	k	k	T	k	T	k
3	0.0389	0.0138	0	0	123.2	0.161
4	0.0526	0.0189	1	0.00648*	150	0.164
5	0.0662	0.0240	2	0.0133	173.2	0.165*
6	0.0795	0.0292	3	0.0203	200	0.166*
7	0.0927	0.0343	4	0.0274	223.2	0.168*
8	0.106	0.0395	5	0.0344	250	0.169*
9	0.119	0.0445	6	0.0416	273.2	0.170*
10	0.132	0.0497	7	0.0487	298.2	0.172*
11	0.144	0.0545	8	0.0528	300	0.172*
12	0.156	0.0594	9	0.0628	323.2	0.173*
13	0.167	0.0646	10	0.0697	350	0.175*
14	0.178	0.0695	11	0.0764	373.2	0.177*
15	0.188	0.0742	12	0.0832	400	0.180*
16	0.198	0.0787	13	0.0898	473.2	0.188*
18	0.214	0.0870	14	0.0963	500	0.192*
20	0.228	0.0943	15	0.102	573.2	0.201*
25	0.245	0.107	16	0.108	600	0.205*
30	0.248	0.115	18	0.119	673.2	0.213*
35	0.244	0.118	20	0.128	700	0.217*
40	0.238	0.121	25	0.142	773.2	0.226*
45	0.236	0.122	30	0.149	800	0.230*
50	0.236	0.124	35	0.151	873.2	0.239*
60	0.236	0.125	40	0.152	900	0.242*
70	0.237	0.126	45	0.153	973.2	0.249*
80	0.238	0.127	50	0.154	1000	0.250*
90	0.240	0.128	60	0.155	1073.2	0.254*
100	0.241	0.128	70	0.156	1100	0.255*
123.2	0.245	0.130	80	0.157	1173.2	0.255*
150	0.247	0.133	90	0.158		
160	0.248	0.133	100	0.159		

†The provisional values are for well-annealed high-purity yttrium, and those below 100K for $k_{\parallel}$, $k_{\perp}$, and k_{poly} are applicable only to specimens having $\rho_0 = 2.30$, 8.70, and 5.54 $\mu\Omega$ cm, respectively.

*Extrapolated or estimated.

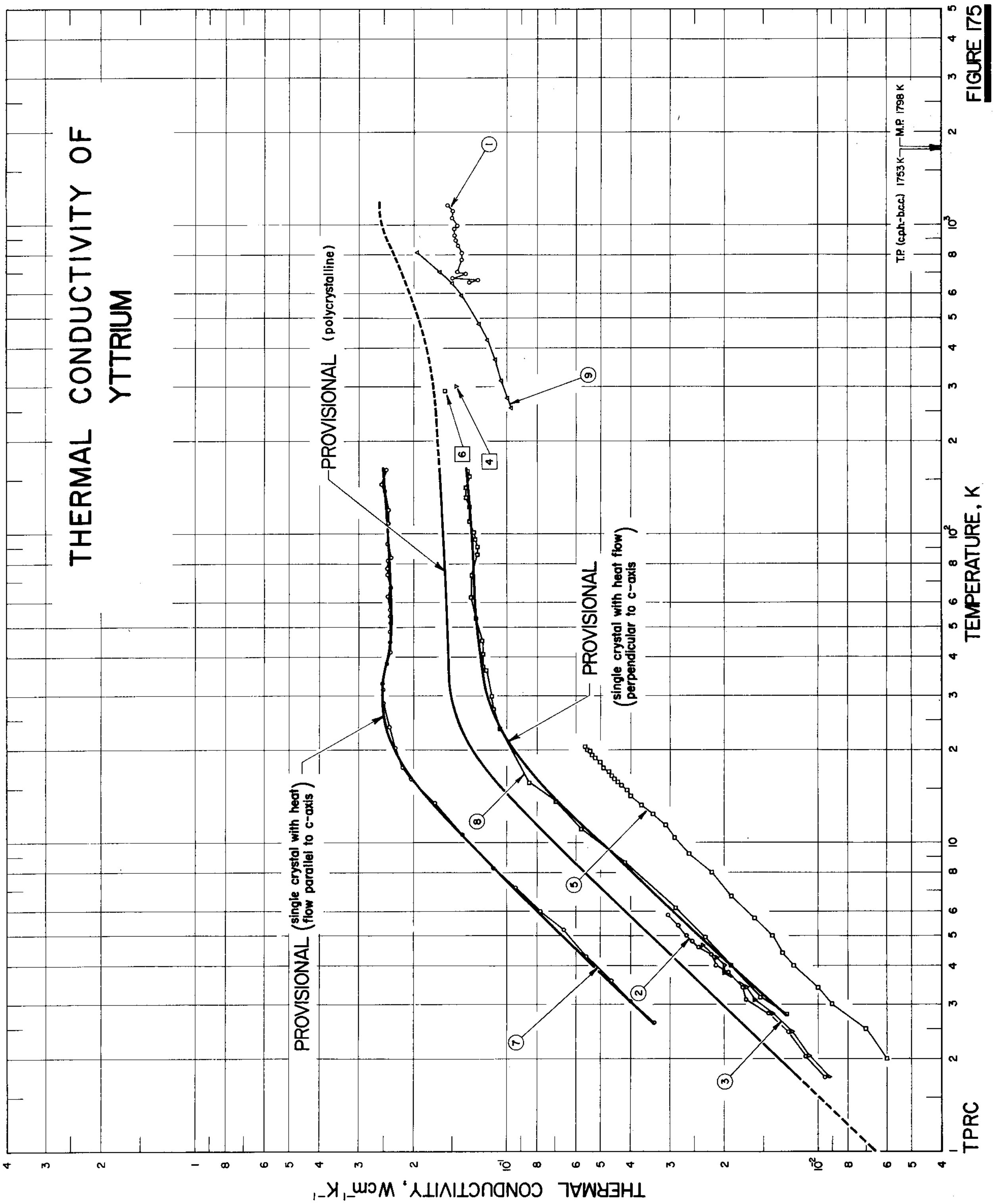

THERMAL CONDUCTIVITY OF YTTRIUM
FIGURE 175
PROVISIONAL (polycrystalline)
PROVISIONAL (single crystal with heat flow parallel to c-axis)
PROVISIONAL (single crystal with heat flow perpendicular to c-axis)
T.P. (cph-b.c.c.) 1753 K
M.P. 1798 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

TABLE 181. THERMAL CONDUCTIVITY OF YTTRIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	868	Lundin, C. E. and Klodt, D. T.	1959		653-1153		No details reported.
2	878	Mamiya, T., Fukuroi, T., and Tanuma, S.	1965	L	1.8-5.9		99.99 nominal purity; polycrystalline; machined from zone-refined ingot; annealed at 1150 C for 75 hrs; residual electrical resistivity in normal state (ρ at 4.2 K) = 5.10 μohm cm; electrical resistivity ratio $\rho(293K)/\rho(4.2K)$ = 13.0; Lorenz number $L_0 = 2.65 \times 10^{-8}\ V^2\ K^{-2}$.
3	878	Mamiya, T., et al.	1965	L	1.8-4.7		The above specimen measured in a magnetic field of 6600 gauss. (This was done for yttrium, a non-superconductor, in order to check the performance of the apparatus and method under magnetic field conditions, before making similar determinations on lanthanum.)
4	831	Legvold, S. and Spedding, F. H.	1954		301.2		No details given.
5	47	Aliev, N. G. and Volkenshtein, N. V.	1965		2.0-21		Approx 99.9 pure; flat specimen 0.25 mm thick; electrical resistivity 80 μohm cm at 293 K; electrical resistivity ratio $\rho(293K)/\rho(4.2K)$ = 7.3; Lorenz number $3.00 \times 10^{-8}\ V^2\ K^{-2}$ at 4.2 K.
6	690	Jolliffe, B. W., Tye, R. P., and Powell, R. W.	1966	C	291		~0.1 Ta, <0.1 other rare-earth metals, and ~0.03 other base metals; polycrystalline; specimen 0.63 cm in dia and 0.63 cm long; electrical resistivity 53 μohm cm at 291 K; data derived by the authors from measurements by 2 different thermal comparators.
7	1387	Tamarin, P. V., Chuprikov, G. E., and Shalyt, S. S.	1968	L	2.6-161	Sample 1	~0.15 O, ~0.12 N, ~0.01 Gd, ~0.002 Cu, ~0.001 Fe, <0.001 each of Dy, H, Ho, and Tb; single crystal; specimen 6 mm in dia and 60 mm long; grown without a crucible by zone melting in a vacuum of ~5×10^{-6} mm Hg; oriented parallel to the principal axis of the crystal; residual electrical resistivity 2.3 μohm cm; electrical resistivity ratio $\rho(293K)/\rho(4.2K)$ = 14.5; electrical conductivity reported as 4.41, 4.41, 4.41, 3.98, 3.77, 1.65, 1.49, 0.34, and 0.30 x 10^{5} ohm cm at 2.59, 3.08, 4.29, 15.3, 20.5, 70.1, 76.9, 279, and 306 K, respectively; Lorenz function reported as 3.01, 3.16, 3.22, 3.14, 2.87, 2.51, 2.31, 2.08, 1.98, 1.96, 1.99, 2.07, 2.16, 2.28, 2.35, 2.44, 2.51, 2.52, and 2.52 x $10^{-8}\ V^2\ deg^{-2}$ at 5.0, 9.7, 15.2, 20.8, 25.3, 30.7, 34.8, 40.9, 47.5, 54.2, 65.9, 77.5, 90.1, 105, 116, 125, 136, 146, and 156 K, respectively; heat flow along c-axis.
8	1387	Tamarin, P. V., et al.	1968	L	2.8-159	Sample 2	Single crystal; grown from the same material in the same dimensions by the same method as the above specimen; oriented perpendicular to the principal axis of the crystal; residual electrical resistivity 8.7 μohm cm; electrical resistivity ratio $\rho(293K)/\rho(4.2K)$ = 8.9; electrical conductivity reported as 1.16, 1.16, 1.04, 0.96, 0.47, 0.42, and 0.13 x $10^{5}\ ohm^{-1}\ cm^{-1}$ at 2.6, 4.3, 15.3, 20.4, 70.1, 79.4, and 303 K, respectively; Lorenz function reported as 4.36, 4.91, 5.00, 4.84, 4.58, 4.35, 4.19, 4.05, 3.97, 3.91, 3.83, 3.80, 3.78, 3.78, and 3.78 x $10^{-8}\ V^2\ deg^{-2}$ at 5.0, 16.1, 20.2, 25.4, 31.0, 36.2, 41.3, 48.1, 55.2, 63.7, 75.3, 87.0, 120, 137, and 154 K, respectively; heat flow perpendicular to c-axis.
9	584	Hampel, C. A.	1961		255-811		No details reported.

Zinc

The low-temperature thermal conductivity measurements on zinc single crystals are found to involve a difficulty that has not occurred with most other metals. The curves for $k_\perp$ and $k_\parallel$ appear to cross both above and below the temperature where the thermal conductivity is a maximum.

This behavior is noticed with curves 22 and 23. Both relate to measurements made by Mendelssohn and Rosenberg [938] on samples prepared from the same batch of 99.997 percent purity zinc. Sample No. 3 (curve 23) has the higher maximum, but gave lower values below about 7 K and above 27 K. This sample was a single crystal with the hexagonal axis at 13 degrees to the rod axis, and thus gave values approximating to $k_\parallel$. Sample No. 2 (curve 22), with the lower maximum, was a single crystal with the hexagonal axis at 80 degrees to the rod axis and so gave values that approximated to $k_\perp$. The data for another sample No. 4 (curve 34) with the hexagonal axis at 13 degrees to the rod axis measured by Rosenberg [1220] agree well with those for sample No. 3.

Goens and Grüneisen [502] had previously made measurements on four single crystals of zinc at temperatures of 21.2, 83.2, and 293.2 K (curves 41–44). From these measurements they derived values for $k_\parallel$ and $k_\perp$. Their values are given in the following table:

Values for ideal underformed zinc crystals parallel and perpendicular to the Hexagonal Axis as extrapolated by Goens and Grüneisen

T, K	$k_\perp$ W cm^{-1} K^{-1}	$k_\parallel$ W cm^{-1} K^{-1}	$k_\perp/k_\parallel$	$\rho_\perp$ $\mu\Omega$ cm	$\rho_\perp$ $\mu\Omega$ cm	$\rho_\parallel/\rho_\perp$
21.2	5.56	7.09	0.797	0.0366	0.0440	1.202
83.2	1.372	1.316	1.043	1.155	1.293	1.119
293.2	1.242	1.242	1.00	5.83	6.05	1.038

These thermal conductivity values seem to be consistent with those of Mendelssohn and Rosenberg at temperatures above T_m. Whereas $k_\parallel > k_\perp$ at 21.2 K, $k_\parallel < k_\perp$ at 83.2 K and the two thermal conductivity values agree at 293.2 K. The electrical resistivity values on the other hand show no similar cross-over. The electrical conductivity for the perpendicular direction exceeds that for the parallel direction at all three temperatures.

Zavaritskii [1601] has made thermal conductivity determinations on zinc single crystals at lower temperatures (curves 45–49). Zinc becomes superconducting at $T_{s.c.} = 0.825$ K* and he was mainly interested in the thermal conductivity of the superconducting state. He found $k_\perp > k_\parallel$ for the normal state at temperatures close to $T_{s.c.}$ as well as for the superconducting state. These findings are also in accord with Mendelssohn and Rosenberg's measurements.

These three sets of available measurements of the low-temperature thermal conductivity of zinc crystals are therefore self-consistent. They show a type of behaviour, however, that is quite incompatible with the treatment of Cezairliyan and Touloukian [250] which has often formed the basis for the evaluation of thermal conductivity values of metallic elements in this low-temperature region, and which with different values of β yields a family of non-intersecting curves.

Whilst this unusual behaviour appears to be reasonably well established, it requires explanation and calls for further experimental investigation. Since the electrical resistivity data of Goens and Grüneisen show no cross-over it seems likely that the explanation might be associated with a marked difference in the anisotropy of the electronic and lattice components of the thermal conductivity. There seems no reason why other non-cubic metals should not show similar departures from what has come to be regarded as normal behaviour.

Pending further information, it is considered ill-advisable to present any recommended curves for the thermal conductivity of single crystals of a well-behaved normal metal* such as zinc that cross one another, and, for the time being the recommendations for zinc will relate only to the polycrystalline form.

The highest low-temperature value is a single observation at 0.825 K reported by Zavaritskii [1601] (curve 47) for a single crystal of zinc having the hexagonal axis perpendicular to the direction of measurement. From this value the corresponding thermal conductivity of a polycrystalline sample has been derived, using the ratio $k_\perp/k_\parallel = 1.63$ obtained by Zavaritskii at this temperature for two other samples and using the relationship $k_{\text{poly}} = \frac{1}{3}(k_\parallel + 2k_\perp)$. This has been used to obtain a value of 0.0525 for β and to derive a curve for polycrystalline zinc in the normal state and up to about 8 K. This curve is only for a sample having $\rho_0 = 0.00128$ $\mu\Omega$ cm.

This treatment ignores the single crystal measurements by Rowe [1227] shown in curve 106. The author does not claim more than about ±10 percent accuracy at higher temperatures and regards the low-temperature values to be "at best rough estimates."

The derived curve is located well above most other low-temperature data and is continued to reach a value of about 1.3 W cm^{-1} K^{-1} at 84 K which conforms to the value indicated for polycrystalline zinc by the single crystal data of Goens and Grüneisen [502] (curves 41–44). It continues about 4 percent above the recent measurements by Wilkes [1557] (curve 58) for an unannealed specimen and shows the weak minimum at about 125 K and the gentle maximum around 230 K. In this region the recommended curve is in fair agreement with the early determinations of Lees [830] (curves 6, 7) and about 2 per-

* Given by Zavaritskii. Recent information $T_{s.c.} = 0.875$ K.

* As compared with the rare-earth metals, for instance.

cent below the mean value at 293 K of Goens and Grüneisen [502]. Above room temperature it decreases linearly to a value of 0.993 W cm^{-1} K^{-1} at the melting point, and lies within about ±3 percent of the data of Griffiths and Shakespear [542] (curve 104), and Shelton and Swanger [1302] (curves 50–52).

Mention should be made of the measurements on several single crystals at 330 K by Cinnamon [278] (curves 63–89). His absolute values of 1.068 and 1.009 W cm^{-1} K^{-1} for directions respectively perpendicular and parallel to the crystal axis are considered low, but the ratio for these two directions at 1.056 is probably acceptable.

A need exists for further measurements on polycrystalline zinc of the high purity now available. A more complete examination of the conducting properties of single crystals of zinc is also desirable.

There is also a very strong case for a redetermination of the thermal conductivity of molten zinc, although the position has been somewhat improved by the recently reported measurements of Dutchak and Panasyuk [383] (curve 56) and of Dutchak, et al. [382] (curve 107). Theirs are the third and fourth determinations made of the thermal conductivity of molten zinc. The earlier measurements of Konno [778] (curve 3) and Bidwell [158] (curve 8) had agreed closely with each other but posed problems when considered in the light of the electrical resistivity. Both workers obtained a negative temperature coefficient, whereas the thermal conductivity as derived by use of the theoretical value of the Lorenz function should have a strong positive coefficient. Also, the ratio of the two conductivities, thermal and electrical, for the solid and liquid states are far from comparable. The present recommended curve gives a thermal conductivity of 0.993 W cm^{-1} K^{-1} for solid zinc at the melting point. In the liquid state, if a mean line is fitted to the data of Konno and Bidwell, it yields a value at the same temperature of 0.60 W cm^{-1} K^{-1}. Hence the ratio $k_S/k_L = 1.66$ and this may be compared with a value of 2.2 as obtained by Roll and Motz [1217] for the ratio ρ_L/ρ_S.

The recent values of Dutchak and Panasyuk [383] (curve 56) and of Dutchak, et al. [382] (curve 107) for the thermal conductivity of molten zinc do show about the expected increase with increase in temperature, but are considered too high since they give a ratio k_S/k_L of only 1.71 and 1.83, respectively.

The solid line shown in figure 177 yields a ratio k_S/k_L of 2.0 and is regarded as being a more likely representation of the thermal conductivity of molten zinc. It is tentatively proposed, and clearly further experimental investigation is required.

The recommended values are thought to be accurate to within ±3 percent of the true values at moderate temperatures, ±5 percent at high temperatures, ±10 percent from 20 to 100 K, and ±15 percent below 20 K. The values at temperatures below 150 K are, of course, applicable only to a sample having $\rho_o = 0.00128$ $\mu\Omega$ cm. For molten zinc the values are provisional and are probably good to ±15 percent.

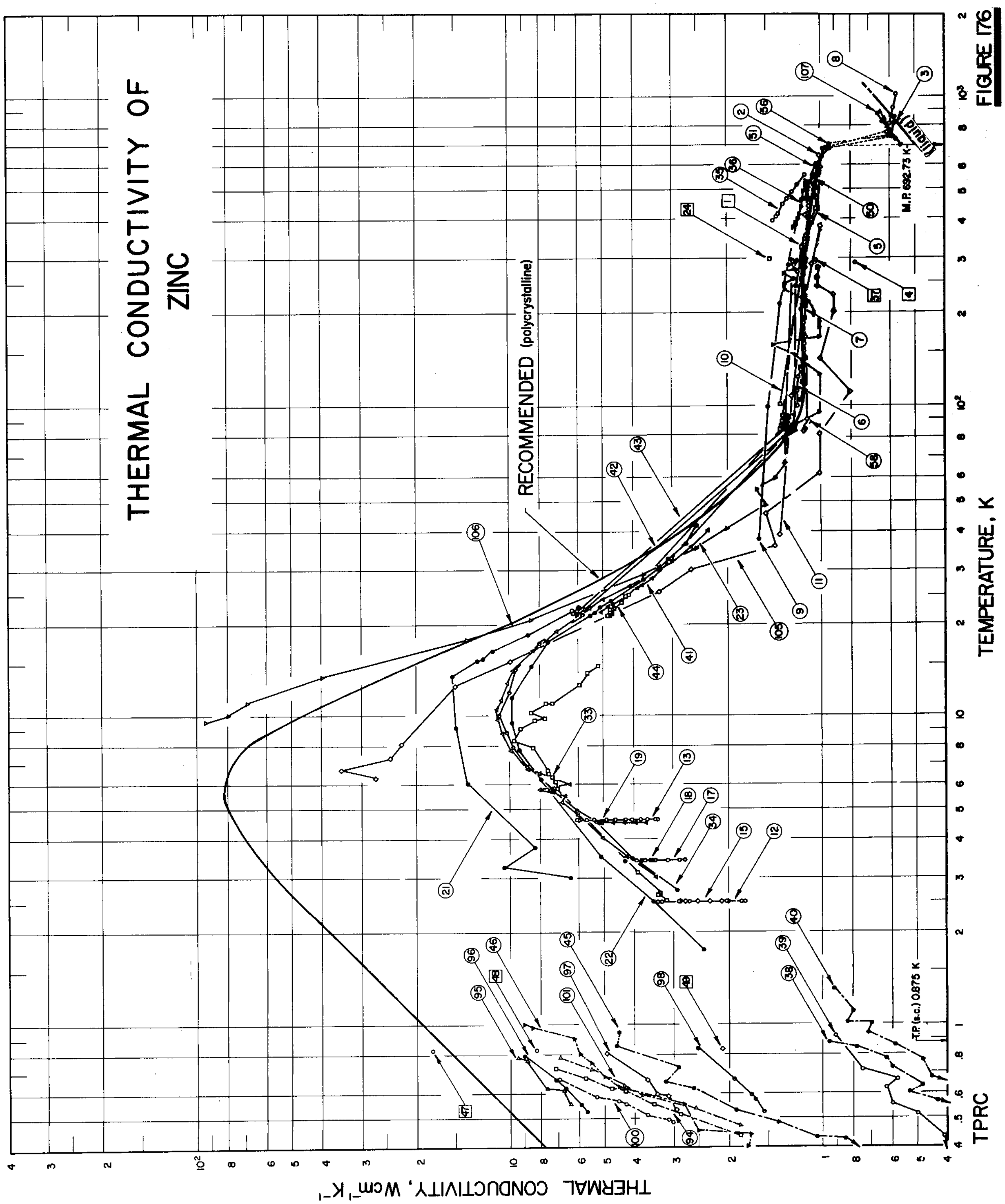
TABLE 182. Recommended thermal conductivity of zinc†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline				Liquid	
T	k	T	k	T	k
0	0	60	1.65	692.73	0.495*
1	19.0	70	1.43	700	0.499*
2	37.9	80	1.30	773.2	0.542
3	55.8	90	1.22	800	0.557
4	70.9	100	1.17	873.2	0.599
5	80.7	123.2	1.16	900	0.615
6	83.1	150	1.17	973.2	0.657
7	78.7	173.2	1.17	1000	0.673
8	69.7	200	1.18	1073.2	0.715*
9	58.0	223.2	1.18	1100	0.730*
10	47.3	250	1.18		
11	38.8	273.2	1.17		
12	31.9	298.2	1.16		
13	26.5	300	1.16		
14	22.4	323.2	1.15		
15	19.2	350	1.14		
16	16.6	373.2	1.12		
18	12.7	400	1.11		
20	9.98	473.2	1.08		
25	6.26	500	1.07		
30	4.42	573.2	1.04		
35	3.42	600	1.03		
40	2.80	673.2	1.00		
45	2.36	692.73	0.993		
50	2.05				

†The values are for well-annealed high-purity zinc, and those below 150 K are applicable only to a specimen having $\rho_o = 0.00128$ $\mu\Omega$ cm. The values for molten zinc are provisional.

*Extrapolated.


THERMAL CONDUCTIVITY OF ZINC
RECOMMENDED (polycrystalline)
M.P. 692.73 K
(liquid)
T.P.(s.c.) 0.875 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC
FIGURE 176

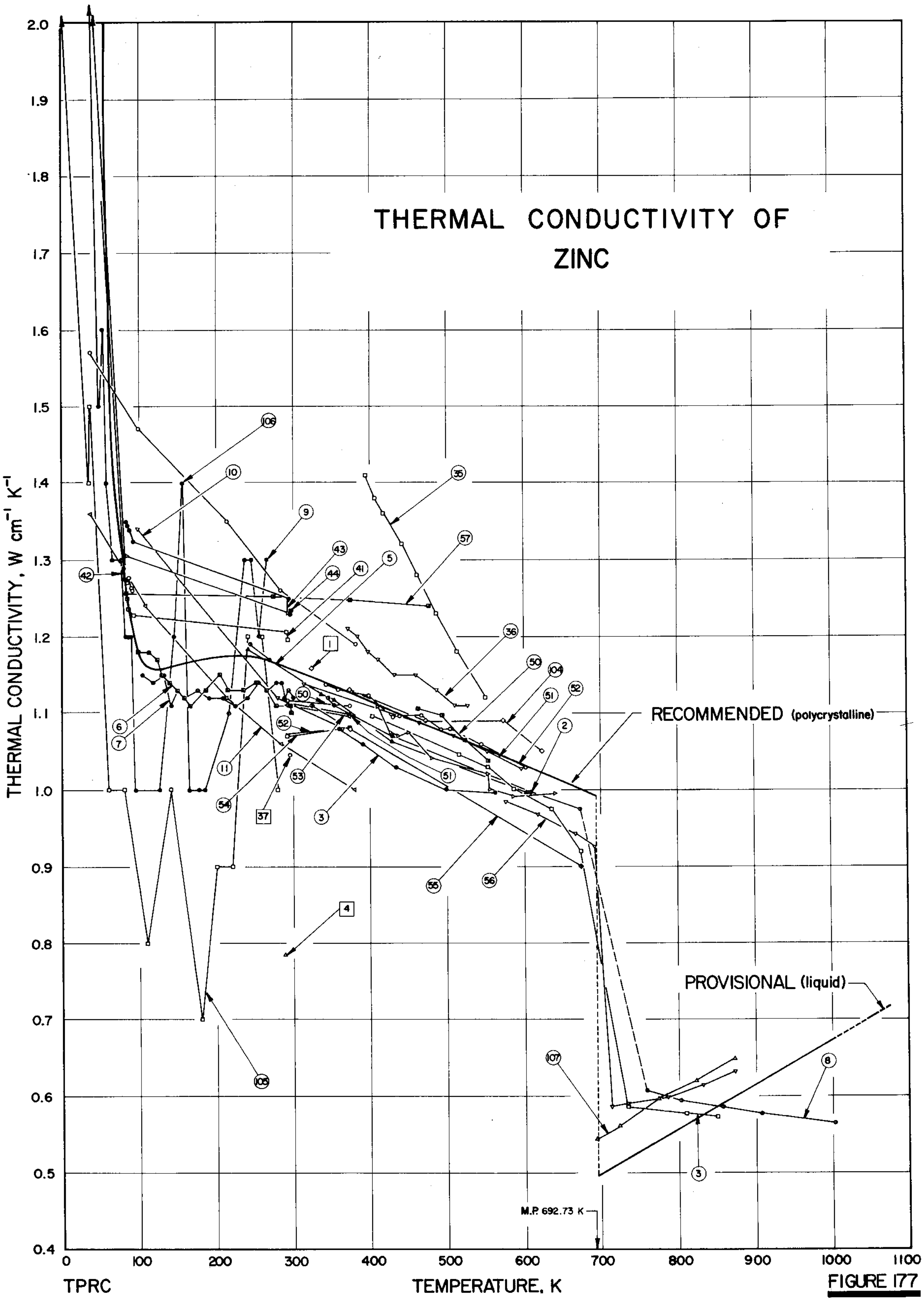

THERMAL CONDUCTIVITY OF
ZINC
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TEMPERATURE, K
RECOMMENDED (polycrystalline)
PROVISIONAL (liquid)
M.P. 692.73 K
TPRC
FIGURE 177

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur.	Ref.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1327	Smith, A. W.	1925	L	323		99.97$^+$ pure; Baker's analyzed metal; cylindrical specimen 10 cm long, 1.9 cm in dia; electrical conductivity at 22 C being 17.0 x 10^4 ohm^{-1} cm^{-1}.
2	106	Bailey, L. C.	1931	L	409-640		"Pure redistilled zinc"; cylindrical specimen of 0.585 cm dia; fracture crystalline with crystals radiating from axis of rod; density 7.10 g cm^{-3} at 21 C; the same specimen used by Lees in 1908 (curve 6).
3	778	Konno, S.	1919	L	402-851		Measured in both solid and liquid states.
4	869	Lussana, S.	1918	L	288.4		Specimen radius 0.685 cm; furnished by the manufacturer Erba.
5	1267	Schofield, F. H.	1925	L	361-562		99.8 pure; obtained from London Zinc Mills; cast from billets, rolled at 200 C, sawed into strips and drawn cold; density 7.13 g cm^{-3} at 21 C; electrical resistivity reported as 6.08, 8.09, 10.48 and 14.50 μohm cm at 35, 105, 200, and 350.2 C, respectively.
6	830	Lees, C. H.	1908	L	99-297		Pure; turned from a cast stick of "pure redistilled zinc"; fracture crystalline with crystals radiating from the axis of rod; cylinder about 7 cm long and 0.585 cm in dia; density 7.1 g cm^{-3} at 21 C; electrical resistivity reported as 1.699, 1.96, 3.26, 3.69, 4.32, 5.36, 6.30, 6.99, 7.14, and 8.01 μohm cm at -180.3, -168.4, -116.3, -99.7, -70.1, -24.7, 16.7, 47.8, 54.3, and 90.3 C, respectively; first experiment.
7	830	Lees, C. H.	1908	L	104-300		Second experiment of the above specimen.
8	158	Bidwell, C. C.	1939	F	243-1003		Specimen 4.5 cm in dia, 20-25 cm long used to find data in the solid state; for the liquid state molten zinc contained in a graphite cylinder to form a specimen 25 cm long and 4 cm in dia.
9	161	Bidwell, C. C. and Lewis, E. J.	1929	F	37-381		99.993 Zn, 0.005 Fe, and 0.0018 Cd; single crystal; obtained from the Bureau of Standards; melted in an evacuated glass tube, lowered from the furnace at the rate of 1 cm h^{-1}; heat flow parallel to the basal plane.
10	161	Bidwell, C. C. and Lewis, E. J.	1929	F	98-434	No. 2	Same composition and supplier as the above specimen; polycrystalline; cast in vacuo in a graphite mold.
11	161	Bidwell, C. C. and Lewis, E. J.	1929	F	38-380	No. 1	Similar to above but cast in open air.
12	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5	Zn 2	99.997 pure; single crystal; 1-2 mm dia x 5 cm long; obtained from Imperial Smelting Corp; specimen axis at 80° with the hexagonal axis; measured in transverse magnetic fields with strength H ranging from 0.17 to 3.73 kilooersteds.
13	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Zn 2	The above specimen measured in transverse magnetic fields with strength H ranging from 0.17 to 3.73 kilooersteds.
14*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.6	Zn 2	The above specimen measured in longitudinal magnetic fields with strength H ranging from 0.17 to 3.73 kilooersteds.
15	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5	Zn 4	Similar to the above specimen but rod axis at 13° with the hexagonal axis; measured in transverse magnetic fields with strength ranging from 0.36 to 3.59 kilooersteds.
16*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	2.5	Zn 4	The above specimen measured in longitudinal magnetic fields with strength ranging from 0.36 to 3.50 kilooersteds.

* Not shown in figure.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
17	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.4	Zn 4	The above specimen measured in transverse magnetic fields with strength ranging from 0.36 to 3.59 kilooersteds.
18	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	3.4	Zn 4	The above specimen measured in longitudinal magnetic fields with strength ranging from 0.36 to 3.75 kilooersteds.
19	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.5	Zn 4	The above specimen measured in transverse magnetic fields with strength ranging from 0.36 to 3.90 kilooersteds.
20*	938	Mendelssohn, K. and Rosenberg, H. M.	1953	L	4.5	Zn 4	The above specimen measured in longitudinal magnetic fields with strength ranging from 0.36 to 3.85 kilooersteds.
21	938	Mendelssohn, K. and Rosenberg, H. M.	1952	L	3.0-23	Zn 1	99.9995 pure; polycrystalline; 1-2 mm dia x 5 cm long; provided by Hilger; H. S. brand (HS 8392); annealed in evacuated quartz tube for several hrs at two-thirds the melting point.
22	938	Mendelssohn, K. and Rosenberg, H. M.	1952	L	1.8-41	Zn 2	99.997 pure; single crystal; 1-2 mm dia x 5 cm long; provided by Imperial Smelting Corp; hexagonal axis at 80° to the specimen axis; annealed as the above specimen.
23	938	Mendelssohn, K. and Rosenberg, H. M.	1952	L	3.0-40	Zn 3	Similar to the above specimen but hexagonal axis at 13° to the specimen axis.
24	210	Bridgman, P. W.	1926	L	298.2		6 mm dia x 10 cm long; single crystal; crystal axis inclined to specimen axis at 86.5°; obtained from Kahlbaum; cast; electrical resistivity 5.911 μohm cm at room temp; reported value uncorrected for heat losses.
25*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 5.912 μohm cm at room temp and the crystal axis inclined to specimen axis at a smaller angle.
26*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 5.918 μohm cm at room temp and the crystal axis inclination still smaller.
27*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 5.965 μohm cm at room temp and the crystal axis inclination still smaller.
28*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 6.009 μohm cm at room temp and the crystal axis inclination still smaller.
29*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 6.012 μohm cm at room temp and the crystal axis inclination still smaller.
30*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 6.057 μohm cm at room temp and the crystal axis inclination still smaller.
31*	210	Bridgman, P. W.	1926	L	298.2		Similar to above but electrical resistivity 6.063 μohm cm at room temp and the crystal axis inclination decreased to 33°.
32*	1416	Todd, G. W.	1927	C	298.2		8.34 mm dia rod; copper used as comparative material; thermal conductivity obtained by comparing thermal expansion of the materials. (Measuring temp assumed 25 C.)
33	1222	Rosenberg, H. M.	1957	L	2.5-14	Zn 2	99.997 pure; single crystal, with the hexagonal axis at 80° to specimen axis; supplied by Imperial Smelting Corp.

* Not shown in figure.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
34	1220	Rosenberg, H. M.	1955	L	2.7-21	Zn 4	99.997 pure; single crystal with the hexagonal axis at 13° to specimen axis; obtained from Imperial Smelting Corp; 2.75 cm x 0.0234 cm^2.
35	969	Mikryukov, V. E. and Rabotnov, S. N.	1944	E	394-550		Single crystal; electrical resistivity reported as 8.32, 8.88, 9.59, 10.10, 10.85, 11.53 and 12.66 μohm cm at 121.1, 143.9, 169.6, 188.4, 213.8, 238.9, and 277.1 C, respectively.
36	969	Mikryukov, V. E. and Rabotnov, S. N.	1944	E	371-529		Polycrystal; electrical resistivity reported as 8.22, 9.09, 9.45, 10.19, 11.04, 11.85, 12.70, and 13.19 μohm cm at 97.9, 111.2, 137.6, 159.4, 186.4, 213.6, 247.1 and 255.8 C, respectively.
37	1065	Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L.	1961	P	295.2		Pure; specimen size 1.9 x 1.16 x 0.282 cm; thermal conductivity value calculated from measured thermal diffusivity using data of specific heat and density taken from Smithsonian Physical Tables (9th ed., 1954).
38	1599	Zavaritskii, N. V.	1958	L	0.14-0.87	Zn 1	0.0001 impurity; single crystal; ~1.5 mm in dia and 100 mm long; specimen axis at an angle of 30° to the [001] direction; measured in a magnetic field of 0.2 oersted; in superconducting state.
39	1599	Zavaritskii, N. V.	1958	L	0.18-0.91	Zn 1	The above specimen measured in a longitudinal magnetic field of 60 oersteds; in normal state.
40	1599	Zavaritskii, N. V.	1958	L	0.22-1.3	Zn 2	Similar to the above specimen but measured in a magnetic field of 0.2 oersted; in superconducting state.
41	502	Goens, E. and Grüneisen, E.	1932	L	22-293	Zn 61	Single crystal; specimen 5.27 cm long, area of cross section 0.0552 cm^2; angle between specimen axis and hexagonal axis $\theta = 3.6°$; electrical resistivity reported as 0.0674, 1.331, 5.69, and 6.16 μohm cm at -252, -190, 0, and 20 C, respectively.
42	502	Goens, E. and Grüneisen, E.	1932	L	21-92	Zn 100	Single crystal; $\theta = 4.9°$; electrical resistivity reported as 0.056, 1.333, 5.72, and 6.20 μohm cm at -252, -190, 0, and 20 C, respectively.
43	502	Goens, E. and Grüneisen, E.	1932	L	21-293	Zn 72	Single crystal; specimen 6.13 cm long, area of cross section 0.0634 cm^2; $\theta = 8.7°$; electrical resistivity reported as 0.0522, 1.3, 5.58, and 6.05 μohm cm at -252, -190, 0, and 20 C, respectively.
44	502	Goens, E. and Grüneisen, E.	1932	L	21-296	Zn 101	Single crystal; specimen 4.94 cm long, area of cross section 0.0623 cm^2; $\theta = 79.7°$; electrical resistivity reported as 0.0524, 1.179, 5.43, and 5.88 μohm cm at -252, -190, 0, and 20 C, respectively.
45	1601	Zavaritskii, N. V.	1960	L	0.10-0.94	Zn 4	Single crystal; grown along the principal crystallographic direction by Kapitza's method; superconducting transition point 0.825 K; heat flow parallel to the hexagonal axis; in superconducting state.
46	1601	Zavaritskii, N. V.	1960	L	0.10-1.00	Zn 7	Similar to above but heat flow perpendicular to the hexagonal axis; in superconducting state.
47	1601	Zavaritskii, N. V.	1960	L	0.825	Zn 1	Similar to above.
48	1601	Zavaritskii, N. V.	1960	L	0.825	Zn 2	Similar to above.
49	1601	Zavaritskii, N. V.	1960	L	0.825	Zn 5	Similar to above but heat flow parallel to the hexagonal axis.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
50	1302	Shelton, S. M. and Swanger, W. H.	1933	C	462-553	Z. S.	99.9$^+$ Zn, 0.04 Pb, and 0.02 Fe; 2 cm dia x 15 cm long; specimen prepared by remelting commercially pure zinc and casting in graphite mold; lead used as comparative material (reference taken from International Critical Tables, Vol V, p. 221: 0.352 Watt cm^{-1} C^{-1} at 0 C).
51	1302	Shelton, S. M. and Swanger, W. H.	1933	C	313-596	Z. S.	Similar to the above specimen except commercial malleable nickel used as the indirect comparative material (based on the data of lead).
52	1302	Shelton, S. M. and Swanger, W. H.	1933	C	342-602	Z. S.	Similar to that of the above specimen except zinc used as the indirect comparative material (based on the data of lead).
53	664	Jaeger, W. and Diesselhorst, H.	1900	L	291, 373	Zinc II	99.97 Zn (by difference), 0.01 Cd, 0.01 Fe, and 0.01 Pb; specimen 27 cm long and 1.805 cm in dia; density 7.11 g cm^{-3}; electrical conductivity reported as 16.51 and 12.59 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively.
54	664	Jaeger, W. and Diesselhorst, H.	1900	L	291, 373	Zinc II, wire	Similar to the above specimen but drawn to a wire with electrical conductivity reported as 15.98 and 12.42 x 10^4 ohm^{-1} cm^{-1} at 18 and 100 C, respectively. Thermal conductivity values derived on the assumption that a corresponding change has occurred.
55	74	Angell, M. F.	1926	R	323, 673		Specimen in the form of a hollow cylinder.
56	383	Dutchak, Ya. I. and Panasyuk, P. V.	1966	C	576-874		Molten specimen placed in a hole 21 mm in dia drilled in an asbestos cement cylinder of 30 mm height; 1Kh 18N9T steel used as comparative material.
57	1358	Staebler, J.	1929	L	83-476		Prepared by melting pure zinc supplied by Firma Kahlbaum in a quartz tube, then quickly solidified in cool water; electrical resistivity reported as 1.658, 5.663, 7.837, and 10.36 μohm cm at 83.2, 273, 374, and 476 K, respectively.
58	1557 1559	Wilkes, K. E. Wilkes, K. E., Powell, R. W., and DeWitt, D. P.	1968	L	82-381		99.999 Zn, impurities 0.0001 each of Cd, Cu, Fe, Pb, Mg, Si, and Ag; 1.207 cm dia x 10.16 cm long; obtained from American Smelting and Refining Corp; density 7.130 g cm^{-3} at 24.5 C; electrical resistivity reported as 1.187, 3.745, 5.559, and 6.129 μohm cm at 77.80, 194.7, 273.2, and 300.9 K, respectively; Lorenz function reported as 1.700, 1.886, 2.178, and 2.328 x 10^{-8} V^2 K^{-2} at 70.2, 100, 200, and 299 K, respectively; measured in a vacuum of 5 x 10^{-6} torr.
59*	492	Girton, W. Z. and Potter, J. H.	1951	R	331.4		Powdered specimen of approx spherical particles with grain size distribution 34 of <1 μ, 42 of 1-3 μ, 18 of 3-5 μ, and 6 of >5 μ; powder packed between two concentric cylinders of 1 in. and 3 in. in dia and 6 in. long, with two transite spiders 2 in. apart placed in the central section as the test cell; apparent density 2.45 g cm^{-3}.
60*	492	Girton, W. Z. and Potter, J. H.	1951	R	330.8		Similar to above but apparent density 2.44 g cm^{-3}.
61*	492	Girton, W. Z. and Potter, J. H.	1951	R	331.0		Similar to above but apparent density 2.46 g cm^{-3}.
62*	492	Girton, W. Z. and Potter, J. H.	1951	R	331.1		Similar to above but apparent density 2.45 g cm^{-3}.
63*	278	Cinnamon, C. A.	1934	L	330.2		99.99$^+$ Zn, 0.0047 Pb, 0.0008 Cd, 0.0004 Fe, 0.002$^+$ Cu, and trace Ag; single crystal; original material taken from a single 50 lb slab of "Evanwall" zinc; specimen 30 cm long with a trapezoidal cross section of 1.24 cm^2 in area; $\cos^2\theta = 0.001$ (θ = the angle between the normal to the basal cleavage plane and the specimen axis).

* Not shown in figure.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
64*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained by placing it horizontally on two supports 10 cm apart, pushed at midpoint down to a depression of 0.079 cm, straightened, similarly bent in the opposite direction the same amount and again straightened.
65*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen annealed at 380 C for 11 hrs.
66*	278	Cinnamon, C. A.	1934	L	330.2		Grown from material taken from the same slab as the above specimen; $\cos^2\theta = 0.016$.
67*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.022$.
68*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.174$.
69*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.257$.
70*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained to a depression of 0.114 cm at the midpoint in the same manner as before (see curve No. 64).
71*	278	Cinnamon, C. A.	1934	L	330.2		Grown from material taken from the same slab as above; $\cos^2\theta = 0.331$.
72*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.514$.
73*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained to a depression of 0.125 cm at the midpoint in the same manner as before (see curve No. 64).
74*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen annealed at 380 C for 11 hrs.
75*	278	Cinnamon, C. A.	1934	L	330.2		Grown from material taken from the same slab as above; $\cos^2\theta = 0.712$.
76*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.815$.
77*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.990$.
78*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.993$.
79*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2\theta = 0.996$.
80*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained to a depression of 0.013 cm at the midpoint in the same manner as before (see curve No. 64).
81*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen annealed at 380 C for 11 hrs.
82*	278	Cinnamon, C. A.	1934	L	330.2		Schilling's type B optically mosaic crystal on most part but normal at one end; grown from the same allotment as the above specimen under similar conditions; $\cos^2\theta = 0.132$.
83*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained in the same manner as before (see curve No. 64).
84*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen annealed at 380 C for 11 hrs.
85*	278	Cinnamon, C. A.	1934	L	330.2		Schilling's type C optically mosaic crystal; grown from the same allotment as the above specimen under similar conditions; $\cos^2\theta = 0.9116$.
86*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen strained in the same manner as before (see curve No. 64).
87*	278	Cinnamon, C. A.	1934	L	330.2		The above specimen annealed at 380 C for 11 hrs.

* Not shown in figure.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
88*	278	Cinnamon, C. A.	1934	L	330.2		Schilling's type A optically mosaic crystal; grown from a cast rod taken from a different lot of Evanwall than the above specimens under somewhat different conditions; $\cos^2 \theta = 0.938$.
89*	278	Cinnamon, C. A.	1934	L	330.2		Similar to above but $\cos^2 \theta = 0.940$.
90*	278	Brown, H. M.	1928	E	312.8		Specimen 10 cm long with a cross-section area 0.861 cm^2; electrical resistivity 5.622 μohm cm at 39.55 C; no changes in thermal conductivity and electrical resistivity observed during the application of magnetic fields of 10 000 gauss in longitudinal and 8000 gauss in transverse direction.
91*	278	Brown, H. M.	1928	E	293.2		Single crystal; 10 cm long with an elliptical cross section 0.0807 cm^2 in area; grown in a glass tube by slowly cooling from the lower end upward at a rate of 2 cm hr^{-1}; electrical resistivity 5.474 μohm cm at 20 C; no changes in thermal conductivity and electrical resistivity observed during the application of magnetic fields of 10 000 gauss in longitudinal and 8000 gauss in transverse direction.
92*	495	Glage, G.	1905	P	323.2		Rod specimen 20-50 cm long; thermal conductivity value calculated from measured thermal diffusivity with density and specific heat capacity data taken from Kohlrausch, F. (Praktischer Physik, 9th ed., 1901).
93*	495	Glage, G.	1905	P	323.2		Similar to above but specimen in ring shape.
94	300, 301	Cotignola, J. M., de la Cruz, F., de la Cruz, M. E., and Platzeck, R. P.	1967	L	0.44-0.72		99.999 pure; effective form ratio $A/\ell = 1.30 \times 10^{-4}$ cm; cut from a bar, rolled down to 0.12 mm thick, polished chemically to 0.1 mm thick; in superconducting state.
95	300, 301	Cotignola, J. M., et al.	1967	L	0.55-0.78		The above specimen measured in a magnetic field of 40 Oe.
96	300, 301	Cotignola, J. M., et al.	1967	L	0.52-0.79		The above specimen measured in a magnetic field of 80 Oe.
97	300, 301	Cotignola, J. M., et al.	1967	L	0.53-0.80		The above specimen measured in a magnetic field of 600 Oe.
98	300, 301	Cotignola, J. M., et al.	1967	L	0.52-0.84		The above specimen measured in a magnetic field of 1300 Oe.
99*	300, 301	Cotignola, J. M., et al.	1967	L	0.52-0.74		The above specimen measured in a magnetic field of 5000 Oe.
100	300, 301	Cotignola, J. M., et al.	1967	L	0.47-0.72		The above specimen measured with magnetic field removed; in superconducting state.
101	300, 301	Cotignola, J. M., et al.	1967	L	0.47-0.78		Same as above.
102*	300, 301	Cotignola, J. M., et al.	1967	L	0.45-0.72		Same as above.
103*	300, 301	Cotignola, J. M., et al.	1967	L	0.12-0.26		Cut from the same bar as the above specimen; effective form factor $A/\ell = 1.72 \times 10^{-3}$ cm; same fabrication method as above; in superconducting state.
104	542	Griffiths, E. and Shakespear, G. A.	1921	L	373-623		99.95 pure rod specimen.
105	1227	Rowe, V. A.	1967	L	6.3-279		99.9999 pure; single crystal; specimen cross-section area 0.0466 cm^2 and 7.391 cm long; supplied by Alfa Inorganics; electrical resistivity ratio $\rho(297K)/\rho(4.2K) = 2600$; heat flow perpendicular to c-axis; measured in a vacuum of 5×10^{-6} mm Hg.

* Not shown in figure.

TABLE 183. THERMAL CONDUCTIVITY OF ZINC - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
106	1227	Rowe, V.A.	1967	L	11-274		99.999 pure; single crystal; specimen cross-sectional area 0.0469 cm^2 and 5.59 cm long; supplied by Research Crystals, Incorp, Richmond, Virginia; electrical resistivity ratio = 15000; heat flow parallel to c-axis; measured in a vacuum of 5×10^{-6} mm Hg.
107	382	Dutchak, Ya.I., Osipenko, V.P., Panasyuk, P.V., and Stets'kiv, O.P.	1968	C	693-873		Liquid specimen contained in an asbestos cement ring; 1Kh 18N9T steel used as comparative material.

Zirconium

The recommended thermal conductivity values at low temperatures for a polycrystalline sample having $\rho_0 = 0.218\ \mu\Omega$ cm are based on the measurements of White and Woods [1554] (curves 14, 15), and, using a value of $\beta = 8.93$, the values were derived to about 20 K. An extension of this curve passes through the data of White and Woods near 90 K, but at higher temperatures considerable uncertainties arise. In the temperature range 94 to 273 K the only determination available is at 121 K. This is the uppermost point due to White and Woods where radiation corrections could lead to some uncertainty. From 298 to about 900 K several sets of experimental data are available; these are consistent in indicating the thermal conductivity versus temperature curve to have a minimum within this range, but this is about the limit of their consistency. The minimum value ranges from about 0.170 to 0.245 W cm^{-1} K^{-1}. Mikryukov [963] obtained this highest value (curve 11) for a 99.9 percent sample of iodide zirconium which is seen to have an unusually low electrical resistivity. Indeed, the quoted value of 36.1 $\mu\Omega$ cm at 331 K (which extrapolates to about 26 $\mu\Omega$ cm at 273 K) has to be compared with Treco's 273 K value of 38.8 $\mu\Omega$ cm [1427], which is the next lowest value reported for zirconium. Treco obtained his value for an oxygen-free high-purity zirconium and found the 273 K resistivity to increase to 57.7 $\mu\Omega$ cm at 2.5 atomic percent of oxygen. As zirconium is a metal that readily combines with oxygen, this seems a factor which could help in explaining some of the conductivity differences. Since zirconium has a hexagonal crystal structure below about 1135 K, another contributing factor could be the varying degrees of preferred orientation. No definite information appears to be available, however, regarding the anisotropy of the thermal conductivity of zirconium.

At high temperatures the three sets of data available for the thermal conductivity again differ considerably. That of Timrot and Peletskii [1411] (curve 20) appears to be much too low in its lower temperature range, for, at 1200 K, use of the electrical resistivity value of 117 $\mu\Omega$ cm [1419] leads to a Lorenz function of only 2.0×10^{-8} V^2 K^{-2}, while that of Jain, et al. [674] (curve 58) appears to be much too high in its higher temperature range.

Over the range 331 to 898 K the mean Lorenz function reported by Mikryukov [963] from his measurements on two samples decreases from 3.42×10^{-8} to 3.11×10^{-8} V^2 K^{-2} whilst that of Powell and Tye [1134] for three samples at 323 K is 3.10×10^{-8} V^2 K^{-2}, decreasing to 2.73×10^{-8} V^2 K^{-2} at 823 K for two samples. Bing, et al. [162] for three samples reported mean values of 3.14×10^{-8} V^2 K^{-2} at 323 K and 2.84×10^{-8} V^2 K^{-2} at 523 K.

Zirconium is clearly a metal that requires considerably more experimental investigation before any very firm recommendation about its thermal conductivity is possible.

For the present a smooth curve showing a steadily decreasing rate of fall of thermal conductivity has been drawn from the value of 0.35 W cm^{-1} K^{-1} at 90 K to 0.232 W cm^{-1} K^{-1} at 273 K, the latter value having been derived from Treco's electrical resistivity and a Lorenz function close to the mean value indicated by the three sets of measurements last mentioned. This value lies 4 percent above the lowest-temperature value of the smooth curve obtained by Moss [1000] (curve 7) from his experimental data for nominally high-purity zirconium, and the curve now proposed continues about this amount above Moss's curve. It crosses the curve of Fieldhouse and Lang [431] (curve 9) at about 1020 K and 1660 K and lies within some 3 percent of their curve to its highest temperatures of 1925 K.

As with titanium but at about 1135 K, the true curve of thermal conductivity of zirconium could be expected to undergo a discontinuous change due to the α to β phase transformation. The electrical resistivity has been found to undergo a drop of about 14 percent in this region, but the only thermal conductivity measurements which extend above and below this region, those of Fieldhouse and Lang, show no comparable increase in thermal conductivity, but possibly a decrease in slope. Hence the proposed curve has been drawn with no discontinuity, but this is clearly another aspect of the thermal conductivity of zirconium requiring further investigation.

The proposed curve may represent the thermal conductivity of high-purity polycrystalline zirconium to about ± 10 percent at temperatures below 800 K, the uncertainty increasing to ± 20 to ± 25 percent as the melting point is approached. At temperatures below 200 K the tabulated values are, of course, only applicable to a sample having $\rho_0 = 0.218\ \mu\Omega$ cm.

Predictions could be made with more certainty at high temperatures if the electrical resistivity determinations were extended to temperatures above the present upper limit of about 1280 K.

TABLE 184. Recommended thermal conductivity of zirconium†

(Temperature, T, K; Thermal Conductivity, k, W cm^{-1} K^{-1})

Solid Polycrystalline			
T	k	T	k
0	0	373.2	0.218
1	0.112*	400	0.216
2	0.224*	473.2	0.211
3	0.335	500	0.210
4	0.444	573.2	0.207
5	0.551	600	0.207
6	0.653	673.2	0.208
7	0.750	700	0.209
8	0.839	773.2	0.213
9	0.918	800	0.216
10	0.988	873.2	0.223
11	1.05	900	0.226
12	1.09	973.2	0.234
13	1.13	1000	0.237
14	1.15	1073.2	0.246
15	1.16	1100	0.249
16	1.16	1173.2	0.257
18	1.13	1200	0.260
20	1.08	1273.2	0.267
25	0.906	1300	0.270
30	0.761	1373.2	0.277
35	0.663	1400	0.279
40	0.590	1473.2	0.286
45	0.538	1500	0.288
50	0.497	1573.2	0.295
60	0.442	1600	0.297
70	0.402	1673.2	0.303
80	0.374	1700	0.306
90	0.350	1773.2	0.312
100	0.332	1800	0.314
123.2	0.302	1873.2	0.320
150	0.278*	1900	0.322
173.2	0.265*	1973.2	0.328
200	0.252*	2000	0.330
223.2	0.245*		
250	0.237*		
273.2	0.232*		
300	0.227		
323.2	0.224		
350	0.221		

†The recommended values are for well-annealed high-purity polycrystalline zirconium, and those below 200 K are applicable only to a specimen having $\rho_0 = 0.218$ $\mu\Omega$ cm.

*Extrapolated or interpolated.

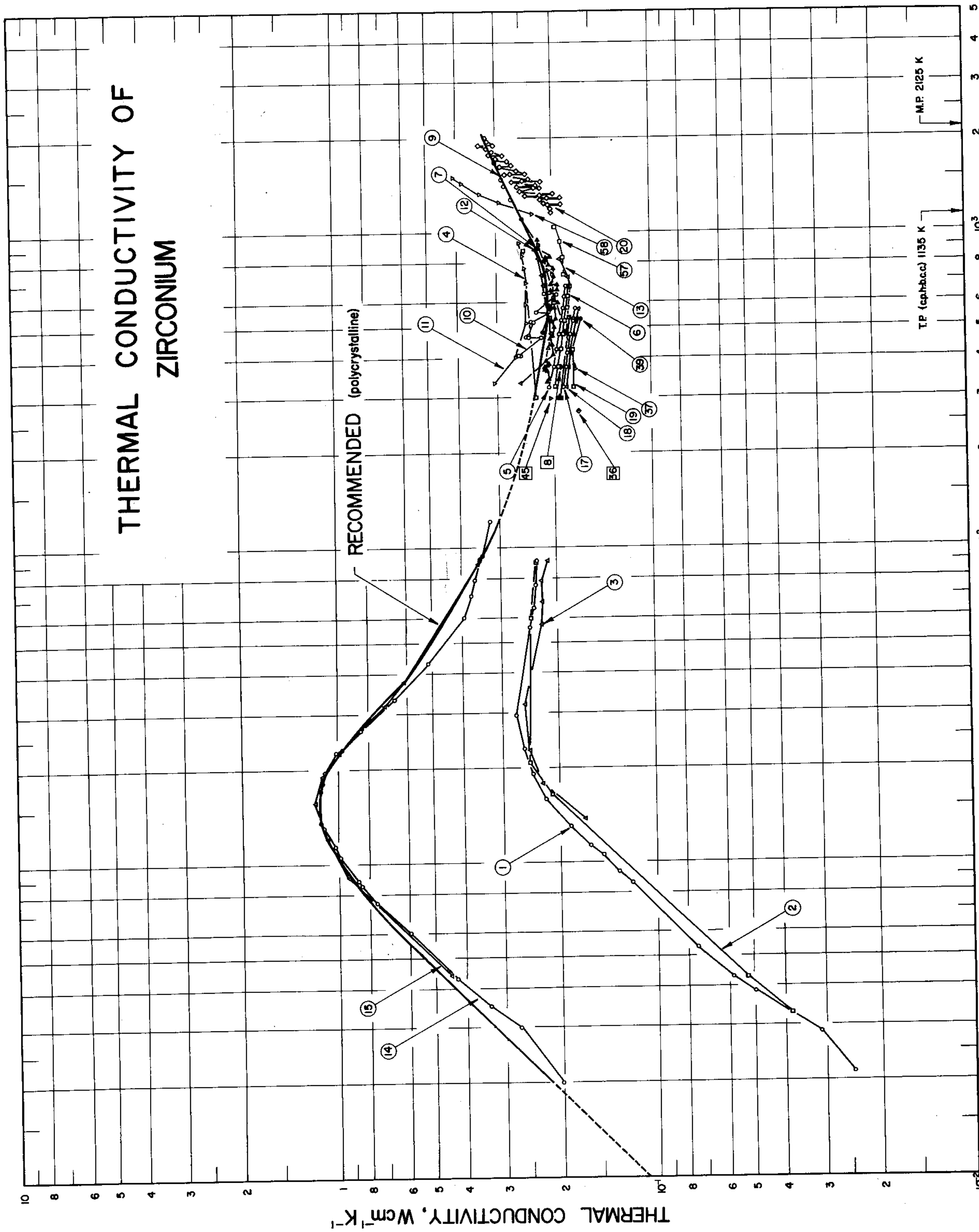

THERMAL CONDUCTIVITY OF ZIRCONIUM
RECOMMENDED (polycrystalline)
M.P. 2125 K
T.P. (c.p.h-b.c.c.) 1135 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, Wcm⁻¹K⁻¹
TPRC

FIGURE 178

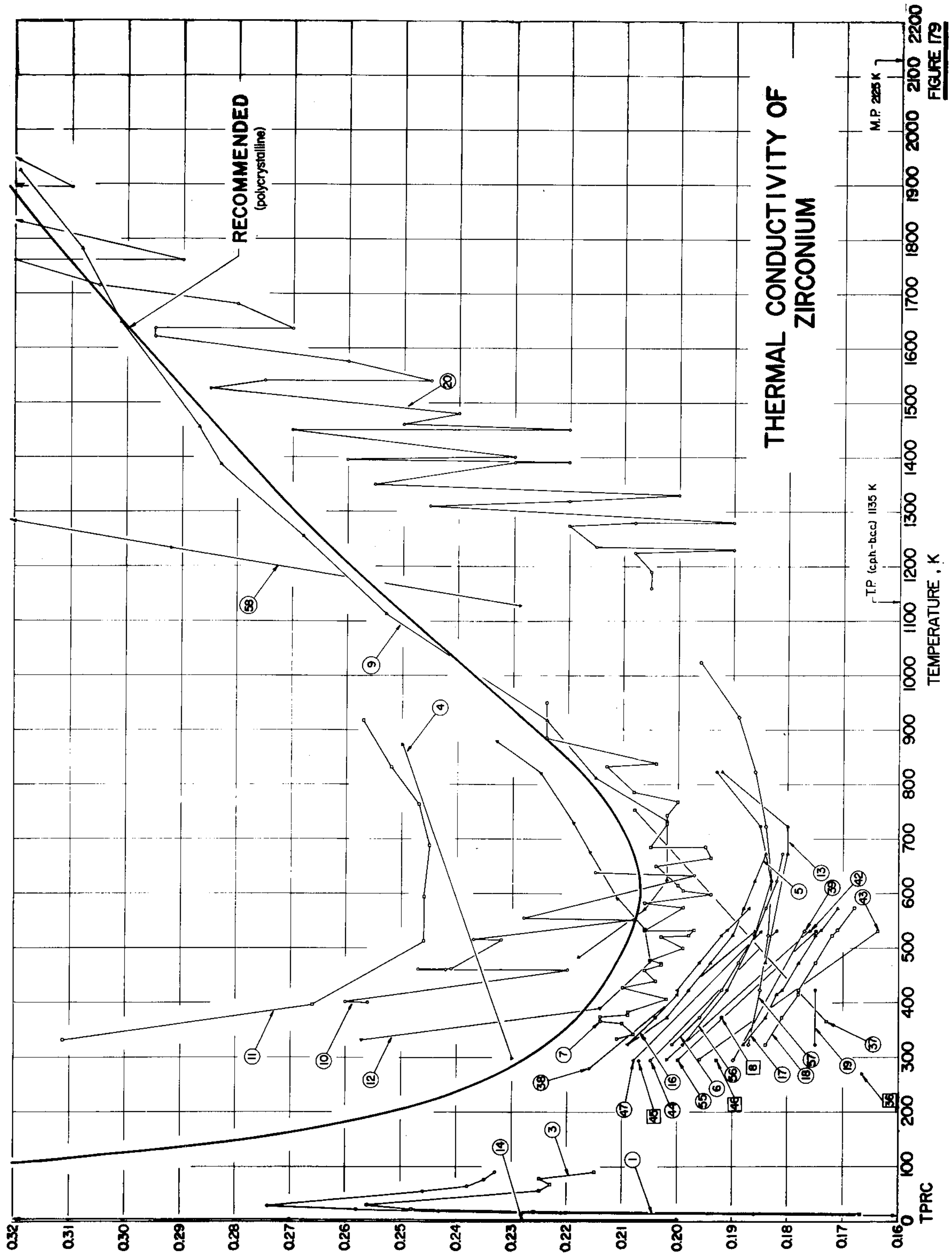

THERMAL CONDUCTIVITY OF ZIRCONIUM
RECOMMENDED
(polycrystalline)
M.P. 2125 K
T.P. (cph-b.c.c.) 1135 K
TEMPERATURE, K
THERMAL CONDUCTIVITY, W cm⁻¹ K⁻¹
TPRC
FIGURE 179

TABLE 185. THERMAL CONDUCTIVITY OF ZIRCONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	738	Kemp, W. R. G., Klemens, P. G., and White, G. K.	1956	L	2.2-91	Zr 1a	99.99 Zr; spectroanalysis shows Fe (all sensitive lines), Hf and Ni (all sensitivelines faintly), Si and Ti (some sensitive lines), and Al, Cr, Cu, and Mg (faintly visible); JM5000 from Johnson, Matthey and Co.; 3 mm dia rod annealed at 950 C for 5 hrs in vacuum; electrical resistivity 48 μohm cm at 293 K, residual electrical resistivity 1.98 μohm cm; mounted in the cryostat with a push fit into copper fitting; measured with the current lead (for the measurements of electrical resistivity) attached.
2	738	Kemp, W. R. G., et al.	1956	L	3.3-90	Zr 1b	The above specimen measured with the current lead removed.
3	738	Kemp, W. R. G., et al.	1956	L	14-90	Zr 1c	The above specimen unintentionally strained when drilling and tapping to inser the connectors for remounting.
4	315	Danielson, G. C.	1954	P	298, 873		Preliminary results.
5	325	Deem, H. W.	1953	C	323-673	2682 A	Pure; 2 cm dia x 15 cm long; arc-melted from WAPD grade 1 crystal bar; Armco iron used as comparative material; data taken from smoothed curve.
6	325	Deem, H. W.	1953	C	323-673	498	Pure; 2 cm dia x 15 cm long; arc-melted from Bureau of Mines sponge Zr; Armco iron used as comparative material; data taken from smoothed curve.
7	1000	Moss, M.	1955	L	336-950		Nominally pure; cylindrical specimen 7.938 in. long, 0.787 in. in dia; obtained from Westinghouse; prepared from Foote Grade I crystal-bar ingot; the ingot melted in tungsten arc furnace, forged at 845 C in argon to the size 10 x 1 x 1 in., annealed in vacuum for 0.5 hr at 1000 C; machined to final shape.
8	1334	Smith, K. F. and Chiswik, H. H.	1956	C	373.2		Hafnium-containing crystal bar.
9	431	Fieldhouse, I. B. and Lang, J. I.	1961	R	484-1925		99.95 Zr, 0.029 Fe, 0.017 C, 0.0045 Hf, and <0.031 other elements; specimen consisted of 5 one-in. dia disks; density 6.49 g cm^{-3}.
10	1485	Vianey, L. R.	1951	L	402-639	D-151	Assumed to be pure; 0.626 in. dia crystal bar; lot No. D-151; obtained from Argonne National Laboratory.
11	963	Mikryukov, V. E.	1957	E	331-917	Iodide Zirconium	99.9 pure; annealed in vacuum for 8 hrs at 700 C; electrical resistivity at 58.0, 124.1, 239.8, 321.0, 415.6, 490.6, 558.8, and 644.0 C, being respectively, 36.1, 47.6, 66.6, 75.8, 87.0, 94.4, 100.0, and 106 μohm cm; Lorenz number reported at these temps were 3.38, 3.33, 3.18, 3.11, 3.08, 3.04, 3.03, and 2.92 x 10^{-8} V^2 K^{-2}, respectively.
12	963	Mikryukov, V. E.	1957	E	332-879		99.78 Zr, 0.14 Hf, and 0.08 C; electrical resistivity reported as 53.76, 64.93, 78.74, 87.71, 95.23, 105.26, 111.11, 120.48, and 125.00 μohm cm at 59.0, 117.0, 202.0, 262.0, 318.0, 402.0, 456.0, 548.0, and 606.0 C, respectively; Lorenz numbers reported at these temps were 3.46, 3.44, 3.54, 3.36, 3.37, 3.34, 3.37, 3.28, and 3.29 x 10^{-8} V^2 K^{-2}, respectively.
13	908	McCreight, L. R.	1952	L, R, C	473-823		Pure; 98-100% of theoretical density.
14	1554	White, G. K. and Woods, S. B.	1959	L	2.0-121	Zr 4	99.95 Zr, 0.0132 Hf, <0.0100 each of P and Zn, 0.0079 C, 0.0021-0.0050 O, 0.0003-0.0050 N, 0.0024 Fe, 0.0011 Ni, 0.0002-0.0007 each of Ca, Cr, H, Mo, and Si, and <0.0010 other elements; arc cast, annealed at 1100 C for 4 hrs, swaged at room temp, annealed at 1000 C, for 15 min and at 800 C in a vacuum of 1-2 x 10^{-6} mm Hg for 15 min, cut to 4 lengths and clamped together.

TABLE 185. THERMAL CONDUCTIVITY OF ZIRCONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
15	1554	White, G.K. and Woods, S.B.	1959	L	4.4-89	Zr 4a	The above specimen unclamped and retightened.
16	162	Bing, G., Fink, F.W., and Thompson, H.B.	1951	C	323-573	Zr 1	0.04 Hf, 0.04 Fe, 0.02 Ni, 0.007 Ti, 0.001 Al, and 0.001 Sn; Westinghouse ingot D-216 forged at 950 C and machined; electrical resistivity reported as 44.1 and 81.3 μohm cm at 298 and 533 K, respectively; smoothed values reported.
17	162	Bing, G., et al.	1951	C	323-573	SA 1568; Zr 7	0.1 Fe, 0.07 Ta, 0.07 C, 0.02 Al, 0.007 Ti, and 0.0055 N; obtained from ANL; annealed; electrical resistivity reported as 50.5, 68.2, and 85.1 μohm cm at 298, 415, and 533 K, respectively; smoothed values reported.
18	162	Bing, G., et al.	1951	C	323-573	SA 1576; Zr 8	0.16 Ta, 0.10 Fe, 0.06 Al, 0.02 C, 0.015 N, and 0.005 Ti; obtained from ANL; electrical resistivity reported as 52.4, 70.1, and 86.6 μohm cm at 298, 415, and 533 K, respectively; smoothed values reported.
19	1134	Powell, R.W. and Tye, R.P.	1961	L, C	323-423	050	99.827 Zr (by difference), 0.11 O, 0.045 Fe, 0.01 C, and 0.008 N; as extruded rod 10 cm long, 1.27 cm in dia; arc-melted; electrical resistivity reported as 59.5 and 75 μohm cm at 323 and 423 K, respectively; Armco iron used as comparative material; energy flow also measured calorimetrically.
20	1411	Timrot, D.L. and Peletskii, V.E.	1965	L	1160-2000	Iodide Zirconium	99.5^+ pure; 14 mm dia x 65 mm long; vacuum annealed; density 6.45 g cm^{-3} at room temp.
21*	1382	Swift, D.L.	1966	→	298.2		Powder specimen contained in a 0.75 in. dia x 2 in. long cylindrical cell; average grain size 36.9 μ; thermal conductivity measured by using the transient line source method; measured in nitrogen at limiting high pressure.
22*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 48.0 μ.
23*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 57.5 μ.
24*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 67.8 μ.
25*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 84.5 μ.
26*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 95.3 μ.
27*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 137 μ.
28*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 164 μ.
29*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 199 μ.
30*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 228 μ.
31*	1382	Swift, D.L.	1966	→	298.2		Similar to above except average grain size 318 μ.
32*	1382	Swift, D.L.	1966	→	298.2		Similar to above; mesh size -70 +80; measured in nitrogen at 1 atm.
33*	1382	Swift, D.L.	1966	→	298.2		Similar to above; mesh size -70 +80; measured in nitrogen under pressures in the range 1.06×10^{-2}-3.89×10^{3} mm Hg.
34*	1382	Swift, D.L.	1966	→	298.2		Similar to above; measured in helium under pressures in the range 1.00×10^{-2}-3.467×10^{3} mm Hg.

* Not shown in figure.

TABLE 185. THERMAL CONDUCTIVITY OF ZIRCONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
35*	1382	Swift, D. L.	1966	→	298.2		Similar to above; measured in argon under pressures in the range 1.00×10^{-2} - 4.786×10^{3} mm Hg.
36	1426	Treco, R. M.	1950	→	273.2		3 x 0.250 x 0.110 in.; degassed at 1055 C in a vacuum of $<5 \times 10^{-6}$ mm Hg; annealed; electrical resistivity 39.34 μohm cm at 0 C; thermal conductivity value calculated from measured electrical resistivity using the Wiedemann-Franz law.
37	1425	Toy, S. M. and Vetrano, J. B.	1960	C			Density 6.49 g cm^{-3}.
38	162	Bing, G., Fink, F. W., and Thompson, H. B.	1951	→	298, 533	1	The same specimen as for curve No. 16; thermal conductivity values calculated from measured electrical resistivity data by the formula k = AσT-BT+C using experimentally determined constants A, B, and C.
39	162	Bing, G., et al.	1951	→	298, 533	7	The same specimen as for curve No. 17; same measuring method as above.
40**	162	Bing, G., et al.	1951	→	298, 533	8	The same specimen as for curve No. 18; same measuring method as above.
41*	162	Bing, G., et al.	1951	→	298.2	9	The above specimen annealed; electrical resistivity 52.3 μohm cm at 25 C; same measuring method as above.
42	162	Bing, G., et al.	1951	→	298, 533	10	0.076 Hf, 0.05 C, <0.05 Sn, 0.04 Al, 0.034 Fe, 0.008 N, and <0.001 Ti; prepared from low-hafnium crystal-bar zirconium by arc-melting, then double arc melted using a tungsten electrode in helium atm., ingot upset forged, rolled to sheet at 950 K (1250 F), annealed at 1061 K (1450 F), sand-blasted; electrical resistivity 47.3 and 85.5 μohm cm at 25 and 260 C, respectively; same measuring method as above.
43	162	Bing, G., et al.	1951	→	298, 533	15	0.18 Fe, <0.05 Sn, 0.027 Hf, 0.021 C, 0.011 Al, 0.008 N, and 0.002 Ti; prepared from Grade 1 crystal-bar zirconium by arc melting, then double arc melted using partial helium atm. and thoriated tungsten electrode, ingot upset forged in air at 1061 K, hot-rolled; electrical resistivity 48.9 and 87.0 μohm cm at 25 and 260 C, respectively; same measuring method as above.
44	162	Bing, G., et al.	1951	→	298, 533	20	0.05 Sn, 0.014 C, and 0.006 N; same fabrication method and measuring method as above; electrical resistivity 46.6 and 83.5 μohm cm at 25 and 260 C, respectively.
45	162	Bing, G., et al.	1951	→	298.2	21	Similar to above but electrical resistivity 46.2 μohm cm at 25 C.
46	162	Bing, G., et al.	1951	→	298.2	25	<0.05 Sn and 0.021 C; same fabrication method and measuring method as above; electrical resistivity 49.7 μohm cm at 25 C.
47	162	Bing, G., et al.	1951	→	298, 533	35	I-deposited; prepared from Grade 3 low-hafnium crystal-bar zirconium received from Foote; machined; electrical resistivity 45.9 and 82.0 μohm cm at 25 and 260 C, respectively; same measuring method as above.
48*	162	Bing, G., et al.	1951	→	298, 533	36	Similar to above but electrical resistivity 45.0 and 81.6 μohm cm at 25 and 260 C, respectively.
49*	162	Bing, G., et al.	1951	→	298, 533	37	Similar to above but electrical resistivity 44.6 and 81.8 μohm cm at 25 and 260 C, respectively.
50*	162	Bing, G., et al.	1951	→	298, 533	38	Similar to above but electrical resistivity 44.6 and 80.5 μohm cm at 25 and 260 C, respectively.

* Not shown in figure.

TABLE 185. THERMAL CONDUCTIVITY OF ZIRCONIUM - SPECIMEN CHARACTERIZATION AND MEASUREMENT INFORMATION (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
51*	162	Bing, G., Fink, F.W., and Thompson, H.B.	1951	→	298, 533	39	Similar to above but electrical resistivity 44.9 and 81.0 μohm cm at 25 and 260 C, respectively.
52*	162	Bing, G., et al.	1951	→	298, 533	40	Similar to above but electrical resistivity 46.4 and 81.8 μohm cm at 25 and 260 C, respectively.
53*	162	Bing, G., et al.	1951	→	298, 533	41	Similar to above but electrical resistivity 44.9 and 81.7 μohm cm at 25 and 260 C, respectively.
54*	162	Bing, G., et al.	1951	→	298, 533	42	Similar to above but electrical resistivity 45.1 and 81.0 μohm cm at 25 and 260 C, respectively.
55	162	Bing, G., et al.	1951	→	298, 533	43	Similar to above but electrical resistivity 47.9 and 85.9 μohm cm at 25 and 260 C, respectively.
56	1134	Powell, R.W. and Tye, R.P.	1961	L, C	323-823		0.3-0.6 O (analysis made after completion of tests), 0.016 C, 0.016 H, 0.012 Fe, and 0.0025 N; specimen 0.435 cm in dia and 9.7 cm long, cold swaged from a bar of about 0.5 cm dia that had been prepared by the Van Arkel method; the bar consisted almost entirely of hexagonal crystals with their c-axis parallel to the axis of the bar, and considerable preferred orientation believed present in the specimen; density of the bar 6.57 g cm^{-3}; electrical resistivity reported as 49.2, 65.6, 82.1, 97.8, 111.2, and 119.7 μohm cm at 323, 423, 523, 623, 723, and 823 K, respectively, at these temps the Lorenz function being, respectively, 3.03, 2.96, 2.92, 2.87, 2.85, and 2.80 x 10^{-8} V^2 K^{-2}; Armco iron used as a reference standard; energy flow also measured calorimetrically.
57	1134	Powell, R.W. and Tye, R.P.	1961	L, C	323-1023	Sample 715	0.1-0.6 O (analysis made after completion of tests), 0.043 C, 0.018 Fe, 0.0075 N, 0.007 Al, 0.007 Nb, and 0.0025 H; specimen 1.27 cm in dia and 10 cm long; in the as-extruded condition, melted in graphite before extrusion; electrical resistivity reported as 53.5, 70.0, 85.0, 98, 110, 119, 127, and 133 μohm cm at 323, 423, 523, 623, 723, 823, 923, and 1023 K, respectively, at these temps the Lorenz function being, respectively, 3.10, 3.06, 2.98, 2.88, 2.80, 2.69, 2.60, and 2.55 x 10^{-8} V^2 K^{-2}; Armco iron used as a reference standard; energy flow also measured calorimetrically.
58	674	Jain, S.C., Sinha, V., and Reddy, B.K.	1970	E	1127-1488	Specimen 2	0.2 cm dia x 20 cm long; obtained from Murex Ltd.; electrical resistivity 130.2, 130.7, 130.6, 128.0, 126.1, 116.7, 114.0, 113.6, 114.0, 113.6, 114.2, 114.6, 114.1, 113.7, 114.0, 114.9, 115.5, and 116.7 μohm cm at 1063, 1100, 1118, 1153, 1169, 1207, 1237, 1254, 1301, 1344, 1390, 1408, 1431, 1439, 1464, 1465, 1488, and 1496 K, respectively; Lorenz function 2.59, 2.75, 2.95, 3.12, and 3.19 x 10^{-8} V^2 K^{-2} at 1100, 1200, 1300, 1400, and 1500 K, respectively.

* Not shown in figure.

Element 104

Element 104, the first transactinide element, belongs to Group IV B and is expected to have chemical properties similar to those of hafnium.

Due to the extremely short half-lives of the isotopes of this element, it is unlikely that its thermal conductivity will ever be determined. However, very rough estimation of its room-temperature thermal conductivity may be made. Element 104 is the last member of Group IV B elements and the thermal conductivities at 300 K of the other three members Ti, Zr, and Hf of Group IV B are 0.219, 0.227, and 0.230 W cm^{-1} K^{-1}, respectively. The extrapolation to atomic number 104 of a smooth curve drawn through these three points in a large working graph of thermal conductivity versus atomic number similar to figure 15 gives a value of 0.23 W cm^{-1} K^{-1} for Element 104 at 300 K. This derived value is probably good to ±50 percent.

Element 105

Element 105, the second transactinide element, belongs to Group V B and is expected to have chemical properties similar to those of tantalum.

Due to the extremely short half-lives of the isotopes of this element it is unlikely that its thermal conductivity will ever de determined. However, very rough estimation of its room-temperature thermal conductivity may be made. Element 105 is the last member of the Group V B elements and the thermal conductivities at 300 K of the other three members, V, Nb, and Ta of Group V B are 0.307, 0.537, and 0.575 W cm^{-1} K^{-1}, respectively. The extrapolation to atomic number 105 of a smooth curve drawn through these three points in a large working graph of thermal conductivity versus atomic number similar to figure 15 gives a value of 0.58 W cm^{-1} K^{-1} for element 105 at 300 K. This derived value is probably good to ±50 percent.

5. References

[1] Abdinov, D. Sh., and Aliev, G. M., "Thermoconductivity of Selenium," Izv. Akad. Nauk Azerb. SSR, (2), 109–14, 1964.

[2] Abdullaev, G. B., Aliev, G. M., and Barkinkhoev, Kh. G., "Effect of Gallium Impurities on the Thermal Conductivity of Hexagonal Selenium," Dokl. Akad. Nauk Azerb. SSR, **19**(8), 9–13, 1963.

[3] Abdullaev, G. B., Aliev, G. M., and Barkinkhoev, Kh. G., "Thermal Conductivity of Selenium," Fiz. Tverd. Tela (USSR), **5**(12), 3614–15, 1963; English translation: Sov. Phys.-Solid State, **5**(12), 2651–2, 1964.

[4] Abdullaev, G. B., Aliev, G. M., and Chetverikov, N. I., "On the Effect of Gallium and Iron Impurities on the Thermal Conductivity of Germanium," Zh. Tekhn. Fiz. **28**(11), 2368–71, 1958; English translation: Sov. Phys.-Tech. Phys., **3**(11), 2173–6, 1959.

[5] Abdullaev, G. B., and Aliev, M. I., "Effect of Iodine on the Thermal Conductivity of Selenium," Dokl. Akad. Nauk SSSR, **114**, 995–6, 1957.

[6] Abdullaev, G. B., Aliev, M. I., and Akhundova, S. A., "On the Influence of Thallium on the Thermal Conductivity of Polycrystalline Selenium," Fiz. Tverd. Tela (USSR), **3**(2), 326–7, 1961; English translation: Sov. Phys.-Solid State, **3**(2), 234–5, 1961.

[7] Abdullaev, G. B., and Bashshaliev, A. A., "Effect of Bromine Impurity on the Thermal Conductivity of Selenium," Zh. Techn. Fiz., **27**(9), 1971–5, 1957; English translation: Sov. Phys.-Tech. Phys., **2**(9), 1827–31, 1957.

[8] Abdullaev, G. B., Dzhalilov, N. Z., and Aliev, G. M., "On Heat Conductivity and Thermoelectromotive Force of Hexagonal Selenium Single Crystals," Phys. Letters (Netherlands), **23**(3), 217–19, 1966.

[9] Abdullaev, G. B., Mekhtiyeva, S. I., Abdinov, D. Sh., and Aliev, G. M., "Amorphous Selenium Thermal Conductivity Study in Softening Region," Phys. Letters (Netherlands), **23**(3), 215–16, 1966.

[10] Abdullaev, G. B., Mekhtieva, S. I., Abdinov, D. Sh., Aliev, G. M., and Alieva, S. G., "Thermal Conductivity of Selenium," Phys. Status Solidi, **13**(2), 315–23, 1966.

[11] Abeles, B., "Thermal Conductivity of Germanium in the Temperature Range 300–1080 K.," Phys. Chem. Solids, **8**, 340–3, 1959.

[12] Abeles, B., "Thermal Conductivity of Germanium in the Temperature Range 300 K to 1080 K," in *Proc. Thermoelectricity Conf.* (1958), 288–94, 1960.

[13] Abeles, B., Beers, D. S., Cody, G. D., Novak, R., and Rosi, F. D., "High Temperature Properties of Semiconductors," USAF Rept., WADD TR 60–266, 1–51, 1960. [AD 246 620]

[14] Abeles, B., and Cody, G. D., "Thermal and Electrical Properties of Materials," RCA Labs., USAF Progr. Rept., 1–8, 1960. [AD 233 193]

[15] Abeles, B., Cody, G. D., Dismukes, J. P., Hockings, E. F., Lindenblad, N. E., Richman, D., and Rosi, F. D., "Thermoelectric Materials for Power Conversion," RCA Labs., Quarterly Progr. Rept. No. 8, 1–92, 1961. [AD 266 128]

[16] Abeles, B., Cody, G. D., and Novak, R., "Thermal and Electrical Properties of Material," RCA Labs. Progr. Rept. No. 1, 1–33, 1959. [AD 225 854].

[17] Abrosimov, V. M., Egorov, B. N., Lidorenko, N. S., and Rubashov, I. B., "Thermal Conductivity of Thin Metal Films," Fiz. Tverd. Tela., **11**(2), 530–2, 1969; English translation: Sov. Phys.-Solid State, **11**(2), 427–8, 1969.

[18] Achener, P. Y., "Alkali Metals Evaluation Program Quarterly Progr. Rept. 1 Jan. through 31 March 1967," USAEC Rept. AGN–8222, 1–26, 1967.

[19] Achener, P. Y., and Jouthas, J. T., "Thermal Conductivity of Liquid Sodium," USAEC Rept. AGN–8191, 1–34, 1969.

[20] Achener, P. Y., and Jouthas, J. T., "Alkali Metals Evaluation Program Thermodynamic and Transport Properties of Cesium and Rubidium Thermal Conductivity of the Vapor," USAEC Rept. AGN–8192, 1–73, 1968.

[21] Acheson, E. G., U. S. Patent 542–982, 1895.

[22] Adams, A. R., Baumann, F., and Stucke, J., "Thermal Conductivity of Selenium and Tellurium Single Crystals and Phonon Drag of Tellurium," Phys. Status Solidi, **23**(1), K99–104, 1967.

[23] Adcock, F., and Bristow, C. A., "Iron of High Purity," Proc. Roy. Soc. (London), **A153**, 173–200, 1935.

[24] Aerojet General Corporation Publication, "Properties of Principal Cryogenics," PRA–SA–DSR, 8/20/64, 3rd Printing, 1966.

[25] Agrawal, B. K., "Lattice Thermal Conductivity of Solid Helium. II. Isotopic Mixtures," Phys. Rev., **162**(3), 731–6, 1967.

[26] Ahtye, W. F., "A Critical Evaluation of Methods for Calculating Transport Coefficient of Partially and Fully Ionized Gases," NASA TN D–2611, 1–110, 1965.

[27] Ahtye, W. F., and Peng, T–C., "Approximations for the Thermodynamic and Transport Properties of High-Temperature Nitrogen with Shock-Tube Applications," NASA TN D–1303, 1–108, 1962.

[28] Albano, V. J., and Soden, R. R., "The Preparation of Ultra-High-Purity Nickel Single Crystals," J. Electrochem. Soc., **113**,511, 1966.

[29] Albany, H. J., and Vandevyver, M., "Effect of Irradiation by Fast Neutrons on the Thermal Conductivity of Silicon Between 80 and 300 K., "Compt. Rend., Acad. Sci. (France), **257**(4), 859–62, 1963.

[30] Albany, H. J., and Vandevyver, M., "Thermal Conductivity of Single Crystals of Germanium Irradiated with Fast Neutrons," J. Physique (France), **25**(11), 978–80, 1964.

[31] Albany, H. J., and Vandevyver, M., "Effects of Fast Neutrons on the Thermal Conductivity of Silicon Between 80 and 300 K, and Recovery Through Annealing," in *Proc. Seventh Intern. Conf. Phys. Semicond. (1964)*, 67–72, 1965.

[32] Albany, H. J., and Vandevyver, M., "Low-Temperature Thermal Conductivity of Fast-Neutron-Irradiated Silicon and Germanium," J. Appl. Phys., **38**(2) 425–30, 1967.

[33] Albany, H. J., and Vandevyver, M., "Effects of Electron Irradiation on the Thermal Conductivity of *n*- and *p*-type Germanium" Phys. Rev., **160**(3), 633–5, 1967.

[34] Albrecht, F., "An Apparatus for Measuring the Heat of Transformation in the Soil," Meteorologische Z., **49**, 294–9, 1932.

[35] Aliev, B. D., Abdullaev, G. B., and Aliev, G. M., "Effect of Bismuth Impurities on the Thermal Conductivity and Self-Diffusion of Selenium," Tr. Inst. Fiz. Akad. Nauk Azerb SSR, **11**, 5–10, 1963.

[36] Aliev, B. D., and Aliev, G. M., "Influence of Cadmium Impurities on the Thermal and Electrical Conductivities of Selenium," Tr. Inst. Fiz., **11**, 19–24, 1963.

[37] Aliev, G. M., "The Effect of Chlorine on the Thermal Conductivity of Selenium," Izv. Akad. Nauk Azerb. SSR, (9), 3–8, 1957.

[38] Aliev, G. M., and Abdullaev, G. B., "The Effect of Chlorine Admixtures on the Thermal Conductivity of Selenium," Dokl. Akad. Nauk SSSR, **116**(4), 598–600, 1957.

[39] Aliev, G. M., and Abdullaev, G. B., "Relationship Between the Thermal Conductivity and the Temperature of Selenium Containing Small Chlorine Impurity," Dokl. Akad. Nauk SSSR, **120**(1), 76–8, 1958.

[40] Aliev, M. I., "The Effect of Iodine on the Electrical and Thermal Properties of Selenium," Tr. Inst. Fiz. i Mat. Akad. Nauk Azerb. SSR, Ser. Fiz., **9**, 27–39, 1958; English translation: RTS-1295 60-19561, 1-26, 1960.

[41] Aliev, M. I., and Akhundova, S. A., "Effects of Temperature and Iodine Additions on the Thermal Conductivity of Selenium," Uchenye Zap. Azerb. Univ., Fiz.-Mat. i Khim. Ser., (3), 55–62, 1959.

[42] Aliev, M. I., and Akundova, S. A., "Influence of Thallium on the Physical Properties of Selenium," Izv. Akad. Nauk Azerb. SSR, Ser. Fiz.-Mat. Tekhn. Nauk, (3), 47–53, 1960.

[43] Aliev, M. I., Fistul, V. I., and Arasly, D. G., "Thermal Conductivity of Heavily Doped Germanium," Fiz. Tverd. Tela, **6**(12), 3700–1 1964; English translation: Sov. Phys.-Solid State, **6**(12), 2962, 1965.

[44] Aliev, M. I., Veliev, M. I., and Kerimov, I. G., "The Thermal Conductivity of Bismuth and Selenium," Izv. Akad. Nauk Azerb. SSR, Ser. Fiz.-Mat. Tekhn. Nauk, (1), 79–84, 1961.

[45] Aliev, N. G., and Volkenshtein, N. V., "Thermal Conductivity of Holmium and Erbium from 2 to 100 K," Fiz. Tverd. Tela., 7(8), 2560–2, 1965; English translation: Sov. Phys.-Solid State, **7**(8), 2068–9, 1966.

[46] Aliev, N. G., and Volkenshtein, N. V., "Thermal Conductivity of Thulium, Ytterbium, and Lutetium at Low Temperatures," Zh. Eksp, Teor. Fiz., **49**(5), 1450–2, 1965; English translation: Sov. Phys.-JETP, **22**(5), 997–8, 1966.

[47] Aliev, N. G., and Volkenshtein, N. V., "Low-Temperature Thermal Conductivity of Scandium and Yttrium," Fiz. Metal. Metalloved., **19**(5), 793, 1965; English translation: Phys. Metals Metallog., **19**(5), 141, 1965.

[48] Aliev, N. G., and Volkenshtein, N. V., "Thermal Conductivity of Gadolinium and Terbium at Low Temperatures," Zh. Eksp. Teor. Fiz., **49**(1), 24–6, 1965; English translation: Sov. Phys.-JETP, **22**(1), 17–18, 1966.

[49] Allen, J. F., and Mendoza, E., "Thermal Conductivity of Copper and Nickel Silver at Liquid-Helium Temperatures," Proc. Cambridge Phil. Soc., **44**, 280–8, 1948.

[50] Allen, R. D., Glasier, L. F., and Jordan, P. L., "Spectral Emissivity, Total Emissivity, and Thermal Conductivity of Molybdenum, Tantalum, and Tungsten above 2300 K," J. Appl. Phys., **31**(8), 1382–7, 1960.

[51] Allison, W. L., "A Determination of the Thermal Conductivity of Molten Lead," MIT, M.S. Thesis, 1–73, 1951.

[52] Alsup, D. L., "Thermal Properties of A Single Crystal of Bismuth at Liquid-Helium Temperatures," North Texas State Univ., M.S. Thesis, 1–37, 1964.

[53] Amdur, I., "Low-Temperature Transport Properties of Gases, I. Helium," J. Chem. Phys., **15**(7), 482–7, 1947.

[54] Amdur, I., "Low-Temperature Transport Properties of Gases, II. Neon, Argon, Krypton, and Xenon," J. Chem. Phys., **16**(3), 190–4, 1948.

[55] Amdur, I., and Mason, E. A., "Properties of Gases at Very High Temperatures," Phys. Fluids, **1**(5), 370–83, 1958.

[56] American Society for Metals, *Metals Handbook*, 1948 Edition, American Society for Metals, 1332 pp., (1948); 8th Edition, Vol. 1, 1300 pp., 1961.

[57] Ames Laboratory, Quarterly Summary Research Report in Physics, ISC-322, 1–14, 1953.

[58] Amirkhanov, Kh. I., Bagduev, G. B., and Kazhlayev, M. A., "Thermal Conductivity of Tellurium," Dokl. Akad. Nauk SSSR, **117**(6), 953–5, 1957; English translation: Sov. Phys. Dokl., **2**, 556–8, 1957.

[59] Amirkhanov, Kh. I., Bagduev, G. B. and Kazhlayer, M. A., "Anisotropy of Thermal Conductivity in Single Crystals of Tellurium," Dokl. Akad. Nauk SSSR, **124**(3), 554–6, 1959.

[60] Amirkhanov, Kh. I., Daibov, A. Z., and Zhuze, V. P., "Change in the Thermal Conductivity of Semiconductors in a Magnetic Field," Dokl. Akad. Nauk SSSR, **98**(4) 557–60, 1954; English translation: SLA TT-65-10804, 1-7, 1965.

[61] Amundsen, T., and Olsen, T., "Oscillatory Thermal Magnetoresistance in Aluminum," Phys. Letters, **4**(5), 304–6, 1963.

[62] Amundsen, T., and Olsen, T., "Size Dependent Thermal Conductivity in Aluminum Films," Phil. Mag., **11**(111), 561–74, 1965.

[63] Anaeker, W. F., and Mannkopff, R., "The Thermal Conductivity of Graphite in the Vicinity of the Sublimation Temperature," Naturwissenschaften, **46**(6), 199–200, 1959.

[64] Anderson, A. C., Peterson, R. E., and Robichaux, J. E., "Thermal and Electrical Conductivity of Silver and Platinum Below 1 K.," Phys. Rev. Lett., **20**(9), 459–61, 1968.

[65] Andersen, H. H., and Nielsen, M., "Electrical Resistivity, Thermal Conductivity and Thermopower of Gold at Low Temperatures," Danish Atomic Energy Commission, Risö Rept. No. 77, 1–22, 1964. [AD 443 218]

[66] Anderson, R. L., Grotzky, D. H., and Kienzle, W. E., "Thermal Diffusivity of High Purity Thorium," in *9th Conference on Thermal Conductivity* (1969), USAEC Rept. CONF-691002, 326–35, 1970.

[67] Andrew, J. F., "Thermal Conductivity of Plutonium Metal," J. Phys. Chem. Solids, **28**(4), 577–80, 1967.

[68] Andrews, F. A., "The Thermal Conductivity of Copper, Aluminum and Tin at Low Temperatures," Yale Univ., Ph.D. Thesis, 1–128, 1950.

[69] Andrews, F. A., Webber, R. T., and Spohr, D. A., "Thermal Conductivity of Copper, Aluminum and Tin at Helium Temperatures," Naval Research Lab. Rept., 1–6, 1950. [AD 147 716]

[70] Andrews, F. A., Webber, R. T., and Spohr, D. A., "Thermal Conductivities of Pure Metals at Low Temperatures. I. Aluminum," Phys. Rev., **84**(5), 994–6, 1951.

[71] Andrussow, L., "Thermal Conductivity, Viscosity, and Diffusion in the Gas Phase. VII. Hydrogen, Deuterium, Helium, Neon, and Their Mixtures," J. Chem. Phys., **49**, 599–604, 1952.

[72] Andrussow, L., "Thermal Conductivity and Diffusion in the Gas Phase. V. Calculation of the Coefficient of Thermal Conductivity," Z. Elecktrochem., **56**(1), 54–8, 1952.

[73] Angell, M. F., "Thermal Conductivity at High Temperatures," Phys. Rev., 1, **33**(5), 421–32, 1911.

[74] Angell, M. F., "Thermal Conductivity of Metals at High Temperatures," Phys. Rev., **27**, 820, 1926.

[75] Angström, A. J., "A New Method of Determining the Thermal Conductivity of Solids," Ann. Physik Chemie, 2, **114**, 513–30, 1861: English translation: Phil. Mag., 4, **25**, 130–42, 1863.

[75a] Angström, A. J., "On the Conducting-Power of Copper and Iron for Heat at Different Temperatures," Ann. Physik Chemie, 2, **118**, 423–31, 1863: English translation: Phil. Mag., 4, **26**(174), 161–7, 1863.

[75b] Angström, A. G., "Supplement to the Article: A New Method of Determining the Thermal Conductivity of Solids," Ann. Physik Chemie, **123**, 628—40, 1864.

[76] Aoyama, S. , and Ito, T., "Thermal and Electrical Conductivities of Nickel-Copper Alloys at Low Temperatures," Nippon Kinzoku Gakkaishi, **4**(1), 3–7, 1940.

[77] Aoyama, S., and Ito, T., "Thermal and Electrical Conductivities of Metals and Alloys at Low Temperatures. II. A Simple Apparatus and Rapid Method of Measuring the Thermal Conductivity of Metals and Alloys," Nippon Kinzoku Gakkaishi, **4**(1), 8–9, 1940.

[78] Aoyama, S., and Ito, T., "Thermal and Electrical Conduc-

tivities of Copper-Zinc Alloys at Low Temperatures," Nippon Kinzoku Gakkaishi, 4(1), 37–40, 1940.

[79] Appel, J. C., Chambers, R. H., and Trozera, T. A., "A Program of Basic Research on Mechanical Properties of Reactor Materials," General Atomic, Quarterly Progr. Rept. on Contract AT (04–3)–167, 1–28, 1965.

[80] Arajs, S., and Colvin, R. V., "Thermal Conductivity and Lorenz Function of Gadolinium Between 5 and 310 K," J. Appl. Phys., Pt. 2, **35**(3), 1043–4, 1964.

[81] Arajs, S., and Colvin, R. V., "Thermal Conductivity of Scandium Between 5 and 320 K," in *Proc. 4th Rare Earth Res. Conf.*, USAEC Rept. CONF–405–23, 1–10, 1964.

[82] Arajs, S., and Colvin, R. V., "Thermal Conductivity and Electrical Resistivity of Terbium Between 5 and 300 K," Phys. Rev., **A136**(2), 439–41, 1964.

[83] Arajs, S., and Dunmyre, G. R., "Thermal Conductivity, Electrical Resistivity, and Lorenz Function of Polycrystalline Erbium Between 5 and 300 K," Physica, **31**(10), 1466–72, 1965.

[84] Arajs, S., and Dunmyre, G. R., "Thermal Conductivity and Electrical Resistivity of Samarium at Low Temperatures," in *Proc. 5th Rare Earth Res. Conf.*, AFOSR–65–1917, 63–73, 1965. [AD 627 222]

[85] Arajs, S., and Dunmyre, G. R., "Electrical Resistivity, Thermal Conductivity and Magnetic Susceptibility of Polycrystalline Samarium at Low Temperatures," Z. Naturforsch., **21A**(11), 1856–9, 1966.

[86] Arajs, S., Oliver, B. F., and Dunmyre, G. R., "Thermal Conductivity of High-Purity Iron at Low Temperatures," J. Appl. Phys., **36**(7), 2210–2, 1965.

[87] Arasly, D. G., and Aliev, M. I., "Phonon Scattering in Silicon and Germanium Alloys," Dokl. Akad. Nauk Azerb. SSR, **22**(8), 26–8, 1966.

[88] Arasly, D. G., and Aliev, M. I., "Influence of Defects and of the Interaction Between Them on Phonon Scattering in Heavily Doped Germanium and Silicon," Phys. Status Solidi, **21**(2), 643–8, 1967.

[89] Arave, R. J., and Huseby, O. A., "Aerothermodynamic Properties of High Temperature Argon," Boeing Aircraft Co. Rept., D2–11238, 1–227, 1962. [AD 285 668]

[90] Archer, C. T., "Thermal Conductivity of Deuterium," Nature (London), **138**, 286–7, 1936.

[91] Archer, C. T., "Thermal Conduction in H_2-D_2 Mixtures," Proc. Roy. Soc. (London), **A165**, 474–85, 1938.

[92] Archibald, M. A., Dunick, J. E., and Jericho, M. H., "Low-Temperature Lattice Thermal Conductivity of Potassium-Cesium Alloys," Phys. Rev., **153**(3), 786–95, 1967.

[93] Argonne National Laboratory, *Handbook of Constants for Selected Pile Materials*, Lemont, Illinois, USAEC Rept. ANL–WH2–122, 1–85, 1947.

[93a] Armco Steel Corporation, "Armco Magnetic Ingot Iron for D-C Applications," Armco Steel Corporation, Middletown, Ohio, Bulletin LE–168, 1968.

[94] Armstrong, L. D., and Dauphinee, T. M., "Thermal Conductivity of Metals at High Temperature. I. Description of the Apparatus and Measurements on Iron," Canad. J. Research, **A25**(6), 357–74, 1947.

[95] Askerov, Ch. M., and Aliev, G. M., "Effect of Sulfur Impurities on the Thermal Conductivity of Crystalline Selenium," Izv. Akad. Nauk Azerb. SSR, (5), 45–8, 1962.

[96] Askerov, Ch. M., Aliev, G. M., and Akhundova, E. G., "Thermal Conductivity, Density and Microhardness of the System Selenium-Sulfur," Izv. Akad. Nauk Azerb. SSR, Ser. Fiz.-Tekhn. Mat. Nauk, (1), 83–9, 1964.

[97] Atkins, K. R., "Thermal Conductivity of Liquid Helium-II in Very Narrow Channels," Phys. Rev., **108**(4), 911–3, 1957.

[98] Atomic International Div., N. American Aviation, Inc., Annual Technical Progress Report, AEC Unclassified Programs, Atomics International Div. North American Aviation Inc., Canoga Park, Calif., USAEC, NAA–SR–5350, 1960.

[99] Babbitt, V. D., Dauphinee, T. M., Armstrong, L. D., and Peria, W., "Thermal Conductivity of Metals at High Temperatures, II. Thermal Conductivity of Uranium. Preliminary Study.," USAEC Rept. AECL–326, CRR–438, 1–37, 1949.

[100] Bäcklund, N. G., "An Experimental Investigation of the Electrical and Thermal Conductivity of Iron and Some Dilute Iron Alloys at Temperatures above 100 K," J. Phys. Chem. Solids, **20**(1/2), 1–16, 1961.

[101] Bäcklund, N. G., and Langermar, K. T., Private Communication, January 24, 1967.

[102] Bäcklund, N. G., "Measurement and Analysis of the Thermal Conductivity of Tungsten and Molybdenum at 100–400 K," J. Phys. Chem. Solids, **28**(11), 2219–23, 1967.

[103] Bacon, G. E., "A Method for Determining the Degree of Orientation of Graphite," J. Appl. Chem., **6**, 477–81, 1956.

[104] Bailey, B. J., and Kellner, K., "The Thermal Conductivity of Argon Near the Critical Point," Brit. J. Appl. Phys., **18**(11), 1645–7, 1967.

[105] Bailey, B. J., and Kellner, K., "The Thermal Conductivity of Liquid and Gaseous Argon," Physica, **39**(3), 444–62, 1968.

[106] Bailey, L. C., "The Thermal Conductivities of Certain Approximately Pure Metals and Alloys at High Temperatures," Proc. Roy. Soc. (London), **A134**, 57–76, 1931.

[107] Bain, R. W., "Tables of Viscosity of Argon and Nitrogen and the Thermal Conductivity of Nitrogen all at Atmospheric Pressure," National Engineering Lab. (Glasgow, Scotland), Heat Div. Rept., Heat 153, 1–12, 1958.

[107a] Baker, C. E., and Brokaw, R. S., "Thermal Conductivities of Ordinary and Isotopically Substituted Polar Gases and Their Equimolar Mixtures," J. Chem. Phys., **43**(10), 3519–28, 1965.

[108] Baker, D. E., "Thermal Conductivity of Irradiated Graphite by a rapid Thermal-Pulse Method," J. Nucl. Mater., **12**(1), 120–4, 1964.

[109] Baker, D. E., "The Thermal Conductivity of Technetium," J. Less-Common Metals, **8**(6), 435–6, 1965.

[110] Bakish, R., Fenster, S. K., and Kambouraglou, A., "Thermal Conductivity of Anistropic Aluminum," J. Appl. Phys., **39**(9), 4473–5, 1968.

[111] Ball, J. G., Lee, J. A., Mardon, P. G., and Robertson, J. A. L., "Determination of Some Physical Properties of Plutonium Metal," Mém. Sci. Rev. Mét., **57**, 49–56, 1960.

[112] Banaev, A. M., and Chekhovskoi, V. Ya., "Experimental Determination of the Coefficient of Thermal Conductivity for Solids at Temperatures 200–1000 Degrees," Teplofiz. Vys. Temp., Akad., **3**(1), 57–63, 1965: English translation: High Temp., **3**(1), 47–52, 1965.

[113] Bannawitz, E., "On the Heat Conduction of Neon," Ann. Physik, **48**(21), 577–92, 1915.

[114] Baranskii, P. I., and Konoplyasova, N. S., "A Study of the Volume-Gradient Thermo-Electric Force and Thermal Conductivity in Germanium Single Crystals of Known Crystallographic Orientation," Zh. Tekhn. Fiz., **28**(8), 1621–30, 1958: English translation: Sov. Phys.-Tech. Phys., **3**(8), 1493–1501, 1958.

[115] Barisoni, M., Williams, R. K., and McElroy, D. L. (Editors, Flynn, D. R. and Peavy, B. A.), "Physical Properties of Indium from 77 to 350 K," in *Thermal Conductivity—Proceedings of the Seventh Conference* (Flynn, D. R., and Peavy, B. A., Jr., Editors), NBS–SP–302, 279–92, 1968.

[116] Barratt, T., "Thermal and Electrical Conductivities of

Some of the Rarer Metals and Alloys," Proc. Phys. Soc. (London), **26**, 347–71, 1913.

[117] Barratt, T., and Winter, R. M., "The Thermal Conductivity of Wires and Rods," Ann. Physik, **77**(9), 1–15, 1925.

[118] Bashashliev, A. A., "The Effect of Bromine Additions on Some Physical Properties of Selenium," Tr. Inst. Fiz. Mat., Akad Nauk. Azerb. SSR, Ser. Fiz., **9**, 42–59, 1958.

[119] Bashashliev, A. A., "The Influence of Bromine Additions on the Thermal Conductivity of Amorphous and Crystalline Selenium," Tr. Inst. Fiz. Mat. Akad. Nauk Azerb. SSR, Ser. Fiz., **9**, 60–9, 1958.

[120] Batalov, V. S., and Pelelskii, V. E., "Method of Determining the Transport Constants from the Rate of Change in Linear Dimensions of Solids," Teplofiz. Vys. Temp., **6**(5), 896–900, 1968; English translation: High Temp., **6**(5), 856–60, 1968.

[121] Bates, J. C., "A Comparison of the Thermal Conductivity of Irradiated and Unirradiated Uranium," UKAEA Rept., R and DB/W/TN–78, 1–5, 1953. [AD 212 839]

[121a] Bates, O. K., Hazzard, G., and Palmer, G., "Thermal Conductivity of Liquids," Ind. Eng. Chem., Anal. Ed., **10**(6), 314–8, 1938.

[122] Battelle Memorial Institute, "Progress Report on Metallurgy of Tuballoy to University of Chicago," Battelle Memorial Inst. Columbus, Ohio, 1–39, 1945.

[122a] Battelle Memorial Institute, "Thermal Properties of Titanium and Titanium Alloys," DMIC Memo 1, 1–23, 1958.

[123] Bean, K. E., Hentzschel, H. P., and Colman, D., "Thermal and Electrical Anisotropy of Polycrystalline Silicon," J. Appl. Phys., **40**(5), 2358–9, 1969.

[124] Bednar, V., Broz, J., Smirous, K., and Trousil, Z., "The Preparation of Very Pure Iron and the Evaluation of Its Purity According to Some Physical Properties," Czech. J. Phys., **4**(3), 345–9, 1954.

[125] Beers, D. S., Cody, G. D., and Abeles, B., "Thermal Conductivity of Germanium, Silicon, and III–V Compounds at High Temperatures," in *Proceedings of the International Conference on the Physics of Semi-conductors* (Exeter, England), 41–8, 1962.

[126] Bell, I. P., "Fast Reactor: Physical Properties of Materials of Construction," UKAEA Rept. R and DB(c) TN–127, 1–10, 1955.

[127] Bell, I. P., "Fast Reactor-Physical Properties of Materials of Construction, Review of Progress from 1st April, 1954 to 1st October, 1954," UKAEA Rept. RDB/C/TN–101, 1–3, 1958.

[128] Bell, I. P., and Makin, S. M., "Fast Reactor-Physical Properties of Materials of Construction, Review of Progress from Sept. 1, 1953 to April 1, 1954," UKAEA Rept. RDB/C/TN–70, 1–17, 1954.

[129] Benbow, R. L., "Thermal Conductivity of Heavily Phosphorus-Doped Silicon from 590 to 1280 K," South Dakota School of Mines and Tech., M.S. Thesis, 1–36, 1967. [AD 649 626]

[130] Benguigui, L., "Thermal Conductivity of Liquid Tellurium Between 740 and 900 K," Physik Konden. Mater., **5**(3), 171–7, 1966.

[131] Benin, D. B., "Thermal Conductivity of Quantum Crystals," Univ. Microfilm Publ. 68–15820, 104 pp., 1968.

[132] Benin, D. B., "Thermal Conductivity of Ne and He^4 Quantum Crystals," Phys. Rev. Lett., **20**(24), 1352–4, 1968. [AD 683 883]

[133] Benin, D. B., "Improved Variational Principles for Transport Coefficients," Phys. Rev., 3, **B1**(6), 2777–84, 1970.

[134] Bergenlid, U., Hill, R. W., Webb, F. J., and Wilks, J., "The Specific Heat of Graphite Below 90 K," Phil. Mag., **45**, 851–4, 1954.

[135] Berger, L., "The Electrical and Thermal Conductivities of Nickel in a Magnetic Field at Low Temperatures," in *Proceedings of 10th International Congr. Refrig.* (Copenhagen), 63–6, 1960.

[136] Berger, L., and Rivier, D., "Electrical and Thermal Resistivity of Pure Nickel and of an Iron-Nickel Alloy in a Magnetic Field at Low Temperatures," Helv. Phys. Acta. (Switzerland), **35**(7/8), 715–32, 1962.

[137] Berget, A., "Measurement of the Thermal Conductivity of Mercury, of Its Absolute Value," Compt. Rend., **105**, 224–9, 1887.

[138] Berman, R., "The Thermal Conductivity of Some Polycrystalline Solids at Low Temperatures," Proc. Phys. Soc. (London), **A65**(12), 1029–40, 1952.

[138a] Berman, R., Private communication, January 20, 1969.

[139] Berman, R., Bounds, C. L., Brock, J. C. F., and Rogers, S. J., "Phonon-Scattering by Isotopes," Bull Inst. Intern. Froid Annexe, 91–9, 1965–2.

[140] Berman, R., Bounds, C. L., Day, C. R., and Sample, H. H., "Thermal Conductivity of Solid He^4 and of Isotopic Mixtures at High Densities," Phys. Letters, **26A**(5), 185–6, 1968. [AD 669 761]

[141] Berman, R., Bounds, C. L., and Rogers, S. J., "The Effect of Isotopes On Lattice Heat Conduction. II. Solid Helium," Proc. Roy. Soc. (London), **A289**(1416), 66–80, 1965.

[142] Berman, R., Brock, J. C. F., and Huntley, D. J., "Properties of Gold + 0.03 percent (At.) Iron Thermoelements Between 1 and 300 K and Behavior in a Magnetic Field," Cryogenics (GB), **4**(4), 233–9, 1964.

[143] Berman, R., Foster, E. L., and Ziman, J. M., "The Thermal Conductivity of Dielectric Crystals: The Effect of Isotopes," Proc. Roy Soc. (London), **A237**, 344–54, 1956.

[144] Berman, R., and MacDonald, D. K. C., "The Thermal and Electrical Conductivity of Sodium at Low Temperatures," Proc Roy. Soc. (London), **A209**, 368–75, 1951.

[145] Berman, R., and MacDonald, D. K. C., "The Thermal and Electrical Conductivity of Copper at Low Temperatures," Proc. Roy. Soc. (London), **A211**, 122–8, 1952.

[146] Berman, R., and Rogers, S. J., "The Thermal Conductivity of bcc ^4He and of Isotopic Mixtures," in *Proc. 9th Int. Conf. Low Temperature Physics*, Plenum Press, N.Y., 262–5, 1965.

[147] Berman, R., Simon, F. E., and Ziman, J. M., "The Thermal Conductivity of Diamond at Low Temperatures," Proc. Roy. Soc. (London), **A220**, 171–83, 1953.

[148] Bernè, A., Boato, G., and dePaz, M., "Experiments on Solid Argon," Nuovo Cimento, **346**(2), 182–209, 1966.

[149] Bertman, B., Fairbank, H. A., Guyer, R. A., and White, C. W., "Thermal Conductivity in Isotopic Mixtures of Solid Helium," Phys. Rev., **142**(1), 79–85, 1966, [AD 629943].

[150] Bertman, B., Fairbank, H. A., White, C. W., and Crooks, M. J., "Thermal Conductivity in Solid He^3 and He^4," Phys. Rev., **142**(1), 74–9, 1966; Bertman, B., Fairbank, H. A., Guyer, R. A., and White, C. W., "Thermal Conductivity in Isotopic Mixtures of Solid Helium," Phys. Rev., **142**(1), 79–85, 1966.

[151] Bertman, B., Fairbank, H. A., White, C. W., and Crooks, M. J., "Thermal Conductivity in Solid He^3 and He^4," Phys. Rev., **142**(1), 74–9, 1966, [AD 629975]

[152] Bertman, B., and Guyer, R. A., "Solid Helium," Sci. Amer., **217**, 85–96, 1967.

[153] Bertman, B., White, C. W., and Fairbank, H. A., "Thermal Conductivity of Isotopic Mixtures of Solid Helium," in *Proceedings of 9th Int. Conf. Low Temperature Physics*, Plenum Press, N.Y., 266–9.

[154] Betterton, J. O., "Electronic Properties of Metals and Alloys," USAEC Rept. ORNL–3870, 27–37, 1965.

[155] Bhagat, S. M., and Manchon, D. D., Jr., "Thermal Conduction in Bismuth at Liquid Helium," Phys. Letters, **A24**(3), 147–8, 1967.

[156] Bhagat, S. M., and Manchon, D. D., "Heat Transport in Bismuth at Liquid-Helium Temperatures," Phys. Rev., **164**(3), 966–70, 1967.

[157] Bidwell, C. C., 'Thermal Conductivity of Li and Na by a Modification of the Forbes Bar Method," Phys. Rev., **28**, 584–97, 1926.

[158] Bidwell, C. C., "A Precise Method of Measuring Thermal Conductivity Applicable to Either Molten or Solid Metals. Thermal Conductivity of Zinc," Phys. Rev., **56**(6), 594–8, 1939.

[159] Bidwell, C. C., "Thermal Conductivity of Metals," Phys. Rev., **58**(2), 561–4, 1940.

[160] Bidwell, C. C., and Hogan, C. L., "Thermal Conductivity of Aluminum, Solid and Liquid States," J. Appl. Phys., **18**, 776–9, 1947.

[161] Bidwell, C. C., and Lewis, E. J., "Thermal Conductivity of Lead and of Single and Polycrystal Zinc," Phys. Rev., **33**(2), 249–51, 1929.

[162] Bing, G. F., Fink, F. W., and Thompson, H. B., "The Thermal and Electrical Conductivities of Zirconium and Its Alloys," USAEC Rept. BMI–65, 1–19, 1951.

[163] Birch, F., "The Electrical Resistance and the Critical Point of Mercury," Phys. Rev., **41**, 641–48, 1932.

[164] Birch, J. A., Kemp, W. R. G., Klemens, P. G., and Tainsh, R. J., "The Lattice Thermal Conductivity of Some Gold Alloys," Aust. J. Phys., **12**(4), 455–65, 1959.

[165] Bird, B. L., "Thermal Conductivity of *n*-type Germanium from 0.3 to 4.2 K," Purdue Univ., Ph.D. Thesis, Univ. Microfilm Publ. 69–2889, N69–36049, 60 pp., 1968.

[166] Bird, B. L., and Pearlman, N., "Thermal Conductivity of N-type Germanium from 0.3 K to 4.2 K," in *Proceedings of the Seventh Conference on Thermal Conductivity* (Flynn, D. R. and Peary, B. A., Jr., Editors), NBS–SP–302, 103–9, 1968.

[167] Blais, N. C., and Mann, J. B., "Thermal Conductivity of Helium and Hydrogen at High Temperatures," J. Chem. Phys., **32**(5), 1459–65, 1960: Mann, J. B. and Blais, N. C., USAEC Rept. LA 2316, 1–39, 1959.

[168] Blewer, R. S., "Low Temperature Study of the Electronic Density of States of Antimony," Louisiana State Univ., Ph.D. Thesis, Univ. Microfilms Publ. 67–8769, 73 pp., 1967.

[169] Blewer, R. S., and Zebouni, N. H., "Lattice Thermal Conductivity of Antimony down to 0.4° K," Phys. Letters, **23**(5), 297–8, 1966.

[169a] Bloch, F., "On the Quantum Mechanics of Electrons in Crystalline Lattice," Z. Physik, **52**, 555–600, 1928.

[170] Boato, G., "Thermoconductivity of Solid Argon," NASA E–302–P, 10 pp., 1963.

[171] Boato, G., "Thermal Conductivity of Solid Argon," Univ. di Genova (Italy) Rept., 1–13, 1964. [AD 601 682]

[172] Bobone, R., Kendall, L. F., and Vought, R. H., "Semiconducting Compounds for Thermoelectric Power Generation," U.S. Army Rept. TCREC–TR–62–112, 1–31, 1962. [AD 297 918]

[173] Bocquet, M., and Micaud, G., "Heat Conduction by Nuclear Graphite," Bull. Inform. Sci. Tech. (Paris), 79, 83–96, 1964.

[174] Bode, K. H., "A New Method to Measure the Heat Conductivity of Metals at High Temperatures," Allgem. Warmetech., **10**(7) , 125–42, 1961.

[175] Bode, K. H., "Measurement of Thermal Conductivity of Pure Platinum between 0 and 100 C," Sonderdr. Aus. Ptb-Mitteilungen, 5, 416–20, 1964.

[176] Bode, K. H., and Fritz, W., "New Apparatus for Measuring the Thermal Conductivities of Metals," Z. Angew. Phys., **10**(10), 470–9, 1958.

[177] Bogaard, R. H., "Thermal Resistivity of Cadmium, Magnesium, and Alloys at Low Temperature," Purdue Univ., Ph.D. Thesis, 48 pp., 1970.

[178] Bogaard, R. H., and Gerritsen, A. N., "Thermal Resistivity of Cadmium and Cadmium-Zinc," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N.Y., 185–90, 1969.

[179] Bokros, J. C., Price, R. J., and Koyama, K. K., "Neutron-Induced Changes in Crystallinity and Thermal Conductivity of Pyrolytic Carbons," Carbon (Oxford), **4**, 293–5, 1966.

[180] Bokros, J. C., Price, R. J., and Koyama, K. K., "Neutron-Induced Changes in Crystallinity and Thermal Conductivity of Pyrolytic Carbons," USAEC Rept. GA–6927, 1–7, 1966.

[181] Booker, J., Paine, R. M., and Stonehouse, A. J., "Investigation of Intermetallic Compounds for Very High Temperature Applications," USAF Rept. WADD–TR–60–889, 1–133, 1961. [AD 265 625]

[182] Borovik, E., Matveev, A., and Panina, E., "Thermal Conductivity of Liquid Nitrogen, Carbon Monoxide, Methane, and Ethylene," J. Tech. Phys. (USSR), **10** (12), 988–98, 1940.

[183] Borovik, E., "Heat Conductivity of Nitrogen," Zh. Eksp. Teor. Fiz., **17**, C328–35, 1947.

[184] Bortz, S. A., and Connors, C. L., "Physical Properties of Refractory Materials," IIT Research Inst., Quarterly Rept. No. 6 for Contract AF 33 (615)–3028, 1–67, 1966. [AD 804 035]

[185] Boughton, R. I., and Yaqub, M., "Size Effect in the Electronic Thermal Conductivity of Gallium Single Crystals," Phys. Rev. Lett., **20**(3), 108–10, 1968.

[186] Bourdeau, R. G., "New Pyrolytic Materials," Mater. in Design Eng., **56**(2), 106–109, 1962.

[187] Bowers, R., "The Thermal Conductivity of Liquid Helium I," Proc. Phys. Soc. (London), **A65**, 511–18, 1952.

[188] Bowers, R., and Mendelssohn, K., "Heat Conductivity of Liquid Helium I," Nature (London), **167**, 111, 1951.

[189] Bowman, H. F., Ziebold, T. O., and Smith, J. L., Jr., "Low Temperature Thermal Conductivity of Copper Irradiated with Reactor Neutrons," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N.Y., 175–84, 1969.

[190] Bowman, J. C., Krumhansl, J. A., and Meers, J. T., "X-Ray and Low-Temperature Thermal Conductivity Study of Defects in Graphite," in *Ind. Carbon and Graphite Conf.* (London, 1957), 52–9, 1958.

[191] Boxer, A. S., "The Thermal Conductivity of Impure Tin at Low Temperatures," Univ. of Connecticut, Ph.D. Thesis, 1–74, 1958.

[192] Boys, D. W., "Thermal Conductivity of Dysprosium, Erbium, and Lutetium Single Crystals," Iowa State Univ., Ph.D. Thesis, 1–80, 1967; USAEC Rept. IS–T–185, 1–80, 1967; Boys, D. W. and Legvold, S., "Thermal Conductivities and Lorenz Functions of Dysprosium, Erbium, and Lutetium Single Crystals," Phys. Rev., **174**(2), 377–84, 1968.

[193] Bradford, C. S., "The Properties of Fluids," Phil. Mag., **34**, 433–71, 1943.

[194] Braun, H. G., "Measuring the Thermal Conductivity of Solids at Elevated Temperatures up to the Melting Point," Intern. Z. Gaswaerme, **15**(7), 207–18, 1966.

[195] Brazel, J. P., "The Thermal Conductivity of ATJ Graphite," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, New York, 573, 1969.

[196] Brazel, J. P., and Kennedy, B. S., "The Thermal Conductivity of ATJ Graphites," in *9th Conf. on Thermal Conductivity* (Shanks, H. R., Editor), USAEC Rept. CONF–691002, 365, 1970.

[197] Brazel, J. P., and Styhr, K. H., "High Temperature Radial Heat Flow Measurements," in *Thermal Conductivity—Proceedings of the Seventh Conference* (Flynn, D.

R., and Peavy, B. A., Jr., Editors), NBS–SP–302, 415–24, 1968.

[198] Breckenridge, R. G. (Coordinator), "Thermoelectric Materials," Union Carbide Corp. Parma Research Lab. Bimonthly Progr. Rept. No. 4, 1–33, 1959. [AD 231 650]

[199] Breckenridge, R. G., "Thermoelectric Materials," Union Carbide Corp. Parma Research Lab. Progr. Rept. No. 8, 28 Mar.–28 May 1960, 1–20, 1960. [AD 245 092]

[200] Breckenridge, R. G., "Thermoelectric Materials," Union Carbide Corp. Parma Research Lab. Progr. Rept. No. 7, 28 Jan.–28 Mar. 1960, 1–20, 1960. [AD 245 217]

[201] Bremmer, H., and deHaas, W. J., "On the Conduction of Heat by some Metals at Low Temperatures: Lead, Copper, Tungsten," Physica, **3**(7), 672–86, 1936.

[202] Brenden, B. B., and Newkirk, H. W., "Method of Determining the Thermal Conductivity of Incandescent Solids," USAEC Rept. HW–59574, 1–45, 1959.

[203] Brewer, D. F., and Edwards, D. O., "Measurements of the Heat of Transport of Liquid Helium-II," Proc. Phys. Soc. (London), **71**, 117–25, 1958.

[204] Brewer, D. F., and Edwards, D. O., "Heat Conductivity and Viscosity of Liquid Helium-II," Proc. Roy. Soc. (London), **A251**, 247–64, 1959.

[205] Brewer, J., "Thermodynamic Data on Oxygen and Nitrogen," USAF Rept. ASD–TR–61–625, 1–151, 1961. [AD 275 728]

[206] Brice, J. C., and Whiffen, P. A. C., "The Temperature Distribution in Pulled Germanium Crystals during Growth," Solid State Electronics, **7**, 183–87, 1964.

[207] Bridgman, P. W., "Two New Modifications of Phosphorus," J. Am. Chem. Soc., **36**, 1344–63, 1914.

[208] Bridgman, P. W., "Further Note on Black Phosphorus," J. Am. Chem. Soc., **38**, 609–12, 1916.

[209] Bridgman, P. W., "Certain Physical Properties of Single Crystals of Tungsten, Antimony, Bismuth, Tellurium, Cadmium, Zinc, and Tin," Proc. Am. Acad. Arts and Sci., **60**(6), 303–449, 1925.

[210] Bridgman, P. W., "Thermal Conductivity and Thermal EMF of Single Crystals of Several Non-Cubic Metals," Proc. Am. Acad. Arts and Sci., **61**, 101–34, 1926.

[211] Briggs, L. J., "Gallium. Thermal Conductivity, Supercooling, Negative Pressure," J. Chem. Phys., **26**(4), 784–6, 1957.

[212] Briggs, R. B., "Molten-Salt Reactor Program," USAEC Rept. ORNL–3626, 161 pp., 1964.

[213] Brookhaven National Lab. Progr. Rept. USAEC Rept. BNL–671 (S–58), 1–64, 1961.

[214] Reference withdrawn.

[215] Brown, A. R. G., Watt, W., Powell, R. W., and Tye, R. P., "Thermal and Electrical Conductivities of Deposited Carbon," Brit. J. Appl. Phys., **7**, 73–6, 1956.

[216] Brown, H. M., "Effect of Magnetic Field upon Thermal Conductivity of Iron, Copper, Silver and Gold," Univ. of Calif., Berkely, Ph.D. Thesis, 1–21, 1927.

[217] Brown, H. M., "Effect of Magnetic Fields upon the Thermal Conductivity of Iron, Copper, Gold, Silver, and Zinc," Phys. Rev., **32**, 508–14, 1928.

[218] Brown, R. M., "Development of an Inductively Heated High Temperature Thermal Conductivity Device," Univ. of Illinois, M. S. Thesis, 63 pp., 1962.

[219] Brown, W. B., "Thermal Conductivities of Some Metals in the Solid and Liquid States," Phys. Rev., **22**, 171–9, 1923.

[220] Buerschaper, R. A., "Thermal and Electrical Conductivity of Graphite and Carbon at Low Temperatures," J. Appl. Phys., **15**, 452–4, 1944.

[221] Bungardt, K., and Spyra, W., "Thermal Conductivity of Alloyed and Plain Steels and Alloys at Temperatures Between 20 and 700°," Arch. Eisenhuettenw., **36**(4), 257–67, 1965.

[222] Bungardt, W., and Kallenbach, R., "Thermal and Electrical Conductivity of Aluminum and Aluminum Alloys," Z. Metallk., **42**, 82–91, 1951.

[223] Burger, R., Dittrich, H., and Kock, K. M., "Changes in the Thermal Conductivity of Ferromagnetic Nickel-Copper Alloys in a Magnetic Field," Z. Naturf. **23**(6), 861–6, 1968.

[224] Burr, A. C., "A Radial Heat Flow Apparatus for the Determination of Thermal Conductivity," Can. J. Tech., **29**(11), 451–7, 1951.

[225] Burstein, E., "The Physics of Semiconductor Materials," NRL Rept. 4595 1–68, 1956. [AD 84 642]

[226] Bursuc, I., "Thermal Conductivities of Iron and Bismuth in Magnetic Field—Determined by a Method in Variable Conditions," Anslete Univ. Iasi Mat. Fiz., **4**(1), 129–43, 1958.

[227] Bursuc, I., "Thermal Conductivity in a Bismuth Rod Under the Action of Ultrasonic Vibrations," An. Stiint. Univ. "Al. I. Cuza" Iasi (Ser. Nova) I (Roumania), Pt. I, **6**, 137–41, 1960.

[228] Burton, J. T. A., and Ziebland, H., "The Thermal Conductivity of Liquid and Gaseous Oxygen," ERDE Rept. 2/R/56, 1–15, 1956. [AD 90 759]

[229] Burton, J. T. A., and Ziebland, H., "The Thermal Conductivities of Nitrogen and Argon in the Liquid and Gaseous States," ERDE Rept. 11/R/57, 1–13, 1957. [AD 145 956]

[230] Busch, G., and Steigmeier, E., "Thermal and Electrical Conductivities, Hall Effect and Thermoelectric Power of InSb," Helv. Phys. Acta (Switzerland), **34**(1), 1–28, 1961.

[231] Bushong, R. M., Zeitsch, K. J., and Higgs, P. H., "Pyrolytic Coating of Carbon Filaments," Union Carbide Corp. Quarterly Progr. Rept. (15 Nov. 63–15 Feb. 64), 18 pp., 1964. [AD 447 951]

[232] Caldwell, R. T., and Walley, D. M., "Physical and Thermodynamic Properties of Potassium," AFAPL–TR–66–104, 1–65, 1966. [AD 804 896]

[233] Calverley, A., Mendelssohn, K., and Rowell, P. M., "Some Thermal and Magnetic Properties of Tantalum, Niobium, and Vanadium at Helium Temperatures," Cryogenics, **2**, 26–33, 1961.

[234] Campbell, J. E., Goodwin, H. B., Wagner, H. J., Douglass, R. W., and Allen, B. C., "Introduction to Metals for Elevated-Temperature Use," Battelle Memorial Inst. Defense Metals Information Center Rept., DMIC 160, 1–92, 1961.

[235] Carlson, J. R., "Thermal Conductivity of Superconducting Niobium," Univ. of Illinois, Ph.D. Thesis, Univ. Microfilm Publ. 69–1311, N 69–30982, 84 pp., 1968.

[236] Carlson, O. N., Chiotti, P., Murphy, G., Peterson, D., Rogers, B. A., Smith, J. F., Smutz, M., Voss, M., and Wilhelm, H. A., "The Metallurgy of Thorium and Its Alloys," in *Proceedings of Int. Conf. for Peaceful Uses of Atomic Energy*, Vol. 9, 74–106, 1955.

[237] Carnegie Inst. of Tech., "The Thermal Conductivity of Inorganic Melts," Annual Rept. and Proposal for Renewal of Contract AT(30–1)–2B60, 1961.

[238] Carpenter, F., Engle, G. B., Goeddel, W., Godsin, W., Pontelandolfo, J., Pyle, R., and Shoffner, J., "The Development and Evaluation of Graphite-Matrix Fuel Compacts for the HTGR, "USAEC Rept. GA–2289, 96 pp., 1961.

[239] Carroll, J. M., "The Thermal Conductivity of Thermocouple Grade Constantan Rod," Final Rept. on Task 5., SRI Rept. 6833–1481–XXIII, NASA–CR–56932, N64–27298, 28 pp., 1964.

[240] Carruthers, J. A., Cochran, J. F., and Mendelssohn, K., "Thermal Conductivity of P-Type Germanium Between 0.2 and 4 K," Cryogenics, **2**(3), 160–6, 1962.

[241] Carruthers, J. A., Geballe, T. H., Rosenberg, H. M., and Ziman, J. M., "The Thermal Conductivity of Germa-

nium and Silicon Between 2 and 300 K," Proc. Roy. Soc. (London), **A238**, 502–14, 1957.

[242] Cartwright, C. H., "The Wiedemann-Franz Constant Heat Conductivity and Thermoelectric Forces of Tellurium," Ann. Physik, **18**(5), 656–78, 1933.

[243] Casimir, H. B. G., "Note on the Conduction of Heat in Crystals," Physica, **5**(6), 495–500, 1938.

[244] Casimir, H. B. G., "Note on the Conduction of Heat in Crystals," Commun. Kamerlingh Onnes Lab., Univ. Leiden, Suppl. No. 85B, 1–6, 1938–42.

[245] Cason, J. L., Jr., "Thermal Conductivity Measurements of EuO Across the Curie Point," South Dakota School of Mines and Techl., M. S. Thesis, N68–10715, 85 pp., 1967.

[246] Cellier, L., "Thermal Conductivity of Carbon for Heat and Electricity," Ann. Physik, **61**, 511–526, 1898.

[247] Cerceo, J. M., "An Instrument for Measuring Thermal Properties." ISA Transactions, **2**(3), 202–6, 1963.

[248] Cezairliyan, A., "Prediction of Thermal Conductivity of Metallic Elements and Their Dilute Alloys at Cryogenic Temperatures," Purdue Univ. TPRC Rept. 14, 1–140, 1962; U.S. Air Force Rept. ASD–TDR–63–291, 1–140, 1963.

[249] Cezairliyan, A., and Touloukian, Y. S., "Generalization and Calculation of the Thermal Conductivity of Metals by Means of the Law of Corresponding States," Teplofiz. Vys. Temp., **3**(1), 75–85, 1965; English translation: High Temp. **3**(1), 63–75, 1965.

[250] Cezairliyan, A., and Touloukian, Y. S., "Correlation and Prediction of Thermal Conductivity of Metals Through the Application of the Principle of Corresponding States," in *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, Proceedings of the Third Symposium on Thermophysical Properties, ASME, 301–13, 1965.

[251] Chakraborti, P. K., "Intermolecular Potential of Radon," J. Chem. Phys., **44**(8), 3137–8, 1966.

[252] Chakraverty, B. K., "On the Excess Entropy of Fusion of Semiconducting and Semimetallic Elements," J. Phys. Chem. Solids, **30**(2), 454–7, 1969.

[253] Champetier, R. J., "Basal Plane Emittance of Pyrolytic Graphite at Elevated Temperatures," Aerospace Rept. TR–0158 (3250–20)–10, 1–39, 1967.

[254] Champion, F. C., "Some Physical Properties of Diamonds," Advances in Phys., **5**(20), 383–411, 1956.

[255] Chang, H., and Blair, M. G., "A Longitudinal Symmetrical Heat Flow Apparatus for the Determination of the Thermal Conductivity of Metals and their Alloys: on Armco Iron." in *Thermal Conductivity—Proceedings of the* Eighth Conf. (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N. Y., 689–98, 1969.

[256] Chao, M. S., and Stenger, V. A., "Some Physical Properties of Highly Purified Bromine," Talanta, **11**, 271–81, 1964.

[257] Chapman, S., and Cowling, T. G., *The Mathematical Theory of Non-Uniform Gases; An Account of the Kinetic Theory of Viscosity, Thermal Conduction, and Diffusion in Gases*, Cambridge Univ. Press, 1939; 2nd Edition, 1952; 3rd Edition, 1970.

[258] Chari, M. S. R., and deNobel, J., "Thermal Conductivity of Some Dilute Silver Alloys at Low Temperatures and in Magnetic Fields," Physica, **25**(1), 60–72, 1959.

[259] Charsley, P., and Salter, J. A. M., "The Lattice Thermal Conductivity of Annealed Copper-Aluminum Alloys," Phys. Status Solidi, **10**(2), 575–83, 1965.

[260] Chase, C. E., "Thermal Conduction in Rotating Liquid Helium II," Phys. Rev., **120**, 688–96, 1960.

[261] Chaudhuri, K. D., Mendelssohn, K., and Thompson, M. W., "Effect of Radiation Damage on the Thermal Conductivity of Superconductors," Cryogenics, **1**(1) 47–8, 1960.

[262] Chechovskoy, V. Ya., and Vertogradski, V. A., "Tungsten Thermal Conductivity as Measured by Modified Method of Experimental Temperature Distribution," in *9th Conference on Thermal Conductivity*, USAEC Rept. CONF–691002, 300–6, 1970.

[263] Chelton, D. B., and Mann, D. B., "Cryogenic Data Book," USAEC Rept. UCRL–3421, 1956.

[264] Chelton, D. B., and Mann, D. B., "Cryogenic Data Book," WADC TR–59–8, 1–144, 1959. [AD 208 155]

[265] Chen, C. Y. C., "Thermal Conductivity of Graphite Compounds," Ohio State Univ., M. S. Thesis, 38 pp., 1961.

[266] Cherpakov, V. P., "Thermal and Electrical Conductivity of Bismuth-Lead Alloys," Moscow Univ. Vestnik Seriia Matematiki Mekhaniki Astronomii Fiziki Khimii, **12**(3), 129–34, 1957.

[267] Cheung, H., "Thermal Conductivity and Viscosity of Gas mixtures," USAEC Rept. UCRL–8230, 1–146, 1958.

[268] Cheung, H., LeBromley, R. A., and Wilke, C. R., "Thermal Conductivity and Viscosity of Gas Mixtures," USAEC Rept. UCRL–8230 Rev., 1–64, 1959.

[269] Child, C. D., and Quick, R. W., "Thermal Conductivity of Copper. Part I, Conductivity at High Temperatures," Phys. Rev., **2**, 412–23, 1894.

[270] Childers, H. M., and Cerceo, J. M., "Electron Beam Techniques for Measuring the Thermophysical Properties of Materials," USAF Rept. WADD TR–60–190, 1–66, 1961.

[271] Childs, G. E., and Hanley, H. J. M., "The Viscosity and Thermal Conductivity Coefficients of Dilute Nitrogen and Oxygen," NBS Tech. Note 350, 27 pp., 1966.

[272] Chiotti, P., and Carlson, O. N., "Semi-annual Hanford Slug Report. July 1 to Dec. 31, 1955," USAEC Rept. ISC–709, 1–23, 1956.

[273] Chirkin, V. S., "Heat Conductivity of Gases," John Crerar Library, SLA Translation Center, Chicago, F–TS–9928/V, 1–21, 1960.

[274] Chirkin, V. S., *Thermal Conductivity of Industrial Materials*, Mashgiz, 1962; See Reference 1239, p. 277.

[275] Chirkin, V. S., "Thermal Diffusivity and Thermal Conductivity of Metallic Beryllium," At. Energ. (USSR), **20**(1), 80–2, 1966.

[276] Chu, Univ. of London, Ph.D. Thesis, 1938; See Reference 1367.

[277] Chubb, W. F., "Thermal Conductivity Determinations. A New Apparatus and Procedure," Metal Ind. (London), **52**, 579–80, 1938.

[278] Cinnamon, C. A., "The Thermal Resistivity and the Wiedemann-Franz Ratio of Single-Crystal Zinc," Phys. Rev., **46**(2), 215–21, 1934.

[279] Ciszek, T. F., "The Thermal Diffusivity and Electrical Resistivity of Platinum at Temperatures above 1000 K," Iowa State Univ., M. S. Thesis, 1–57, 1966.

[280] Cleary, R. E., and Kapelner, S. M., "Alkali-Metal Physical Properties Programme at Pratt and Whitney Aircraft, Canel," USAEC Rept. BNL–756, 19–39, 1961.

[281] Clifford, J. M., "Thermal and Electrical Conductivities of Lead-Bismuth Alloys," Univ. Microfilms Publ. 13036, 1–82, 1955.

[282] Cacciotti, J. J., "Graphite and Its Properties," General Electric Co., Flight Propulsion Laboratory Dept., 1–63, 1958, Rev. 1960.

[283] Cohen, A. F., "Low-Temperature Thermal Conductivity of Nonmetals," USAEC Rept. ORNL–2413, p. 69, 1957.

[284] Cohen, E. G. D., Offerhaus, M. J., and deBoer, J., "Transport Properties and Equation of State of Gaseous Mixtures of Helium Isotopes," Physica, **20**, 501–15, 1954.

[285] Coleman, R. V., Private communication to D. C. Lawson and B. T. Boiko, cited as Ref. 11 in Appl. Phys. Lett., **5**(8), 155–6, 1964.

[286] Collins, D. J., Grief, R., and Bryson, A. E., Jr., "Measurement of the Thermal Conductivity of Helium in the Temperature Range 1600–6700 K," Int. J. Heat Mass Transfer, **8(9)**, 1209–16, 1965.
[287] Collins, D. J., and Menard, W. N., "Measurement of the Thermal Conductivity of Noble Gases in the Temperature Range 1500 to 5000 K," J. Heat Mass Transfer, **88C**(1), 52–6, 1966.
[287a] Collins, J. G., and Ziman, J. M., "Low-Temperature Transport Properties of the Alkali Metals. II. The Transport Coefficients," Proc. Roy. Soc. (London), **A264**, 60–87, 1961.
[288] Colvin, R. V., and Arajs, S., "Thermal Conductivity of Polycrystalline Dysprosium from 5 to 305 K," Phys. Rev., **A133**(4), 1076–9, 1964.
[289] Colvin, R. V., Legvold, S., and Spedding, F. H., "Electrical Resistivity of the Heavy Rare-Earth Metals," Phys. Rev., **120**(3), 741–5, 1960.
[290] Compton, A. H. (Project Director), "Metallurgical Project," Rept. for period ending November 27, 1943, OTS CP–1087, 30 pp., 1943.
[291] Connolly, A., and Mendelssohn, K., "Thermal Conductivity of Tantalum and Niobium Below 1 K," Proc. Roy. Soc. (London), **266**, 429–39, 1962.
[292] Cooke, J. W., "The Experimental Determination of the Thermal Conductivity of Molten Lithium from 600 to 1550 F," Univ. of Tennessee, M. S. Thesis, USAEC Rept. ORNL–3390, 1–151, 1964.
[293] Cooke, J. W., "Thermophysical Property Measurements of Alkali Liquid Metals." in *Proc. 1963 High Temp. Liquid-Metal Heat Trans. Tech. Meeting* (ORNL, Tenn., 1964), USAEC Rept. ORNL–3605, Vol. 1, 66–87, 1964.
[294] Cooke, J. W., "Experimental Determination of the Thermal Conductivity of Molten Lithium from 320 to 830 Degrees," J. Chem. Phys., **40**(7), 1902–9, 1964.
[295] Cook, J. G., and van der Meer, M. P., "The Thermal Conductivity and Electrical Resistivity of Gold from 80 to 340 K," Can. J. Phys., **48**(3), 254–63, 1970.
[296] Cooper, M. H., "Measurement of Thermal Conductivity of a Yellow Brass and Cadmium at Low Temperature," Georgia Institute of Technology, Atlanta, Georgia, M. S. Thesis, 77 pp., 1964.
[297] Correia, P., Schramm, B., and Schäfer, K., "The Thermal Conductivity of Gases in a Large Temperature Range," Ber. Bunsenges. Phys. Chem., **72**(3), 393–9, 1968.
[298] Corrucini, R. J., Liquid Hydrogen Technology Paper, Grenoble, France, 1965.
[299] Costas, L. P., "Thermal Conductivity of Aluminum-Lithium Alloys Containing up to 8% Lithium," USAEC, 6 pp., 1960.
[300] Cotignola, J. M., de la Cruz, F., de la Cruz, M. E., and Platzeck, R. P., "Thermal Conductivity of Polycrystalline Zinc Below 1 K," Rev. Sci. Instr., **38**(1), 87–92, 1967.
[301] Cotignola, J. M., de la Cruz, F., de la Cruz, M. E., and Platzeck, R. P., "Thermal Conductivity of Polycrystalline Zinc," NASA, N68–25587, CNCA–202, 23 pp., 1967.
[301a] Cotton, J. E., "Thermal Conductivity of Binary Mixtures of Gases," Univ. of Oregon, Ph.D. Thesis, 1962.
[302] Cox, M., "Thermal and Electrical Conductivities of Tungsten and Tantalum," Phys. Rev., **64**, 241–7, 1943.
[303] Crary, A. P., "Thermal Conductivity of Acheson Graphite," Phys., **4**, 332–3, 1933.
[304] Crooks, M. J., and Fairbank, H. A., "The Thermal Conductivity of Solid ^3He and Solid ^4He," in *Proceedings of the Eighth International Conf. on Low Temperature Physics* (London, 1962), Butterworths, 417–8, 1963.
[305] Curie, M., and Lepape, A., "Electricity. Thermal Conductivity of Rare Gases," Compt. Rend., 193, 842–3, 1931.
[306] Curie, M., and Lepape, A., "Thermal Conductivity of Rare Gases," J. Phys. Radium, **2**, 393–97, 1931.
[307] Currie, L. M., Hamister, V. C., and MacPherson, H. G., "The Production and Properties of Graphite for Reactors," in *Proc. Int. Conf. Peaceful Uses Atomic Energy*, 1–49, 1955.
[308] Curry, M. A., Legvold, S., and Speeding, F. H., "Electrical Resistivity of Europium and Ytterbium," Phys. Rev., **117**(4), 953–4, 1960.
[309] Cutler, M., "Small Area Contact Methods," Advanced Energy Conversion, **2**, 29–43, 1962.
[310] Cutler, M., and Cheney, G. T., "Measurement of Thermal Conductivity of Electrical Conductors at High Temperatures," J. Appl. Phys. (USA), **34**(6), 1714–18, 1963.
[311] Cutler, M., and Mallon, C. E., "Thermoelectric Study of Liquid Semiconductor Solutions of Tellurium and Selenium," J. Chem. Phys., **37**, 2677–83, 1962.
[312] Cutler, M., Snodgrass, H. R., Cheney, G. T., Appel, J. C., Mallon, C. E., and Meyer, C. H., Jr., "Thermal Conductivity of Reactor Materials," Final Report, General Dynamics Corp. San Diego, Calif., USAEC, GA–1939, 1–99, 1961.
[313] Damon, D. H., and Klemens, P. G., "Electrical Resistivity of Some Gold Alloys: A Search for Effects Due to Local Modes," Phys. Rev., **138**(5A) A1390–4, 1965.
[314] Danielson, G. C., (Chiotti, P., and Carlson, O. N.), USAEC Rept. ISC–314, 1–26, 1953.
[315] Danielson, G. C., Quarterly Summary Research Report in Physics for October, November, and December 1954, USAEC Rept. ISC–577, 1–13, 1954.
[316] Danielson, G. C., (Chiotti, P., and Carlson, O. N.) Quarterly Report, Hanford Slug Program, October, November, December 1953., USAEC Rept. ISC–452, 1–39, 1954.
[317] Dauphinee, T. M., Armstrong, L. D., and Woods, S. B., "The Thermal Conductivity of Pure Lead," Can. J. Phys., **44**(9), 2035–39, 1966.
[318] Davey, G., and Mendelssohn, K., "Heat Conductivity of Pure Metals Below 1 K," Phys. Letters (Netherlands) **7**(3), 183–4, 1963.
[319] Davidson, J. M., and Music, J. F., "Experimental Thermal Conductivity of Gases and Gaseous Mixtures at Zero Degrees Centigrade ," USAEC Rept. HW–29021, 7–30, 1953.
[320] Davis, M., Densem, P. C. E., and Rendall, J. H., "The Manufacture and Properties of High-Strength Nickel-Tungsten Alloys," J. Inst. Metals, **84**, 160–64, 1955–6.
[321] Day, R. K., "Thermal Conductivity of High Conductivity Materials, I. Measurement," Am. Ceram. Soc. Bull., **44**(8), 608–11, 1965.
[322] DeCombarieu, A., "The Effects of Irradiation on the Thermal Conductivity at Low Temperatures of Pseudo-Monocrystalline Graphite," Bull. Inst. Intern. Froid, Annexe 1965–2, 63–72, 1965.
[323] DeCombarieu, A., "Thermal Conductivity of almost Monocrystalline Graphite and Effects of Neutron Irradiation. I. Measurements," J. Physique (Paris), **28**(11–12), 951–4, 1967.
[324] Deegan, G. E., "Thermal and Electrical Properties of Graphite Irradiated at Temperatures from 100 to 425 K," USAEC Rept. NAA–SR–1716, 1–77, 1956.
[325] Deem, H. W., "Thermal Conductivity of Zirconium and Zirconium-Tin Alloys," USAEC Rept. BMI 849, 1–9, 1953.
[326] Deem, H. W., "Thermal Conductivity and Electrical Resistivity of Hafnium," USAEC Rept. BMI 853, 1–12, 1953.
[327] Deem, H. W., and Lucks, C. F., "Thermal Conductivity of Uranium and UO_2." From Progress Relating to Civilian Applications During January 1959, Battelle

Memorial Inst., Columbus, Ohio, USAEC Rept. BMI 1315, 7–9, 1959.

[328] Deem, H. W., and Matolich, J., Jr., "The Thermal Conductivity and Electrical Resistivity of Liquid Potassium and the Alloy Niobium—1 Zirconium," Battelle Memorial Inst. Columbus, Ohio, NASA, BATT–4673–T6, 1–26, 1963.

[329] Deem, H. W., and Nelson, H. R., "Thermal Conductivity of Powder-Metallurgy Uranium," USAEC Rept. BMI 745, OTS, 7–15, 1952.

[330] Deem, H. W., Pobereskin, M., Lusk, E. C., Lucks, C. F., and Calkins, G. D., "Effect of Radiation on the Thermal Conductivity of Uranium–1.6 w/o Zirconium," USAEC Rept. BMI–986, 1–19, 1955.

[331] Deem, H. W., Wood, W. D., and Lucks, C. F., "The Relationship between Electrical and Thermal Conductivities of Titanium Alloys," Trans. Met. Soc., Amer. Inst. Min. Met. Eng., **212**(4), 520–3, 1958.

[332] de Haas, W. J., and Biermasz, Th., "On Thermal Conductivity at Low Temperatures," 7E Congr. Internat. Froid 1er Comm. Internat. Rapports et Communic, 204–16, 1936.

[333] de Haas, W. J., and Biermasz, Th., "Thermal Conductivity of Diamond and Potassium Chloride," Physica, **5**, 47–53, 1938.

[334] de Haas, W. J., and Bremmer, H., "Determination of the Heat Resistance of Mercury at the Temperatures Obtainable with Liquid Helium," Physica, **3**, 687–91, 1936.

[335] de Haas, W. J., and Capel, W. H., "A Method for the Determination of the Thermal Resistance of Metal Single Crystals at Low Temperatures (Bismuth)," Physica, **1**, 725–34, 1934.

[336] de Haas, W. J., and Capel, W. H., "The Thermal Resistance of Bismuth Single Crystals at Low Temperatures," Physica, **1**, 929–34, 1934.

[337] de Haas, W. J., and de Nobel, J. B., "The Thermal and the Electrical Resistance of a Tungsten Single Crystal at Low Temperatures and in Magnetic Fields," Physica, **5**(5), 449–63, 1938.

[338] de Haas, W. J., Gerritsen, A. N., and Capel, W. H., "The Thermal Resistance of Bismuth Single Crystals at Low Temperatures and in a Magnetic Field," Physica, **3**, 1143–58, 1936.

[339] de Haas, W. J., and Rademakers, A., "Thermal Conductivity of Lead in the Superconducting and the Normal State," Physica, **7**, 992–1002, 1940.

[340] de la Cruz, M. E., de la Cruz, F., Cotignola, J. M., Bressan, O. J., and Luengo, C. A., "Thermal and Electrical Conductivities of very-high-purity Indium," Phys. Rev., **176**(3), 871–5, 1968.

[341] Delle, W., Private Communication, 1964.

[342] Denman, G. L., Unpublished Data, 1966.

[343] Denman, G. L., "Recent Thermal Diffusivity Measurements of Tantalum-Tungsten and Hafnium-Tantalum Alloys," High Temp.-High Pressures, **1**(3), 327–37, 1969.

[344] de Nobel, J., "Thermal and Electrical Resistance of a Tungsten Single Crystal at Low Temperatures and High Magnetic Fields," Physica, **15**, 532–40, 1949.

[345] de Nobel, J., "Heat Conductivity of Steels and a Few Other Metals at Low Temperatures," Physica, **17**, 551–62, 1951.

[346] de Nobel, J., "Thermal Conduction and Heat Capacity of Dilute Silver Alloys at Low Temperatures," Bull. Inst. Intern. Froid Annexe, **2**, 97–109, 1956.

[347] de Nobel, J., "Thermal and Electrical Resistivity of Some Tungsten Single Crystals at Low Temperatures and in Strong Magnetic Fields," Physica, **23**, 261–9, 1957.

[348] DeSorbo, W., and Nichols, G. E., "A Calorimeter for the Temperature Region 1 to 20 K—The Specific Heat of Some Graphite Specimens," J. Phys. Chem. Solids, **6**(4), 352–66, 1958.

[349] DeSorbo, W., and Tyler, W. W., "The Specific Heat of Graphite from 13 to 300 K," J. Chem. Phys., **21**(10), 1660–3, 1953.

[349a] Despretz, C., "On the Conductivity of Several Solid Substances," Ann. Chim. Phys., **19**, 97–106, 1822.

[349b] Despretz, C., "The Conductivity of the Principal Metals and Some Earthly Substances," Ann. Chim. Phys., **36**, 422–6, 1827.

[350] Detwiler, D. P., "The Thermal Conductivity of Superconductors," Yale Univ., New Haven, Conn., 66 pp., 1952.

[351] Detwiler, D. P., and Fairbank, H. A., "Thermal Conductivity in the Intermediate State of Pure Superconductors," Phys. Rev., **86**, 574, 1952.

[352] Detwiler, D. P., and Fairbank, H. A., "The Thermal Resistivity of Superconductors," Phys. Rev., Series 2, **88**(5), 1049–52, 1952.

[353] Deverall, J. E., "The Thermal Conductivity of a Molten Pu-Fe Eutectic (9.5a/o Fe)," USAEC Rept., LA–2269, 1–62, 1959.

[354] de Voto, R. S., "Argon Plasma Transport Properties," Aeron. and Astron. Dept. Rept., SUDAER 217, Stanford Univ. (Inst. for Plasma Res. Rept. SU AA 217 Stanford., 1965), 1–53, 1956.

[355] Devyatkova, E. D., Moizhes, B. Ya., and Smirnov, I. A., "Thermal Conductivity of Tellurium with Various Impurity Concentrations in the 80—480 K Range," Fiz. Tverd. Tela (USSR), **1**(4), 613–27, 1959; English translation: Sov. Phys.-Solid State, **1**(4), 555–69, 1959.

[356] Devyatkova, E. D., and Smirnov, I. A., "The Thermal Conductivity of Germanium," Zh. Tekhn. Fiz., **27**(9), 1944–9, 1957; English translation: Sov. Phys.-Tech. Phys., 1957.

[357] Devyatkova, E. D., and Smirnov, I. A., "Thermal Conductivity of P- and N-Type Germanium with Different Carrier Concentrations in the Temperature Range 80—440 K," Fiz. Tverd. Tela, **2**(4), 561–5, 1960; English translation: Sov. Phys.-Solid State, **2**(4), 527–32, 1960.

[358] Devyatkova, E. D., and Smirnov, I. A., "Thermal Conductivity of P- and N-Type Germanium," Fiz. Tverd. Tela, **4**(6), 1669–71, 1962. English translation: Sov. Phys.-Solid State, **4**(6), 1227–8, 1962.

[359] Devyatkova, E. D., Zhuze, V. P., Golubkov, A. V., Sergeeva, V. M., and Smirnov, I. A., "Thermal Conductivity of Samarium, Praseodymium, and Their Monochalcogenides," Fiz. Tverd. Tela, **6**(2), 430–5, 1964; English translation: Sov. Phys-Solid State, **6**(2), 343–6, 1964.

[360] Dickens, B. G., "The Effect of Accommodation on Heat Conduction Through Gases," Proc. Roy. Soc. (London), **A143**, 517–40, 1934.

[361] Digesu, F. L., and Pears, C. D., "The Determination of Design Criteria for Grade CFZ Graphite," USAF Rept. AFML–TR–65–142, 1–279, 1965. [AD 471 337]

[362] Diller, D. E., Hanley, H. J. M., and Roder, H. M., "The Density and Temperature Dependence of the Viscosity and Thermal Conductivity of Dense Simple Fluids," Cryogenics, **10**(4), 286–294, 1970.

[363] Diller, D. E., and Roder, H. M., "Thermal Conductivity Measurements on Fluid Hydrogen at 17 to 200 K and Pressures to 10 MN/M^2," Cryog. Eng. Conf. (U. Calif. Los Angeles), Paper D–1, 7 pp., 1969.

[364] Dismukes, J. P., Ekstrom, L., Steigmeier, E., Kudman, I., and Beers, D. S., "Thermal and Electrical Properties of Heavily Doped Ge-Si Alloys up to 1300 K," J. Appl. Phys., **35**(10), 2899–2907, 1964.

[365] Dobbs, E. R., and Jones, G. O., "Theory and Properties of Solid Argon," Rept. Progr. Phys., **20**, 516–64, 1957.

[366] Donth, E., and Gladun, C., "Measurement of Thermal Conductivity at Low Temperatures by a Nonstationary Method," Cryogenics (GB), **2**(4), 223–5, 1962.

[367] Downey, H. A., and Micinski, E., "The Industrial Graph-

ite Engineering Handbook," National Carbon Co., Union Carbide Corp., 1948.
[368] Drangel, I., and Murray, G. T., "Parameters Pertinent to the Electron Beam Zone Refinement of Refractory Metals," AIME Refractory Metal Symp., New York, 1964, Gordon and Breach, N. Y., 1965.
[369] Dreyfus, B., Lacaze, A., Thomas, P., and Weil, L., "Thermal Conductivity of Gold-Cobalt Alloys at Low Temperatures," J. Phys. Chem. Solids, **24**, 219–24, 1963.
[370] Droher, J. J., and Domingo, F. A. (Inman, G. M., Editor), "Sodium Graphite Reactor Quarterly Progress Report for June-August 1953.," USAEC Rept. NAA–SR–878, 1–118, 1954.
[371] Drut, R., "Thermodynamic Characteristics of Helium," Centre d'Etudes Nucléaires de Saclay, France, CEA–R–3791, 44 pp., 1969.
[372] Duggin, M. J., Private communication, December 1968.
[373] Duggin, M. J., "The Thermal Conductivity of Liquid Mercury," Phys. Letters (Netherlands), **27A**(5), 257–8, 1968.
[374] Duggin, M. J., "The Thermal Conductivity of Liquid Gallium," Phys. Letters (Netherlands), **29A**(8), 470–1, 1969.
[375] Duggin, M. J., "An Apparatus for Measuring the Thermal Conductivity of Liquid Metals: Measurements on Mercury," in *Proceedings of the Eighth Conference on Thermal Conductivity*, (Ho, C. Y., and Taylor, R. E., Editors), TPRC, Purdue Univ., 727–35, 1969.
[376] Dull, R. B., "Research Program to Obtain Comprehensive Design Criteria for Grade CFN Graphite, Quarterly Progr. Rept. No. 5, 1 Sept.–30 Nov. 1964," Union Carbide Corp., 1–66, 1964. [AD 454 905]
[377] Dull, R. B., "Research and Development on Advanced Graphite Materials. Vol. XXVI. Physical Properties of Some Newly Developed Graphite Grades," USAF WADD–TR–61–72, **26**, 1964. [AD 602 607]
[378] Dull, R. B., and Lafyatis, P. G., "Property Determinations for CFW Graphite," AFML–TR–65–185, 204 pp., 1965. [AD 477 578]
[379] Dunworth, R. J., Private communication, 1963.
[380] Dupré, A., Van Itterbeek, A., and Michiels, L., "Heat Conductivity of Copper Below 1 Degree," Phys. Letters, **8**(2), 99–100, 1964.
[381] Durand, R. E., and Klein, D. J., "The Effect of Reactor Irradiation at Temperatures Between 400 and 700 C on the Thermal Conductivity of Graphite," USAEC Rept. NAA–SR–1520, 1–33, 1956.
[382] Dutchak, Ya. I., Osipenko, V. P., Panasyuk, P. V., and Stets'kiv, O. P., "Thermal Conductivity of Liquid Sn-Zn Alloys," Ukrain. Fiz. Zh., **13**(4), 695–7, 1968; English translation: Ukr. Phys. J., **13**(4), 494–5, 1968.
[383] Dutchak, Ya. I., and Panasyuk, P. V., "Investigation of the Heat Conductivity of Certain Metals on Transition from the Solid to the Liquid State," Fiz. Tverd. Tela, **8**(9), 2805–8, 1966; English translation: Sov. Phys.-Solid State, **8**(9), 2244–6, 1967.
[384] Dutchak, Ya. I., and Panasyuk, P. V., "Thermal Conductivity and Electric Conductivity of Copper-Antimony Alloys in the Liquid State," Teplofiz. Vys. Temp., **4**(4), 592–3, 1966; English translation: High Temp., **4**(4), 560–1, 1966.
[385] Dwyer, R. F., Cook, G. A., and Berwaldt, O. E., "The Thermal Conductivity of Solid and Liquid Parahydrogen," J. Chem. Eng. Data, **11**, 351–3, 1966.
[386] Ebrahimi, J., "Thermal Diffusivity Measurement of Small Silicon Chips," J. Phys. D (Appl. Phys.), **3**(2), 236–9, 1970.
[387] Eckert, E. R. G., Ibele, W. E., and Irvine, T. F., Jr., "Prandtl Number, Thermal Conductivity and Viscosity of Air-Helium Mixtures," NASA TN–D–533, 1–39, 1960. [AD 241 819]
[388] Edwards, D. O., Sarwinski, R. E., Seligmann, P., and Tough, J. T., "The Thermal Conductivity of AGOT Graphite Between 0.3 and 3 K," Cryogenics, **8**(6), 392–3, 1968.
[389] Edwards, L. R., "Transport Properties of Thulium Single Crystals," Iowa State Univ., Ph.D. Thesis, AEC–IS–T–173, 85 pp., 1967.
[390] Edwards, L. R., and Legvold, G., "Transport Properties of Thulium Single Crystals," Phys. Rev., **176**(2), 753–60, 1968.
[391] El-Darwish, A. S., "A Periodic Comparative Measurement of Thermal Diffusivity of Metals," Eidgenöss. Techn. Hochschule, Zürich, Thesis, **2800**, 41 pp., 1958.
[392] Ellis, W. C., Morgan, F. L., and Sager, G. F., "The Thermal Conductivities of Copper and Nickel, and some Alloys of Nickel," Rensselaer Polytech. Inst. Bull. No. 21, 1–23, 1928.
[393] Emery, A. F., and Smith, J. R., "The Measurement of Thermal Properties of Metals using a Pulsed Infrared Laser," in *Proceedings of the 4th Symposium on Thermophysical Properties*, Amer. Soc. Mech. Eng., 432–9, 1968.
[394] Engle, G. B., and Koyama, K., "Dimensional and Property Changes of Graphite Irradiated at High Temperatures," Carbon (Oxford), **6**(4), 455–66, 1968.
[395] Erdmann, J., "The Magnetic Thermoelectric Force Change of Germanium at Low Temperatures," Z. Naturforsch., **13a**, 650–62, 1958.
[396] Erdmann, J., Schultz, H., and Appel, J. C., "Magnetic E. M. F. of Germanium Single Crystals at Low Temperatures," Z. Naturforsch, **A12**(2), 171–4, 1957.
[397] Erez, G., and Even, U., "The Wiedemann-Franz Ratio of Metallic Uranium at Elevated Temperatures," J. Appl. Phys., **37**(13), 4633–4, 1966.
[398] Erfling, H. D., and Grüneisen, E., "Further Investigation of Beryllium Crystals in Transverse and Magnetic Fields," Ann. Physik, **41**(2), 89–99, 1942.
[399] Eriksen, N. O., and Hälg, W., "Thermal Conductivity and Electrical Resistivity of Uranium," J. Nucl. Energy, **1**, 232–3, 1955.
[400] Eucken, A., "On the Temperature Dependence of the Thermal Conductivity of Solid Nonmetallics," Ann. Physik, **34**(2), 185–221, 1911.
[401] Eucken, A., "On the Temperature Dependency of the Thermal Conductivity of Several Gases," Physik. Z., **12**, 1101–7, 1911.
[402] Eucken, A., "On the Thermal Conductivity, Specific Heat and Viscosity of Gas," Physik. Z., **14**, 324–32, 1913.
[403] Eucken, A., "General Relation Governing Thermal Conductivity of Various Materials in Different States of Aggregation," Forsch. Gebiete Ingenieurw., **11B**, 6–20, 1940.
[404] Eucken, A., and Dittrich, K., "Toward the Knowledge of the Wiedemann-Franz Law. II," Z. Phys. Chem., **125**, 211–28, 1927.
[405] Eucken, A., and Gehlhoff, G., "Electrical, Thermal Conductivity, and Wiedemann-Franz Constants of Sb-Cd Alloys between 0 and 190 C," Verh. Deut. Phys. Ges., **14**, 169–82, 1912.
[406] Eucken, A., and Neumann, O., "Toward the Knowledge of the Weidemann-Franz Law. I," Z. Physik Chem., **111**, 431–46, 1924.
[407] Eucken, A., and Warrentrup, H., "An Apparatus for the Determination of the Thermal Conductivity of Metal Plates," Z. Techn. Physik, **16**(4), 99–104, 1935.
[408] Euler, J., "The Heat Conductivity of Artificial Graphite Rods at Temperatures between 3300 and 3700 K," Naturwissenschaften, **39**, 568–9, 1952.
[409] Euler, J., "The Axial Temperature Distribution on the Internal Anode of a Carbon Arc and the Thermal Conductivity of Graphite at High Temperatures," Ann. Physik, 6, **18**, 345–69, 1956.

[410] Evangelisti, R., and Isacchini, F., "Experimental Determination of the Lorenz Number of Liquid Sodium," Energia Nucl. (Milan), **12**(11), 601–4, 1964.

[411] Evangelisti, R., and Isacchini, F., "The Thermal Conductivity of Sodium in the Temperature Range 90–850 C," Int. J. Heat Mass Transfer, **8**(10), 1303–17, 1965.

[412] Evangelisti, R., and Isacchini, F., "Method for the Experimental Determination of the Thermal Conductivity of Na at Elevated Temperatures," Calore, **36**(10), 498–519, 1965.

[413] Evans, J. E., Jr., "Thermal Conductivity of 14 Metals and Alloys Up to 1100 F (595 C)," NACA Research Memo. E50L07, 1–15, 1951.

[414] Ewing, C. T., and Grand, J. A., "Measurements of the Thermal Conductivity of Sodium and Potassium," NRL Rept. 3835, 1–18, 1951.

[415] Ewing, C. T., Grand, J. A., and Miller, R. R., "Thermal Conductivity of Liquid Sodium and Potassium," J. Am. Chem. Soc., **74**, 11–14, 1952.

[416] Ewing, C. T., Seebold, R. E., Grand, J. A., and Miller, R. R., "Thermal Conductivity of Mercury," NRL–4506, 1–11, 1955. [AD 59 252]

[417] Fain, S. C., Jr., and Lazarus, D., "Combined Thermal Conductivity and X-Ray Study of Hexagonal Close-Packed Helium 4," Phys. Rev., **A1**(5), 1460–7, 1970.

[418] Fairbank, H. A., and Lee, D. M., "Heat Transport in Liquid He^3," in *Proceedings of the International Conference on Low Temperature Physics*, (Madison, Wisc.), 90–3, 1957.

[419] Fairbank, H. A., and Wilks, J., "Thermal Conductivity of Liquid Helium below 1.0 K," Phys. Rev., **95**, 277–8, 1954.

[420] Fairbank, H. A., and Wilks, J., "Heat Transfer in Liquid Helium below 1 K," Proc. Roy. Soc. (London), **A231**, 545–55, 1955.

[421] Farrell, T., and Greig, D., "The Thermal Conductivity of Nickel and its Alloys," J. Phys. C (Solid State Phys.), **2**(8), 1465–73, 1969.

[422] Feith, A. D., "Measurements of the Thermal Conductivity and Electrical Resistivity of Molybdenum," USAEC GE–TM–65–10–1, 1–25, 1965.

[423] Feith, A. D. (compiled by Wechsler, A.), "Development of High Temperature Thermal Conductivity Standards," AFML–TR–69–2, B3, 1–38, 1969. [AD 689 851]

[424] Fenton, E. W., "The Lorenz numbers of Gold and Silver," Univ. of Alberta, Canada, M. S. Thesis, 60 pp., 1962.

[425] Fenton, E. W., Rogers, J. S., and Woods, S. B., "Lorenz Numbers of Pure Al, Silver, and Gold at Low Temperatures," Can. J. Phys., **41**, 2026–33, 1963.

[426] Fieldhouse, I. B., Hedge, J. C., and Lang, J. I., "Measurements of Thermal Properties," WADC–TR–58–274, 1–79, 1958. [AD 206 892]

[427] Fieldhouse, I. B., Hedge, J. C., Lang, J. I., Takata, A. N., and Waterman, T. E., "Measurements of Thermal Properties," WADC–TR–55–495, Pt. I, 1–64, 1956. [AD 110 404]

[428] Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E., "Measurements of Thermal Properties," WADC–TR–55–495, Pt. II, 1–18, 1956. [AD 110 510]

[429] Fieldhouse, I. B., Hedge, J. C., Lang, J. I., and Waterman, T. E., "Thermal Properties of High Temperature Materials," WADC–TR–57–487, PB 131 718, 1–78, 1957.

[430] Fieldhouse, I. B., Hedge, J. C., and Waterman, T. E., "Measurements of Thermal Properties," WADC–TR–55–495, Pt. III, 1–10, 1956. [AD 110 526]

[431] Fieldhouse, I. B., and Lang, J. I., "Measurement of Thermal Properties," WADD–TR–904, 1–119, 1961. [AD 268 304]

[432] Fieldhouse, I. B., Lang, J. I., and Blau, H. H., "Investigation of Feasibility of Utilizing Available Heat Resistant Materials for Hypersonic Leading Edge Applications, Vol IV. Thermal Properties of Molybdenum Alloy and Graphite," WADC–TR–59–744, **4**, 1–78, 1960. [AD 249 166]

[433] Filippov, L. P., "Measurement of the Thermal Conductivity of Liquids and Gases. Use of the Comparative Plane-Layer Method," Vestnik. Moskov. Univ., Ser. Fiz-Mat. i Estestven. Nauk No. 6, **8**(9), 109–14, 1953.

[434] Filippov, L. P., "Methods of Simultaneous Measurement of Heat Conductivity, Heat Capacity, and Thermal Diffusivity of Solid and Liquid Metals at High Temperatures," Int. J. Heat Mass Transfer, **9**(7), 681–91, 1966.

[435] Filippov, L. P., "Liquid Thermal Conductivity Research at Moscow University," Int. J. Heat Mass Transfer, **11**(2), 331–45, 1968.

[436] Filippov, L. P., and Makarenko, I. N., "Method for Measuring a Series of Thermal Characteristics of Metals at High Temperatures," Teplofiz. Vys. Temp., **6**(1), 149–56, 1968; English translation: High Temp. (USSR), **6**(1), 143–9, 1968.

[437] Filippov, L. P., and Simonova, Yu. N., "Measurement of the Thermal Conductivity of Metals at High Temperatures. II. Method of Measuring Thermal Conductivity," Teplofiz. Vys Temp., **2**(2), 188–91, 1964; English translation: High Temp. (USSR), **2**(2), 165–8, 1964.

[438] Fischbach, D. B., "The Magnetic Susceptibility of Pyrolytic Carbon," in *Proceedings of the 5th Conference on Carbon*, (Univ. Park, Penn., 1961), **2**, 27–36, 1963.

[439] Fischer, G., White, G. K., and Woods, S. B., "Thermal and Electrical Resistivity of Tellurium at Low Temperatures," Phys. Rev., **106**, 480–3, 1957.

[440] Fischer, E. S., and Dever, D., "Elastic Module and Phase Transition in Uranium at Temperatures Below 43 K," Phys. Rev., **170**(3), 607–13, 1968.

[441] Flerov, G. N., "Soviet Synthesis of Element 105," Science, **170**(3953), 15, 1970.

[442] Flerov, G. N., Oganesyan, Yu. Ts., Lobanov, Yu. V., Kuznetsov, V. I., Druin, V. A., Perelygin, V. P., Gavrilov, K. A., Tret'jakova, S. P., and Plotko, V. M., "Synthesis and Physical Identification of the Isotope with Mass Number 260 of Element 104," At. Energ. (USSR), **17**(4), 310–2, 1964; English translation: Soviet J. At. Energy, **17**(4), 1046–8, 1964.

[443] Fletcher, J. F., and Snyder, W. A., "Use of Graphite in the Atomic Energy Program," Am. Ceram. Soc. Bull., **36**(3), 101–4, 1957.

[444] Flynn, D. R., "Thermal Conductivity of Semiconductive Solids, Method for Steady-State Measurements on Small Disk Reference Samples," Natl. Bur. Stand. Rept. 7740, 1–41, 1962.

[445] Flynn, D. R., "Current NBS Efforts Toward Development of Thermal Conductivity Reference Standards," Natl. Bur. Stand.Rept. 7836, 1–22, 1963. [AD 407 802]

[446] Flynn, D. R., Private communication, March, 1965.

[447] Flynn, D. R., "Thermal Conductivity of a 2-cm Diameter Bar of Engelhard E–2 Grade Platinum," Natl. Bur. Stand., Private communication, 1966.

[448] Flynn, D. R., and O'Hagan, M. E., "Measurements of the Thermal Conductivity and Electrical Resistivity of Platinum from 373 to 1373 K," Natl. Bur. Stand. Rept. 9387, 172 pp., 1966.

[449] Flynn, D. R., and O'Hagan, M. E., "Measurements of the Thermal Conductivity and Electrical Resistivity of Platinum from 100 to 900 C," J. Res. Natl. Bur. Stand., **71**(4), 255–84, 1967.

[450] Flynn, D. R., and O'Hagan, M. E., "Measurements of the Thermal Conductivity and Electrical Resistivity of Platinum from 100 C to 900 C," Engelhard Ind. Tech. Bull., **8**(4), 117–47, 1968.

[451] Flynn, D. R., Robinson, H. E., and Watson, T. W., Private communication, 1964.
[451a] Forbes, J. D., "On the Progress of Experiments on the Conduction of Heat, Undertaken at the Meeting of the British Association at Edinburgh in 1850," Brit. Assoc. Adv. Sci., Rept. Ann. Meeting, **21**, 7–8, 1851.
[451b] Forbes, J. D., "On Experiments on the Laws of the Conduction of Heat," Brit. Assoc. Adv. Sci., Rept. Ann. Meeting, **22**, 260–1, 1852.
[451c] Forbes, J. D., "Experimental Inquiry into the Laws of the Conduction of Heat in Bars, and into the Conducting Power of Wrought Iron," Trans. Roy. Soc. Edinburgh, **23**, 133–46, 1864.
[451d] Forbes, J. D., "Experimental Inquiry into the Laws of the Conduction of Heat in Bars. Part II. On the Conductivity of Wrought Iron, Deduced from the Experiments of 1851," Trans. Roy. Soc. Edinburgh, **24**, 73–110, 1865.
[451e] Fordyce, G., "An Account of an Experiment on Heat," Phil. Trans. Roy. Soc. (London), **77**, 310–7, 1787.
[452] Forsythe, W. E., and Worthing, A. G., "The Properties of Tungsten and the Characteristics of Tungsten Lamps," Astrophys. J., **61**, 146–85, 1925.
[453] Francis, E. L. (compiler), *Uranium Data Manual*, UKAEA Industrial Group, H. Q. Risley Lanes England, HMSO IGR–R/R–287, 1–49, 1958.
[454] Franck, E. U., "Temperature Dependence of the Thermal Conductivity of Several Gases," Z. Elektrochem., **55**, 636–43, 1951.
[455] Franck, E. U., "Thermal Conduction in Highly Compressed Gases," Chem.-Ingr.-Tech., **25**, 238–44, 1953.
[456] Franck, E. U., and Wicke, E., "Thermal Conductivity and Dissociation of Fluorine," Z. Elecktrochem., **55**, 643–7, 1951.
[457] Francl, J., and Kingery, W. D., "IX. Experimental Investigation of Effect of Porosity on Thermal Conductivity," J. Am. Ceram. Soc., **37**, 99–107, 1954.
[458] Francl, J., and Kingery, W. D., "Apparatus for Determining Thermal Conductivity by a Comparative Method, Data for Pb, Al_2O_3, BeO, and MgO," J. Am. Ceram. Soc., **37**, 80–4, 1954.
[459] Frank, V., and Jeppesen, O. G., "The Hall Coefficient of Calcium," Phys. Rev., **89**(5), 1153–4, 1953.
[460] Frederikse, H. P. R., "Thermoelectric Power of Germanium Below Room Temperature," Phys. Rev., **92**(2), 248–52, 1953.
[461] Freedman, J. F., and Robertson, W. D., "Electrical Resistivity of Liquid Sodium, Liquid Lithium, and Dilute Liquid Sodium Solutions," J. Chem. Phys., **34**, 769–80, 1961.
[462] Friedman, A. S., and Hilsenrath, J., "The Thermodynamic and Transport Properties of Liquid Hydrogen and Its Isotopes, Pt. 1," Natl. Bur. Stand. Rept. 3163, 1–12, 1954.
[463] Fritsch, G., and Lüscher, E., "Thermal Conductivity of Na in the Temperature Range 35 to 98 Degrees," Z. Phys., **225**(5), 407–15, 1969.
[464] Fritz, W., and Bode, K. H., "A Simple Method for Measuring Relatively the Thermal Conductivity of Small Metal Samples," Z. Angew Phys., **12**(3), 121–4, 1960.
[465] Fulkerson, W., Moore, J. P., and Graves, R. S., "Physical Properties of Tungsten," Metals and Ceram. Div. Annual Progr. Rept., Period Ending June 30, 1965, 131–33, 1965.
[466] Fulkerson, W., Moore, J. P., Graves, R. S., and McElroy, D. L., "Heat Transport in Silicon from 100 to 1300 K," in *Proceedings of the 6th Conference on Thermal Conductivity*, (AFML, Dayton, Ohio, Oct. 19–21, 1966), 429–78, 1966.
[467] Fulkerson, W., Moore, J. P., and 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., **37**(7), 2639–53, 1966.
[468] Fulkerson, W., Moore, J. P., Williams, R. K., Graves, R. S., and McElroy, D. L., "Thermal Conductivity, Electrical Resistivity, and Seebeck Coefficient of Silicon from 100 to 1300 K," Phys. Rev., Pt. 2, **167**(3), 765–82, 1968.
[469] Gabler, F., "A Simple Method for the Determination of the Thermal Conductivity of Metals," Physik. Z., **38**(3), 78–82, 1937.
[470] Gallo, C. F., Chandrasekhar, B. S., and Sutter, P. H., "The Transport Properties of Bismuth Single Crystals. From Theoretical Quarterly Progr. Rept. No. 4," Westinghouse Res. Lab., Pittsburg, Pa., 1–34, 1962. [AD 410 287]
[471] Gallo, C. F., Chandrasekhar, B. S., and Sutter, P. H., "Transport Properties of Bismuth Single Crystals," J. Appl. Phys., **34**, 144–52, 1963.
[472] Gambhir, R. S., Gandhi, J. M., and Saxena S. C., "Thermal Conductivity of Rare Gases, Deuterium, and Air," Indian J. Pure and Applied Phys., **5**(10), 457–63, 1967.
[473] Ganz, E., "Thermal Conductivity of Liquid Helium-II," Helv. Phys. Acta (Switzerland), **12**, 294–5, 1939.
[474] Gardiner, W. C., and Schäfer, K., "Transport Phenomena in Gases and Intermolecular Forces," Z. Electrochem., **60**, 588–94, 1956.
[475] Garfinkel, M. S., "Thermal Conductivity of Impure Tin at Liquid Helium Temperatures," Rutgers Univ., Ph.D. Thesis, 60 pp., 1957.
[476] Garfinkel, M. S., and Lindenfeld, P., "Lattice Conductivity of Tin," Phys. Rev., 2, **110**(4), 883–7, 1958.
[477] Garlick, A., "Thermal Conductivity Measurements at 60 C on Irradiated Uranium," in *Some RDL Studies on Irradiation Effects* (Shaw, D., Editor), UKAEA, TRG Rept. 611(w), 11 pp., 1963.
[478] Garlick, A., and Shaw, D., "The Thermal Conductivity of Irradiated Uranium," J. Nucl. Mater., **16**, 333–40, 1965.
[479] Garth, R. C., and Sailor, V. L., "Thermal Conductivity of Graphite," Brookhaven National Lab., Upton, N. Y., USAEC BNL–69, 1–19, 1949.
[480] Geballe, T. H., and Hull, G. W., "Isotopic and Other Types of Thermal Resistance in Germanium," Phys. Rev., 2, **110**(3), 773–5, 1958.
[481] Gehlhoff, G., and Neumeier, F., "On the Thermal and Electrical Properties of Bismuth-Antimony Alloys Between −190 and 100 C," Verh. Deut. Phys. Ges., **15**, 876–96, 1913.
[482] Gehlhoff, G., and Neumeier, F., "Contributions to the Knowledge of Thermal and Electrical Properties of Pressed Powders from Antimony, Bismuth, and Galena," Verh. Deut. Phys. Ges., **15**, 1069–81, 1913.
[483] Gehlhoff, G., and Neumeier, F., "Thermal Conductivity, Electrical Conductivity, Thermoelectric Force, and Wiedemann-Franz Number of Mercury between Minus 190 and Plus 150 C and Their Changes at the Transition from the Solid to the Liquid State," Verh. Deut. Phys. Ges., **21**, 201–17, 1919.
[484] Geier, H., and Schafer, K., "Heat Conductivity of Pure Gases and Gas Mixtures at 0–1200 Degrees," Allgem. Warmetech., **10**, 70–5, 1961.
[485] Gel'd, P. V., "Thermal and Thermoelectric Properties of the Alloys of Silicon with the Transition Metals," Zh. Tekhn. Fiz., **27**(1), 113–8, 1957; English translation: Sov. Phys.-Tech. Phys., **2**(1), 95–9, 1957.
[486] General Electric Company, "High Temperature Materials Program, Progress Rept. No. 51, Pt. A," USAEC GEMP–51A, 1–59, 1965.
[487] Gerritsen, A. N., and Linde, J. O., "Thermal Conductivity of Some Dilute Silver Alloys," Physica, **22**, 821–31, 1956.

[488] Ghiorso, A., Nurmia, M., Harris, J., Eskola, K., and Eskola, P., "Positive Identification of Two Alpha-Particle-Emitting Isotopes of Element 104," Phys. Rev. Letters, **22**(24), 1317–20, 1969.

[489] Ghiorso, A., Nurmia, M., Eskola, K., Harris, J., and Eskola, P., "New Element Hahnium, Atomic Number 105," Phys. Rev. Lett., **24**(26), 1498–1503, 1970.

[490] Gibbons, R. M., and Kuebler, G. P., "Research on Materials Essential to Cryocooler Technology. Thermophysical and Transport Properties of Argon, Neon, Nitrogen, and Helium 4," AFML–TR–68–370, 569 pp., 1968. [AD 852 010]

[491] Giebe, E., "On the Determination of the Thermal Conductivity at Low Temperatures," Verh. Deut. Phys. Ges., **2**, 60–6, 1903.

[492] Girton, W. Z., and Potter, J. H., "Apparatus and Technique for Measuring Thermal Conductivity of Powdered Material," ASTM Bull., **172**, 47–52, 1951.

[493] Giuliani, S., "Measurement of the Thermal Conductivity of Materials for Nuclear Use between 100 and 500 C," European Atomic Energy EUR–3644, 38 pp., 1967.

[494] Gladun, C., and Holzhauser, W., "Studies of Heat Conductivity at Low Temperatures," Monatsber. Deut. Akad. Wiss. Berlin, **6**(4), 310–3, 1964.

[495] Glage, G., "F. E. Neumann's Method for the Determination of Thermal Conductivity of Good Conducting Bodies in Flat and Ring Forms and Results for Iron, Steel, Copper, Silver, Lead, Tin, Zinc, Brass, Nickel, and Silver," Ann. Physik, 4, **18**, 904–40, 1905.

[496] Glassbrenner, C. J., "Thermal Conductivity of Silicon from 3 K to the Melting Point and of Germanium from 300 K to the Melting Point," Univ. of Connecticut, Ph.D. Thesis, Univ. Microfilms Publ. 64–3533, 1–208, 1963.

[497] Glassbrenner, C. J., and Slack, G. A., "Thermal Conductivity of Silicon and Germanium from 3 K to the Melting Point," Phys. Rev., **A134**(4), 1058–69, 1964.

[498] Glasser, J., and Glasser, W. J., *Directory of Graphite Availability*, 2nd Ed., U. S. Air Force Rept. AFML–TR–67–113, 1–345, 1967.

[499] Gniewek, J. J., and Clark, A. F., "Preparation of Copper Crystals with Low Electrical Resistivity," J. Appl. Phys., **36**(10), 3358–9, 1965.

[500] Godfrey, T. G., Fulkerson, W., Kollie, T. G., Moore, J. P., and McElroy, D. L., "Thermal Conductivity of Uranium Dioxide and Armco Iron by an Improved Radial Heat Flow Technique," USAEC Rept. ORNL–3556, 1–67, 1964.

[501] Godfrey, T. G., Moore, J. P., and McElroy, D. L., "Thermal Properties of Grade CGB Graphite," USAEC, CONF–764–6, 9 pp., 1964.

[502] Goens, E., and Grüneisen, E., "Electrical and Thermal Conductivities of Single Crystals of Zinc and Cadmium," Ann. Physik, **14**, 164–80, 1932.

[503] Goff, J. F., "Radiation-Damage Research (I. The Thermal Conductivity of Germanium Semi-Conductors at Low Temperatures. II. Resistance Changes in Germanium after Bombardment)," USAEC–COO–104, 1–17, 1953.

[504] Goff, J. F., "The Transport Properties of N-Type Germanium at Low Temperatures," Purdue Univ., Dept. of Phys., Ph.D. Thesis, 194 pp., 1962.

[505] Goff, J. F., "The Thermal Conductivity of Chromium Above and Below the Néel Temperature—An Analysis," in *Proceedings of the 7th Conference on Thermal Conductivity*, Gaithersburg, Maryland, 311–21, 1968.

[506] Goff, J. F., and Pearlman, N., "III. Low Temperature Problems. Transport Properties of Germanium at Low Temperatures. From *Semiconductor Research*. Sixth Quarterly Rept.," Purdue Univ., Dept. of Phys., Lafayette, Ind., PRF and U.S. Signal Corps., 9–12, 1957. [AD 156 245]

[507] Goff, J. F., and Pearlman, N., "Transport Properties of Germanium at Low Temperatures," from *Semiconductor Research*, Purdue Univ., PRF and U.S. Signal Corps., 9th Quarterly Rept., 9–12, 1958. [AD 212 815]

[508] Goggin, P. R., and Reynolds, W. N., "The Annealing of Thermal Conductivity Changes in Electron-Irradiated Graphite," Phil. Mag., **8**, 265–72, 1963.

[509] Goglia, M. J., Hawkins, G. A., and Deverall, J. E., "Determination of Thermal Conductivity of Copper and Deoxidized Copper-Iron Alloys. Apparatus and Technique," Anal. Chem., **24**, 493–6, 1952.

[510] Golde, H., "Apparatus for Determining the Absolute Thermal Conductivity of Metals Within the Temperature Range of 20 to 600 Degrees," Feingeräte-Technik, **14**(12), 541–7, 1965.

[511] Golden, G. H., and Tokar, J. V., *Thermophysical Properties of Sodium*, USAEC Rept. ANL–7323, 1–102, 1967.

[512] Goldsmid, H. J., and Lacklison, D. E., "The Thermomagnetic Figure of Merit of Reheated Pyrolytic Graphite at Liquid Helium Temperature," Brit. J. Appl. Phys., **16**, 573–5, 1965.

[513] Goldsmith, A., Waterman, T. E., and Hirschhorn, H. J., *Handbook of Thermophysical Properties of Solid Materials*, The MacMillan Co. Ltd., New York, Vol. 1, 437 pp., 1961.

[514] Golovina, E. S., and Kotova, L. L., "Relationships in the High-Temperature Reaction of Carbon," Dokl. Akad. Nauk (SSSR), **169**(4), 807–9, 1966; English translation: Sov. Phys.-Dokl., **11**(8), 689–91, 1967.

[515] Golubkov, A. V., Devyatkova, E. D., Zhuze, V. P., Sergeeva, V. M., and Smirnov, I. A., "Thermal Conductivity of Lanthanum and its Monochalcogenides," Fiz. Tverd. Tela, **8**(6), 1761–71, 1966; English translation: Sov. Phys.-Solid State, **8**(6), 1403–10, 1966.

[516] Golubev, I. F., and Kalsina, M. V., "Thermoconductivity of Nitrogen and Hydrogen at Temperatures from 20 to −195 C and Pressures from 1 to 500 Atm.," Gazov. Promy., **9**(8), 41-3, 1964; English translation: LA–TR–65–1, 8 pp., 1964.

[517] Goodman, B. B., "The Thermal Conductivity of Superconducting Tin Below 1 K," Proc. Phys. Soc. (London), **A66**, 217-27, 1953.

[518] Gorter, F. W., and Noordermeer, L. J., "The Lattice Thermal Conductivity and Related Properties of Pure Gallium Single Crystals at Low Temperatures," Physica, **46**, 507–30, 1970.

[519] Gotgil'f, T. L., Garmash, V. M., Tikhonov, V. E., and Roitberg, M. B., "Structural Changes in Liquid Thallium," Russian J. Phys. Chem., **41**(7), 909–12, 1967.

[520] Gottlieb, M., Zollweg, R. J., "Thermal Conductivity of Cesium Vapor," Advanced Energy Conversion, **3**, 37–48, 1963.

[521] Gottlieb, M., Zollweg, R. J., DeSteese, J. G., Taylor, C. R., and Ennulat, D. F., "Heat Diode Converter. Interim Scientific Rept. No. 5, May 1, 1962 to July 31, 1962," Westinghouse Res. Labs., Pittsburgh, Pa., USAF, 1962. [AD 287 519]

[522] Gottlieb, M., Zollweg, R. J., Richardson, L. S., DeSteese, J. G., Taylor, C. R., and Ennulat, D. F., "V. Cesium Vapor Thermal Conductivity. From Heat Diode Converter. Interim Scientific Rept. 4. 1 Feb.–30 April, 1962." Westinghouse Res. Labs., Pittsburgh, Pa., USAF, 1–28, 1962. [AD 276 411]

[523] Graham, G. M., "The Thermal Conductivity of Tin and Indium Below 1 K," Proc. Roy. Soc. (London), **A248**, 522–38, 1958.

[524] Grard, C., and Villey, J., "The Thermal Conductivity of Light Alloys," Compt. Rend., **185**, 856–8, 1927.

[525] Gray, J. H., "On a Method for Determining the Thermal Conductivity of Metals, with Applications to Copper, Silver, Gold, and Platinum," Proc. Roy. Soc. (London), **56**, 199–203, 1894.

[526] Green, S. E., "The Spherical Shell Method of Determining the Thermal Conductivity of a Thermal Insulator," Proc. Phys. Soc. (London), 3, **44**(243), 295–313, 1932.

[527] Gregory, H. S., "Effect of Temperature on the Thermal Conductivity and the Accommodation Coefficient of Hydrogen," Proc. Phys. Soc. (London), **A149**, 35–56, 1935.

[528] Gregory, H. S., and Archer, C. T., "The Variation of the Thermal Conductivity of Gases with Pressure," Phil. Mag., **1**, 593–606, 1926.

[529] Gregory, H. S., and Archer, C. T., "Experimental Determination of the Thermal Conductivities of Gases," Proc. Roy. Soc. (London), **A110**, 91–122, 1926.

[530] Gregory, H. S., and Dock, E. H., "Effect of Temperature on the Thermal Conductivity and the Accommodation Coefficient of Hydrogen Below 0 Degrees," Phil. Mag., **25**, 129–47, 1938.

[531] Gregory, H. S., and Marshall, S., "The Thermal Conductivity of Carbon Dioxide," Proc. Roy. Soc. (London), **A114**, 354–66, 1927.

[532] Gregory, H. S., and Marshall, S., "Thermal Conductivities of Oxygen and Nitrogen," Proc. Roy. Soc. (London), **A118**, 594–607, 1928.

[533] Greig, D., and Harrison, J. P., "The Low Temperature Electrical Transport Properties of Nickel and Dilute Nickel-Copper Alloys," Phil. Mag., **12**(115), 71–9, 1965.

[534] Grenell, L. H., Linebrink, O. L., and Johnson, K. L., Unpublished data taken from *The Metal Beryllium* (Editors: White, D. W. and Burke, J. E.), The American Society for Metals, Cleveland, Ohio, 310 pp., 1955.

[535] Grenier, C. G., "Thermal Conductivity of the Liquid Helium I," from *Low Temperature Physics*, Low Temp. Lab., Rice Institute, 25–8, 1950. [AD 121 132]

[536] Grenier, C. G., "Thermal Conductivity of Liquid Helium," Phys. Rev., **83**, 598–603, 1951.

[537] Grenier, C. G., "Thermal Conductivity of Liquid Helium I," from *Low Temperature Physics*, Natl. Bur. Stand. Circ. 519, 193–4, 1952.

[538] Grenier, C. G., Reynolds, J. M., and Sybert, J. R., "Electron Transport Phenomena in Bismuth at Liquid-Helium Temperatures," Phys. Rev., **132**(1), 58–73, 1963.

[539] Grieco, A., and Montgomery, H. C., "Thermal Conductivity of Germanium," Phys. Rev., **86**, 570, 1952.

[540] Grier, N. T., "Calculation of Transport Properties and Heat-Transfer Parameters of Dissociating Hydrogen," NASA–TN–D–1406, 1–64, 1962.

[541] Griffin, C. S., Mendelssohn, K., and Mortimer, M. J., "Self-Irradiation Damage in the Actinide Metals," Cryogenics, **8**(2), 110–1, 1968.

[542] Griffiths, E., and Shakespear, G. A., "Thermal Conductivity of Al and Its Alloys," J. Inst. Metals, **28**, 581–2, 1922.

[543] Grilly, E. R., and Hammel, E. F., "Liquid and Solid Helium 3," *Progr. Low Temp. Physics*, Chapter 4, 113–52, 1964.

[544] Grison, E., Lord, W. B. H., and Fowler, R. D. (Editors), *Plutonium 60*, Cleaver-Hume Press, London, 107–8, 1961.

[545] Grosse, A. V., "Simple Relationship between Electrical Conductivity of Liquid Metals and Temperature over Their Entire Liquid Temperature Range, i.e., From the Melting Point to the Critical Point," The Research Institute of Temple University, Philadelphia, Pa., 1–40, 1964.

[546] Grosse, A. V., "Thermal Conductivity of Liquid Metals Over the Entire Liquid Range, i. e., from the Melting Point to Critical Point, in Relation to Their Electrical Conductivities and the Fallacy of Dividing Metals into 'Normal' and 'Abnormal' Thermally Conducting Ones," The Research Institute of Temple University, Philadelphia, Pa., 1–71, 1965.

[547] Grosse, A. V., "Some Physical and Chemical Properties of Element 118 (Eka-Em) and Element 86 (Em)," J. Inorg. Nucl. Chem., **27**, 509–19, 1965.

[548] Grosse, A. V., "Electrical and Thermal Conductivities of Metals over Their Entire Liquid Range, i. e., from Melting Point to Critical Point and the Containment of Metallic Substances up to 5000 K for Substantial Periods of Time," Rev. Intern. Hautes Temp. Réfractaires, **3**(2), 115–46, 1966.

[549] Grosse, A. V., "Electrical and Thermal Conductivity of Metallic Potassium, Over Its Entire Liquid Range, from the Melting Point (336.4 K) to the Critical Point (2450 K)," J. Inorg. Nucl. Chem., **28**(3), 795–802, 1966.

[550] Grosse, A. V., "Comparison of the Experimental Entropies of Vaporization of Rubidium and Cesium from the Melting Point to the Critical Region with Those of Mercury and the Validity of the Principle of Corresponding States for Metals," J. Inorg. Nucl. Chem., **28**, 2125–9, 1966.

[551] Grosse, A. V., Research Institute of Temple University, Private communication to Y. S. Touloukian, February 11, 1969.

[552] Grossmann, G., "The Electrical and Thermal Conductivity of Some Copper-Tin Alloys," Ann. Phys. Beibl., **29**, 178–81, 1905.

[553] Grüneisen, E., "Thermal Conductivity of Metals and Their Relation to the Electrical Conductivity," Ann. Physik, 4, **3**, 43–74, 1900.

[554] Grüneisen, E., and Adenstedt, H., "Anisotropy in the Thermal Conductivity and Thermoelectric Force of Regular Metals (Tungsten) in a Transverse Magnetic Field at 20 K," Ann. Physik, **29**(7), 597–604, 1937; English translation: N67–38020, NASA–TT–F–11079, 7 pp., 1967.

[555] Grüneisen, E., and Adenstedt, H., "The Effect of Transverse Magnetic Fields Upon the Electrical and Thermal Conductivity of Pure Metals at Low Temperatures," Ann. Physik, 5, **31**(8), 714–44, 1938.

[556] Grüneisen, E., and Erfling, H. D., "Electric and Thermal Resistance of Beryllium Crystals in a Transverse Magnetic Field," Ann. Physik, **38**, 399–420, 1940.

[557] Grüneisen, E., and Gielessen, J., "Researches on Bismuth Crystals. I. Heat and Electrical Conductivity in Transverse Magnetic Fields," Ann. Physik, 5, **26**(5), 449–64, 1936.

[558] Grüneisen, E., and Gielessen, J., "Investigations on Bismuth Crystals. III. Heat and Electrical Conductivity in the Transition from Transverse to Longitudinal Magnetic Fields," Ann. Physik, 5, **28**(3), 225–39, 1937.

[559] Grüneisen, E., and Goens, E., "Investigations of Metal Crystals. V. Electrical and Thermal Conductivity of Single and Polycrystalline Metals of the Cubic System," Z. Physik, **44**, 615–42, 1927.

[560] Grüneisen, E., Rausch, K., and Weiss, K., "Conduction of Electricity and Heat in Bismuth Single Crystals in a Transverse Magnetic Field," Ann. Physik, **7**, 1–17, 1950; English translation: SLA–63–10741, 24 pp., 1962.

[561] Grüneisen, E., and Reddemann, H., "Electronic and Lattice Conduction of Heat in Metals," Ann. Physik, **20**, 843–77, 1934.

[562] Guénault, A. M., "Thermal Conduction in Normal and Superconducting Tin and Indium," Proc. Roy. Soc. (London), **A262**, 420–34, 1961.

[563] Gueths, J. E., Clark, N. N., Markowitz, D., Burckbuchler, F. V., and Reynolds, C. A., "Effect of the Superconducting Energy-Gap Anistropy on The Thermal Conductivity of Tin," Phys. Rev., **163**(2), 364–72, 1967.

[564] Gulevskaya, A. S., Lipatava, V. A., and Gel'd, P. V., "Thermal Conductivity of Alloys of Iron and Silicon

Containing β -Lebeauite," Tr. Ural. Politech. Inst., **114**, 90–5, 1961.

[565] Gumenyuk, V. S., Ivanov, V. E., and Lebedev, V. V., "Determination of Thermal and Electric Conductivity of Metals at Temperatures above 1000," Pribory i. Tekhn. Eksperim., **7**(1), 185–9, 1962: English translation: Instrum. Exper. Tech. (USA), No. 1, 188–92, 1962.

[566] Gumenyuk, V. S., Ivanov, V.E., and Lebedev, V. V., "Determination of the Thermal Conductivity of Metals at Temperatures Above 1000 Degrees," Tepl. I Massoperenos Pervoe Uses Soveshch. Minsk (1961), **1**, 94–101, 1962.

[567] Gumenyuk, V. S., and Lebedev, V. V., "Investigation of the Thermal and Electrical Conductivity of Tungsten and Graphite at High Temperatures," Phys. Metals Metallog. USSR, **11**(1), 30–5, 1961.

[568] Gunther, W., Halle Univ., Germany, Ph.D. Thesis, 1906.

[569] Gurney, R. W., "Lattice Vibrations in Graphite," Phys. Rev., **88**(3), 465–6, 1952.

[570] Guyer, R. A., and Hogan, E. M., "Thermal Conductivity of Oriented Single Crystals of HCP Helium 4," in *Solid State Commun.*, **5**(11), 909–12, 1967. [AD 665 083]

[571] Haarman, J. W., "A Selected Method for the Determination of the Thermal Conductivity Coefficient of Gases," Delft Uitgevers Maatsehappij, Delft N. V., Thesis, 1969.

[572] Habachi, M., Azou, P., and Bastien, P., "Thermal Diffusivity of Metals and of Alloys," Compt. Rend., Groupe 7, **261**(15), 2899–902, 1965.

[573] Hackspill, M. L., "The Electrical Resistance of Alkali Metals," Compt. Rend., **151**, 305–8, 1910.

[574] Haen, P., and Meaden, G. T., "The Thermal Conductivity, Thermoelectric Power, and Electrical Resistivity of Thorium Between 5 and 100 K," Cryogenics, **5**(4), 194–8, 1965.

[575] Haen, P., and Weil, L., "Measurement of the Thermal Conductivity and the Thermoelectric Force Between 4 and 40 K of Uranium-Molybdenum Alloys in the γ Phase," Compt. Rend. **258**(25), 6130–3, 1964.

[576] Hall, E. H., "Concerning Thermal Conductivity in Iron," Phys. Rev., **10**(5), 277–310, 1900.

[577] Hall, P. M., Legvold, S., and Spedding, F. H., "Electrical Resistivity of Yttrium Single Crystals," Phys. Rev., **116**(6), 1446–7, 1959.

[578] Hall, P. M., Legvold, S., and Spedding, F. H., "Electrical Resistivity of Dysprosium Single Crystals," Phys. Rev., **117**(4), 971–3, 1960.

[579] Hall, T. A., and Tsao, P. H., "Heat Transfer at Low Temperature between Tube Walls and Gases in Turbulent Flow," Proc. Roy. Soc. (London), **A191**, 6–21, 1947.

[580] Hall, W. C., "Measurements on the Thermal Conductivities of Mercury, Sodium, and Sodium Amalgams," Univ. of Kansas, Ph.D. Thesis, 81 pp., 1936.

[581] Hall, W. C., "The Thermal Conductivities of Mercury, Sodium and Sodium Amalgams in the Liquid State (Compounds Na_5Hg_2 and Na_3Hg)," Phys. Rev., 2, **53**(12), 1004–9, 1938.

[582] Hall, W. J., Powell, R. L., and Roder, H. M., "Thermal Conductivities of Common Commercial Aluminum Alloys," Paper from *Advances in Cryogenic Engineering*, Plenum Press, New York, **3**, 408–15, 1960.

[583] Hammann, G., "Thermal Conductivity of Liquid Oxygen Liquid Nitrogen and Their Mixtures," Ann. Physik, **32**, 593–607, 1938.

[584] Hampel, C. A. (Editor), *Rare Metals Handbook*, 2nd Edition, Reinhold Publishing Corp., London, 661, 1961.

[585] Hanley, H. J. M., and Childs, G. E., "The Viscosity and Thermal Conductivity Coefficients of Dilute Neon, Krypton and Xenon," NBS Technical Note, No. 352, 1–24, 1967.

[586] Hanley, H. J. M., and Childs, G. E., "The Viscosity and Thermal Conductivity Coefficients of Dilute Neon, Krypton and Xenon," N. B. S. Technical Note, No. 352, 1–24, 1967; Hanley, H. J. M., and Klein, M., "On the Selection of the Intermolecular Potential Function: Application of Statistical Mechanical Theory to Experiment," N. B. S. Technical Note No. 360, 1–82, 1967; Childs, G. E., and Hanley, H. J. M., "Applicability of Dilute Gas Property Tables to Real Gases," Cryogenics, **8**(2), 94–7, 1968.

[587] Hanley, H. J. M., McCarty, R. D., and Intemann, H., "The Viscosity and Thermal Conductivity of Dilute Gaseous Hydrogen from 15 to 5000 K," J. Res. Natl. Bur. Stand., **74A**(3), 331–53, 1970.

[588] Hansen, C. A., "Furnace Electrode Losses," Trans. Electrochem. Soc., **16**, 329–62, 1909.

[589] Hansen, D., and Rogers, C. E., "The Thermal Conductivity of Some Non-Ferrous Alloys," J. Inst. Metals, **48**, 37–45, 1932.

[590] Harper, A. F. A., Kemp, W. R. G., Klemens, P. G., Tainsh, R. J., and White, G. K., "The Thermal and Electrical Conductivity of Chromium at Low Temperatures," Phil. Mag., 8, **2**, 577–83, 1957.

[591] Hase, R., Heierberg, R., and Walkenhorst, W., "Measurement of Thermal and Electric Conductivity of Pure Aluminum and Aluminum-Magnesium Alloys Up to 400 Degrees," Aluminum, **22**, 631–5, 1940.

[592] Hashin, Z., and Shtrikman, S., "Conductivity of Polycrystals," Phys. Rev., **130**(1), 129–33, 1963.

[593] Hattori, D., "On the Thermal Conductivity of Pure Iron," Sci. Repts. Tohoku Imp. Univ., **26**, 190–205, 1937.

[594] Heal, T. J., "Mechanical and Physical Properties of Magnesium and Niobium Canning Materials," in *Proc. 2nd Int. Conf. Peaceful Uses At. Energy* (Geneva), Vol. 5, 208–19, 1958.

[595] Heal, T. J., and McIntosh, A. B., "High Temperature Properties of Uranium and Its Alloys," A/Conf. 15/P/49 USAEC, 48 pp., 1958.

[596] Hecht, H., "Method to Determine the Thermal Conductivity of Poorly Conducting Bodies in Sphere and Cube Form and its Performance on Marble, Glass, Sandstone, Gypsum and Serpentine, Basalt, Sulfur, Coal," Ann. Physik, **14**, 1008–30, 1904.

[597] Hedge, J. C. (compiled by Wechsler, A. E.), "Development of High Temperature Thermal Conductivity Standards," Wright-Patterson AFB, Ohio, AFML-TR-69-2, N69-39266, B4-1-12, 1969. [AD 689 851]

[598] Hedge, J. C., and Fieldhouse, I. B., "Measurement of Thermal Conductivity of Uranium Oxide," ARF Proj. G022 D3 AECU 3381, 1–10, 1956.

[599] Hercus, E. O., and Laby, T. H., "The Thermal Conductivity of Air," Proc. Roy. Soc. (London), **A95**, 190–210, 1919.

[600] Herring, C., "Simple Property of Electron-Electron Collisions in Transition Metals," Phys. Rev. Letters, **19**(4), 167–8, 1967; Errata, **19**(11), 684, 1967.

[601] Heubner, U., "Thermal and Electrical Conductivity of Vanadium Alloys Between 20 and 650°," J. Nucl. Mater., **32**(1), 88–100, 1969.

[602] Higgins, R. J., Marcus, J. A., and Whitmore, D. H., "Intermediate-Field deHaas-Van Alphen Effect in Zinc," Phys. Rev., **137A**, A1172–81, 1965.

[603] Hill, R. W., and Schneidmesser, B., "Thermal Conductivity of Solid Hydrogen," Z. Phys. Chem., **16**, 257–66, 1958.

[604] Hilsenrath, J., Beckett, C. W., Benedict, W. S., Fano, L., Hoge, H. J., Masi, J. F., Nuttall, R. L., Touloukian, Y. S., and Wolley, H. W., "Tables of Thermodynamic and Transport Properties of Air, Argon, Carbon Dioxide, Carbon Monoxide, Hydrogen, Nitrogen, Oxygen, and Steam," Natl. Bur. Stand. Circ. 564, 1–488, 1955.

[605] Hilsenrath, J., and Touloukian, Y. S., "The Viscosity,

Thermal Conductivity, and Prandtl Number for Air, O, N, NO, H, CO, CO_2, H_2O, He, and A," Trans. Am. Soc. Mech. Engrs., **76**, 967–85, 1954.

[606] Hirschfelder, J. O., Curtiss, C. F., and Bird, R. B., *Molecular Theory of Gases and Liquids*, Wiley and Sons, New York, 1219 pp., 1954.

[607] Ho, C. Y., Powell, R. W., and Liley, P. E., "Thermal Conductivity of Selected Materials, Part 2," National Standard Reference Data Series—National Bureau of Standards NSRDS–NBS 16, 1–146, 1968.

[608] Ho, C. Y., Powell, R. W., and Liley, P. E., "Standard Reference Data on the Thermal Conductivity of Selected Materials (Part 3)," Thermophysical Properties Research Center, Final Rept. on NBS–NSRDS Contract CST–1346, 1–435, 1968.

[608a] Ho, C. Y., Powell, R. W., and Liley, P. E., "Thermal Conductivity of the Elements," J. Phys. Chem. Ref. Data, **1**(2), 279–421, 1972.

[609] Ho, J., and Wright E. S., "General Research in Materials and Propulsion." Jan. 1959–Jan. 1960, Vol. II. Metallurgy and Chemistry. Lockheed Aircraft Corp. Missiles and Space Div., ASTIA LMSD 288140, 1960. [AD 241 410]

[610] Hoch, M., and Jun, C. K., "Thermophysical Properties of Ta, W, Re, and Their Alloys in the Temperature Range 1500–3000 K," Chimia, **21**(7), 290–5, 1967.

[611] Hoch, M., and Nitti, D. A., "New Method for the Determination of Thermal Conductivities between 1000 and 3000 C," Cincinnati Univ., Ohio, ASD–TR–51–528, N62–16415, 1–59, 1962. [AD 284 544]

[612] Hoch, M., and Vardi, J., "Thermal Conductivity of Anisotropic Solids at High Temperatures. The Thermal Conductivity of Molded and Pyrolytic Graphites. Part I," ASD–TDR–62–608 (Pt. 1), 1–19, 1962. [AD 292 326]

[613] Hochman, J. M., and Bonilla, C. F., "The Electrical and Thermal Conductivity of Liquid Cesium to 1650 C and the Critical Point of Cesium," Nucl. Sci. Eng., **22**(4), 434–42, 1965.

[614] Hochman, J. M., and Bonilla, C. F., "The Electrical and Thermal Conductivity of Liquid Cesium to 3000 F and the Critical Point of Cesium," Trans. Am. Nucl. Soc., **7**, 101–2, 1965.

[615] Hogan, C. L., "The Thermal Conductivity of Metals at High Temperature," Lehigh Univ., Bethlehem, Pa., Ph.D. Thesis, 1–42, 1950.

[616] Hogan, E. M., Guyer, R. A., and Fairbank, H. A., "Thermal Conductivity of Oriented Single Crystals of Hexagonal Close-Packed Helium 4," Phys. Rev., **185**(-1), 356–73, 1969. [AD 700 534]

[617] Holborn, L., Scheel, R., and Henning, F. (Editors), *Results of the Thermal Investigation at the Physical-Technical Institute, Thermal Tables.*, Fried. Vieweg and Sohn, Braunschweig, 29, 69–70, 1919.

[618] Holcomb, R. W., "Heavy Elements: A Feud Over 104 and a Future for 114," Science, **166**(3910), 1254-5, 1969.

[619] Holcomb, R. W., "Element 105 Synthesized and Named Hahnium be Berkeley Researchers," Sience, **168**(3933), 810, 1970.

[620] Holland, M. G., "Low Temperature Thermal Conductivity of Silicon," *Semiconductor Physics*, Conf., Prague, 633-7, 1960.

[621] Holland, M. G., "Effect of Oxygen on the Thermal Conductivity of Silicon," in *Proc. 7th Int. Conf. Low Temp. Physics (Toronto, Can, 1960*, 280-4,1961.

[622] Holland M. G., "Thermal Conductivity of Several Optical Maser Materials," J. Appl. Phys., **33**, 2910-11, 1962.

[623] Holland, M. G., Klein, C. A., and Straub, W. D., "The Lorenz Number of Graphite at Very Low Temperatures," J. Phys. Chem. Solids, **27**(5), 903–6, 1966.

[624] Holland, M. G., and Neuringer, L. J., "The Effect of Impurities on the Lattice Thermal Conductivity of Silicon," in *Proc. Int. Conf. on the Physics of Semi-Conductors*, Execter, England, 474–81, 1962.

[625] Holm, R., "Heat Conductivity Measurements by a High Temperature Variation of the Kohlrausch Method," Z. Tech. Physik, **10**(12), 621–3, 1929.

[626] Holm, R., and Störmer, R., "Measurement of the Thermal Conductivity of a Platinum Probe in the Temperature Range 19–1020 C," Wiss. veroffentl. Siemens-Konzern, **9**(2), 312–22, 1930.

[627] Holyer, R. J., "A System for Low-Temperature Measurements of Thermal Conductivity Measurements on Silicon from 77 to 300 K," Tech. Rept., South Dakota School of Mines and Tech., M. S. Thesis, 1965. [AD 621 152]

[628] Honda, K., and Simidu, T., "On the Thermal and Electrical Conductivities of Carbon Steels at High Temperatures," Sci. Repts. Tohoku Imp. Univ., **6**, 219–33, 1917.

[629] Hooker, C. N., Ubbelohde, A. R., and Young, D. A., "Thermal Conductance of Graphite in Relation to Its Defect Structure," Proc. Roy. Soc. (London), **276A**(1364), 83–95, 1963.

[630] Hooker, C. N., Ubbelohde, A. R., and Young, D. A., "Anisotropy of Thermal Conductance in Near-Ideal Graphite," Proc. Roy. Soc. (London), **284A**(1396), 17–31, 1965.

[631] Hooker, C. N., Ubbelohde, A. R., and Young, D. A., "Dependence of Thermal Conduction of Well-Oriented Graphite on Crystal Defects," in *Second Conf. on Industrial Carbon and Graphite* (London, 1965), 114–20, 1966.

[632] Hopkins, M. R., and Griffith, R. L., "The Determination of the Lorenz Number at High Temperatures," Z. Phys., **150**, 325–31, 1958.

[633] Hopkins, M. R., and Jones, D. I., "The Lorenz Number for Iron and Nickel at High Temperatures," in course of publication; private communication from M. R. Hopkins, July 29, 1969.

[634] Horn, F. H., "The Change in Electrical Resistance of Magnesium on Melting," Phys. Rev., **84**(4), 855–6, 1951.

[635] Hornbeck, J. W., "Thermal and Electrical Conductivities of the Alkali Metals," Phys. Rev., **2**, 217–40, 1913.

[636] Horner, P., Univ. of London, Ph.D. Thesis, 1961.

[637] Hove, J. E., and Smith, A. W., "Interpretation of Low-Temperature Thermal Conductivity of Graphite," Phys. Rev., **104**(4), 892–900, 1956.

[638] Howard, R. A., and Piper, E. L., "Research and Development on Advanced Graphite Materials. Vol. XIII. Development of a Fine Grain Isotropic Graphite for Structural and Substrate Applications," WADD–TR–61–72, 43 pp., 1964. [AD 602 606]

[639] Howl, D. A., "The Thermal Conductivity of Springfields Adjusted Uranium in the Temperature Range 160–620 C," J. Nucl. Mater., **19**, 9–14, 1966.

[640] Howling, D. H., Mendoza, E., and Zimmerman, J. E., "Preliminary Experiments on the Temperature Wave Method of Measuring Specific Heats of Metals at Low Temperatures," Proc. Roy. Soc. (London), **229A**, 86–109, 1955.

[641] Hulm, J. K., "Thermal Conductivity of Superconductors," Nature (London), **163**, 368–9, 1949.

[642] Hulm, J. K., "The Thermal Conductivity of Tin, Mercury, Indium, and Tantalum at Liquid-Helium Temperatures," Proc. Roy. Soc. (London), **A204** 98–123, 1950.

[643] Hulm, J. K., "Heat Transfer in Superconducting Alloys. From Low Temperature Physics," N. B. S. Supt. of DOCS USGPO NBS Circ. 519, 37–41, 1952.

[644] Hultgren, R., Orr, R. L., Anderson, P. D., and Kelley, K. K., *Selected Values of Thermodynamic Properties of*

Metals and Alloys, John Wiley and Sons, Inc., New York, 963 pp., 1963.

[645] Hurst, W. S., "Thermal Conductivity of Silicon in the Boundary Scattering Regime," Penn. State Univ., Ph.D. Thesis, Univ. Microfilms Publ. 69–14529, 163 pp., 1968.

[646] Hust, J. G., "Thermal Conductivity Standard Reference Materials from 4 to 300 K. I. Armco Iron," Nat. Bur. Stand. Rept. 9740, 1–97, 1969.

[647] Hust, J. G., "High Temperature Thermal Conductivity in Bismuth Telluride and Silicon". Tech. Rept. No. 2, Masters Thesis, 1961, South Dakota School of Mines and Tech., Rapid City South Dakota, ASTIA, 1–87, 1961. [AD 251 689]

[648] Hust, J. G., "Thermal Conductivity Standard Reference Materials From 4 to 300 K. I. Armco Iron," in *Proc. 9th Conf. on Thermal Conductivity*, USAEC Rept. Conf–691002, 217–33, 1970.

[649] Hutcheon, J. M., and Price, M. S. T., "The Dependence of the Properties of Graphite on Porosity," in *Proceedings of the Fourth Conf. on Carbon* (Buffalo, New York, 1959), Pergamon Press, New York, 645–56, 1960.

[650] Hyman, J., Jr., "Measurements of the Resistivity of Cesium at Elevated Temperatures," J. Chem. Phys., **35**, 992–4, 1961.

[651] Ibbs, T. L., and Hirst, A. A., "Thermal Conductivity of Gas Mixtures," Proc. Roy. Soc. (London), **A123**, 134–42, 1929.

[652] Ibele, W. E., Novotny, J. L., and Eckert, E. R. G., "Prandtl Number Measurements and Thermal Conductivity, Viscosity Predictions for Air, Helium, and Air-Helium Mixtures," NASA CR 55273, 1–49, 1963.

[653] Icole, M., "Determination at Different Temperatures of the Thermal Conductivity of Graphite and Cuprous Sulfide," Ann. Chim. et Phys., **25**, 137–44, 1912.

[654] Ikenberry, L. D., and Rice, S. A., "Kinetic Theory of Dense Fluids, XIV. Experimental and Theoretical Studies of Thermal Conductivity in Liquid Ar, Kr, Xe, and CH_4," J. Chem. Phys., **39**(6), 1561–71, 1963.

[655] IIT Research Inst., "Physical Properties of Refractory Materials," 1–34, 1966. [AD 800 343]

[655a] Ingen-Hausz, J., "On Metals as Conductors of Heat," J. Physique (France), **34**, 68, 380, 1789.

[656] Ioffe, A. V., "Dependence of the Thermal Conductivity of the Crystal Lattice on the Degree of Ionicity of the Compound," Fiz. Tverd. Tela USSR, **5**(11), 3336–8, 1963; English translation: Sov. Phys.-Solid State, **5**(11), 2446–7, 1964.

[657] Ioffe, A. V., and Ioffe, A. F., "Simple Method of Measuring Thermal Conductivity," Zh. Tekh. Fiz., **22**(12), 2005–13, 1952.

[658] Ioffe, A.V., and Ioffe, A.F.," Certain Regularities in the Values of the Thermal Conductivities of Semiconductors," Dokl. Akad. Nauk SSSR, **97**, 821–2, 1954.

[659] Isin, A., and Coleman, R. V., "Magnetoresistance of Iron Whiskers," Phys. Rev., **137**(5A), A1609–13, 1965.

[660] Israel, S. L., Hawkins, T. D., and Hyman, S. C., "Thermal Properties of Solids and Porous Tungsten at Temperatures to 5000 F," NASA CR–402, 1–46, 1966.

[661] Israel, S. L., Hawkins, T. D., Salter, R. T., and Hyman, S. C., "Hydrogen Thermal Conductivity at Temperatures from 2000 to 4000 F," United Nuclear Corp., White Plains, N. Y., NASA–CR–78167 UNC–5082, N66–37325, 132 pp., 1964.

[662] Istrati, M. I., "Coefficient of Interior Thermal Conductivity of Mercury," Ann. Sci. Univ. Jassy, **14**, 23–7, 1926.

[663] Jackson, J. J., Argonne National Lab., Private communication to T. F. Connolly, Research Materials Information Center, ORNL, 1965.

[664] Jaeger, W., and Diesselhorst, H., "Thermal Conductivity, Electrical Conductivity, Heat Capacity, and Thermal Power of Some Metals," Wiss. Abhandl. Physik-tech. Reichsanstalt, **3**, 269–425, 1900.

[665] Jaeger, F. M., and Rosenbaum, E., "The Temperature Coefficient of the Electrical Resistance of Ruthenium and its Thermo-electric Behavior With Respect to Platinum," Proc. Netherland Akad. van Wetensar., **44**, 144–52, 1941.

[666] Jaeger, F. M., and Veenstra, W. A., "The Exact Measurement of the Specific Heats of Solid Substances at High Temperatures. VI—The Specific Heats of Vanadium, Niobium, Tantalum and Molybdenum," Rec. Trav. Chim., **53**, 677–87, 1934.

[667] Jaffee, R. I., "Refractory Metals. From Advance Papers of an International Symposium on High Temperature Technology, Oct. 6–9, 1959," ASTIA, 80–107, 1959. [AD 249 297]

[668] Jain, S. C., and Goel, T. C., "Thermal Conductivity of Memals at High Temperatures by the Jain and Krishnan Method. I. Nickel," Brit. J. Appl. Phys., **1**, 573–80, 1968.

[669] Jain, S. C., Goel, T. C., and Chandra, I., "Thermal and Electrical Conductivities and Spectral and Total Emissivities of Nickel at High Temperatures," Phys. Letters (Netherlands), **24A**(6), 320–1, 1967.

[670] Jain, S. C., Goel, T. C., and Narayan, V., "Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. III. Platinum," Brit. J. Appl. Phys. (J. Phys. D), **2**(1), 109–13, 1969.

[671] Jain, S. C., and Krishnan, K. S., "The Distribution of Temperature Along a Thin Rod Electrically Heated in Vacuo. Part 2. Theoretical. Part 3. Experimental. Part 4. Many Useful Emperical Formulae Verified," Proc. Roy. Soc. (London), **A225**, 1–32, 1954.

[672] Jain, S. C., Narayan, V., and Goel, T. C., "Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. II. Cobalt," Brit. J. Appl. Phys. (J. Phys. D), **2**(1), 101–7, 1969.

[673] Jain, S. C., Sinha, V., and Reddy, B. K., "Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Methods. IV. Palladium," Brit. J. Appl. Phys. (J. Phys. D), **2** (9), 1283–9, 1969.

[674] Jain, S. C., Sinha, V., and Reddy, B. K., "Thermal Conductivity of Metals at High Temperatures by the Jain and Krishnan Method. V. Zirconium," Brit. J. Appl. Phys. (J. Phys. D), **3**(9), 1359–62, 1970.

[675] Jamieson, C. P., and Mrozowski, S., "Thermal Conductivities of Polycrystalline Carbons and Graphites," in *Proc. 1st and 2nd Conf. on Carbon* (Univ. Buffalo, 1953, 1955), 155–66, 1956.

[676] Jeans, J., *Dynamical Theory of Gases*, Dover Publications, N. Y., Cambridge Univ. Press, Cambridge, England, 444 pp., 1954.

[677] Jenkins, R. J., Parker, W. J., and Butler, C. P., "A Method of Determining the Thermal Properties of Metals Above 1000 K Using Electrically Heated Wires," USNRDL–TR–348, 1–24, 1959. [AD 226 896]

[678] Johannin, P., "Thermal Conductivity of Nitrogen Between 75 and 700 C and up to 1000 to 1600 Amagats," J. Recherches C. N. R. S., **43**, 116–55, 1958.

[679] Johannin, P., "Experimental Determination of the Thermal Conductivity of Nitrogen at High Pressures and Elevated Temperatures," in *Proc. of Thermodynamic and Transport Properties Fluids* (London, 1957), 193–4, 1958.

[680] Johannin, P., "Thermal Conductivity of Nitrogen Between 75 and 700 C and from 1000 to 1600 Atmospheres," Univ. Paris, Thesis, 1–39, 1958.

[681] Johansen, E. S., *Heat, Thermodynamics and Molecular Kinetic Theory*, Gjellerups—Forlag, Copenhagen, 34 pp., 1950.

[682] Johansson, C. H., and Linde, J. O., "Crystal Structure,

Electrical Resistance, Thermoelectric Force, Heat Conductivity, Magnetic Susceptibility, Hardness and Aging Phenomena of the System Au Pt in Connection with the Phase Diagram," Ann. Physik, **5**, 762–92, 1930.

[683] Johnson, H. V., Unpublished data, National Carbon Company, as quoted in Ref. 307.

[684] Johnson, V. J., "A Compendium of the Properties of Materials at Low Temperatures (Phase 1), Part 1. Properties of Fluids," WADD-TR-60-56, Pt. I, 1960. [AD 249 644]

[685] Johnson, W., and Watt, W., "The Thermal Conductivity of Pyrolytic Graphite at Elevated Temperatures," Royal Aircraft Establishment, 1-27, 1963. [AD 417 736]

[686] Johnson, W., and Watt, W., "Thermal Conductivity of Pyrolytic Graphite," *in Special Ceramics* 1962, Brit. Ceram. Res. Assoc. (England), 237–59, 1963.

[687] Johnston, H. L., "Liquid Hydrogen Propellant for Aircraft and Rockets," 20th Bi-Monthly Progr. Rept. USAF ATI 45490, 1-10, 1948.

[688] Johnston, H. L., "Liquid Hydrogen—Propellant for Aircraft and Rockets," 22nd Bi-Monthly Progress Report, Ohio State Univ. Research Foundation, USAF ATI 54990, 1-79, 1959. [ATI 54 990]

[689] Johnston, H. L., and Grilly, E. R., "The Thermal Conductivities of Eight Common Gases Between 80 and 380 K," J. Chem. Phys., **14**, 233–8, 1946.

[690] Jolliffe, B. W., Tye, R. P., and Powell, R. W., "The Thermal and Electrical Conductivities of Scandium, Yttrium, and Manganese and Twelve Rare-Earth Metals, at Normal Temperatures," J. Less-Common Metals, **11**(6), 388–94, 1966.

[691] Jones, I. W., "Calculations of the Thermal Conductivity of Hydrogen in the Liquid and Dense Gaseous State," Min. of Aviation (U. K.) E. R. D. E. Rept. 20/R/65, 1-18, 1965.

[692] Jones, L. V., and Wittenberg, L. J., "Reactor Fuels and Materials Development—Plutonium Research: January-March, 1963," Monsanto Res. Corp., Mound Lab. MLM-1156, 27 pp., 1963.

[693] Jones, R. E., and Toxen, A. M., "Thermal Conductivity of Pure Indium," Phys. Rev., **120**, 1167–70, 1960.

[694] Jones, R. E., and Toxen, A. M., "Thermal Conductivity of Pure Indium," in *Proceedings of the Seventh International Conference on Low Temperature Physics*, Univ. of Toronto Press, Canada, 407–9, 1961.

[695] Jones, T. I., Street, K. N., Scoberg, J. A., and Baird, J., "Relation Between Microstructure and Thermal Conductivity in Aluminum-Uranium Alloys," Can. Met. Quart, **2**(1), 53–72, 1963.

[696] Julian, C. L., "Theory of Heat Conduction in Rare-Gas Crystals," Phys. Rev., **A137**, 128–37, 1965.

[697] Jun, C. K., and Hoch, M., "The Thermal Conductivity of Molybdenum at Elevated Temperatures: Influence of Grain Size," in *Advances in Thermophysical Properties at Extreme Temperatures and Pressures*, Proc. 3rd Symp. on Thermophysical Properties, ASME, Purdue Univ., Lafayette, Ind., 296–300, 1965.

[698] Jun, C. K., and Hoch, M., "Thermal Conductivity of Tantalum, Tungsten, and Ta-W Alloys," AFML-TR-65-191, 1-11, 1965. [AD 477 224]

[699] Jun, C. K., and Hoch, M., "Thermal Conductivity of Tantalum, Tungsten, Rhenium, Ta-10W, T_{111}, T_{222}, W-25 Re in the Temperature Range 1500–2800 K," AFML-TR-66-367, 1-17, 1966. [AD 807 299]

[700] Juul, N. H., "Determination of the Thermal Diffusivity for Polycrystalline Graphites at High Temperatures," in *Proc. 5th Conf. on Carbon* (Univ. Park, Pa.), Pergamon Press, Vol. 1, 533–46, 1962.

[701] Juul, N., Sato, S., and Strauss, H. E., "Progr. Rept. No. 17, Nov. 62-1 May 1963," Buffalo, N. Y., USAF DDC NP-12878, 17, 1-14, 1963. [AD 416 276]

[702] Kannuluik, W. G., "On the Thermal Conductivity of Some Metal Wires," Proc. Roy. Soc. (London), **A131**, 320–35, 1931.

[703] Kannuluik, W. G., "Thermal Conductivity of Deuterium," Nature (London), **137**, 741, 1936.

[704] Kannuluik, W. G., and Carman, E. H., "The Temperature Dependence of the Thermal Conductivity of Air," Austral. J. Sci. Res., **A4**, 305–14, 1951.

[705] Kannuluik, W. G., and Carman, E. H., "The Thermal Conductivity of Rare Gases," Proc. Phys. Soc. (London), **B65**, 701–9, 1952.

[706] Kannuluik, W. G., and Donald, H. B., "The Pressure Dependence of the Thermal Conductivity of Polyatomic Gases at 0," Austral. J. Sci. Res., **A3**, 417–27, 1950.

[707] Kannuluik, W. G., Eddy, C. E., and Oddie, T. H., "The Thermal and Electrical Conductivities of Several Metals between −183 and 100 C," Proc. Roy. Soc. (London), **A141**, 159–68, 1933.

[708] Kannuluik, W. G., and Laby, T. H., "The Thermal and the Electrical Conductivity of a Copper Crystal at Various Temperatures," Proc. Roy. Soc. (London), **A121**, 640–53, 1928.

[709] Kannuluik, W. G., and Law, P. G., "The Thermal Conductivity of Carbon Dioxide between −78.50 C and 100 C," Proc. Roy. Soc. (London), **58**(I–II), 142–56, 1947.

[710] Kannuluik, W. G., and Martin, L. H., "The Thermal Conductivity of Some Gases at 0 degree," Proc. Roy. Soc. (London), **A144**, 496–513, 1934.

[711] Kapelner, S. M., "The Electrical Resistivity of Lithium and Sodium-Potassium Alloy," Pratt and Whitney Aircraft Div. United Aircraft Corp., Middletown, Conn., USAEC PWAC-349, 1-33, 1961.

[712] Kapelner, S. M., and Bratton, W. D., "The Electrical Resistivity of Sodium, Potassium, Rubidium, and Caesium in the Liquid State," USAEC Rept. PWAC-376, 1-31, 1962.

[713] Kapitza, P. L., "The Study of Heat Transfer in Helium II," J. Phys. (USSR), **4**, 181–210, 1941.

[714] Karagyozyan, A. G., and Rao, K. V., "Anomalous Thermal Conductivity in Gadolinium Below 4 K," Phys. Letters (Netherlands), **A25**(3), 235–6, 1967.

[715] Karagyozyan, A. G., and Rao, K. V., "Thermal Conductivity of Polycrystals and Single Crystals of Terbium between 1 and 4 K," Zh. Eksp. Teor. Fiz., **55**(4), 1168–72, 1968: English translation: Sov. Phys.-JETP, **28**(4), 609–11, 1969.

[716] Karamargin, M. C., Lipschultz, F. P., Reynolds, C. A., and Klemens, P. G., Private communication from Karamargin, M. C., 9 June, 1970.

[717] Karweil, J., and Schaefer, K., "Thermal Conductivity of Poorly Conducting Alloys between 3 Degrees and 20 K," Ann. Physik, **36**, 567–77, 1939.

[718] Kasatochkin, V. I., Zamoluev, V. K., Kaverov, A. T., and Usenbaev, K., "The Thermal Properties of Transitional Forms of Carbon," Proc. Acad. Sci. USSR, Physical Chemistry Sect., **135**(1), 1009–12, 1960.

[719] Kaspar, J., "Thermal Propagation in Carbons and Graphites at Very High Temperatures," USAF Rept. SSD-TR-67-56, Aerospace Corp. Rept. TR-1001 (9250-02)-1, 1-40, 1967.

[719a] Kasuya, T., "On the Theory of Thermal Conductivity of Monovalent Metals," Progr. Theoret. Phys. (Kyoto), **13**, 561–70, 1955.

[720] Kaye, G. W. C., "The Thermal and Electrical Resistance of Bismuth Single Crystals. The Effects of Temperature and Magnetic Fields," Proc. Roy. Soc. (London), **A170**, 561–83, 1939.

[721] Kaye, G. W. C., and Higgins, W. F., "The Thermal Conductivity of Solid and Liquid Sulphur," Proc. Roy. Soc. (London), **A122**, 636–46, 1929.

[722] Kaye, G. W. C., and Higgins, W. F., "Thermal Conductivity of a Single Crystal of Bismuth in a Transverse Magnetic Field," Phil. Mag., 7, **8**, 1056–9, 1929.
[723] Kaye, G. W. C., and Laby, T. H., "Tables of Physical and Chemical Constants and Some Mathematical Functions, 13th Ed.," Longmans, Green, and Co., Ltd., London, 249 pp., 1966.
[724] Kaye, G. W. C., and Roberts, J. K., "The Thermal Conductivities of Metal Crystals. I. Bismuth," Proc. Roy. Soc. (London), **A104**, 98–114, 1923.
[725] Keesom, P. H., and Pearlman, N., "Atomic Heat of Graphite between 1 and 20 K," Phys. Rev., **99**, 1119–24, 1955.
[726] Keesom, W. H., *Helium*, Elsevier Publ. Co., Amsterdam, 494 pp., 1942.
[727] Keesom, W. H., and Duyckaerts, G., "The Thermal Conductivity and the Thermomechanical Effect of Liquid Helium-II," Physica, **13**, 153–79, 1947.
[728] Keesom, W. H., and Keesom, A. P., "The Heat Conductivity of Liquid Helium," Physica, **3**, 359–60, 1936.
[729] Keesom, W. H., and Saris, B. F., "Further Measurements on the Heat Conductivity of Helium II," Physica, **7**, 241–52, 1940.
[730] Keesom, W. H., Saris, B. F., and Meyer, L., "New Measurements on the Heat Conductivity of Liquid Helium II," Physica, **7**, 817–30, 1940.
[731] Kelly, B. T., "The Thermal Conductivity of Graphite," in *Chemistry and Physics of Carbon* (Walker, P. L., Jr., Editor), Vol. 5, Marcel Dekker, Inc., New York, 119–215, 1969.
[732] Kelly, B. T., and Gilchrist, K. E., "The Basal Thermal Conductivity of Highly Oriented Pyrolytic Graphite as a Function of Degree of Graphitization," UKAEA TRG Rept. 1672(c), 1–8, 1968.
[733] Kelly, B. T., and Gilchrist, K. E., "The Basal Thermal Conductivity of Highly Oriented Pyrolytic Graphite as a Function of Degree of Graphitization," Carbon (Oxford), **7**, 355–8, 1969.
[734] Kelman, L. R., Dunworth, R. J., Savage, H., and Rhude, H. V., "Properties of Uranium-Plutonium-Fizzium Alloys," ANL–7000, 3–7, 1964.
[735] Kelman, L. R., Dunworth, R. J., Savage, H., and Rhude, H. V., "Status of Metallic Plutonium Fast Power-Breeder Fuels," in *Proceedings of the 3rd International Conference on Plutonium* (London, 1965), 458–84, 1967.
[736] Kemp, W. R. G., Klemens, P. G., Sreedhar, A. K., and White, G. K., "The Thermal and Electrical Conductivity of Palladium at Low Temperatures," Phil. Mag., 7, **46**, 811–14, 1955.
[737] Kemp, W. R. G., Klemens, P. G., and Tainsh, R. J., "Thermal and Electrical Conductivities of Rhodium and Iron," Ann. Physik, 7, **5**, 35–41, 1959.
[738] Kemp, W. R. G., Klemens, P. G., and White, G. K., "Thermal and Electrical Conductivities of Iron, Nickel, Titanium, and Zirconium at Low Temperatures," Austral. J. Phys., **9**, 180–8, 1956.
[739] Kemp, W. R. G., Sreedhar, A. K., and White, G. K., "The Thermal Conductivity of Magnesium at Low Temperatures," Proc. Phys. Soc., **A66**(11), 1077–8, 1953.
[740] Kempf, L. W., Smith, L. S., and Taylor, C. S., "Thermal and Electrical Conductivities of Aluminum Alloys," Trans. AIMME, **124**, 287–98, 1937.
[741] Kennard, E. H., *Kinetic Theory of Gases*, McGraw-Hill, N. Y., 483 pp., 1938.
[742] Kerrisk, J. F., Rogers, J. D., and Hammel, E. F., "Transport Properties of He^3, He^4, H_2, and Ne in the Liquid State According to the Quantum Mechanical Principle of Corresponding States," LADC 5791, 1–21, 1963.
[743] Kestin, J., and Wakeham, W., "The Viscosity and Thermal Conductivity of Binary Gaseous Mixtures," in *Proceedings of the Fifth Symposium on Thermophysical Properties*, A. S. M. E., New York, 55–63, 1970.
[744] Kettel, F., "The Thermal Conductivity of Germanium at High Temperatures," Phys. and Chem. Solids, **10**(1), 52–8, 1959.
[745] Keyes, F. G., "Thermal Conductivities for Several Gases with a Description of New Means for Obtaining Data at Low Temperatures and Above 500 C," M. I. T. Project Squid Tech. Memo MIT–1, 1–34, 1952. [AD 5117]
[746] Keyes, F. G., "The Heat Conductivity, Viscosity, Specific Heat and Prandtl Numbers for 13 Gases," M. I. T. Project Squid Tech. Rept. No. 37, 1–33, 1952.
[747] Keyes, F. G., "Thermal Conductivity of Gases," Trans. Amer. Soc. Mech. Eng., **76**, 809–16, 1954.
[748] Keyes, F. G., "Thermal Conductivity of Gases," Trans. Am. Soc. Mech. Engrs., **77**, 1395–6, 1955.
[749] Keyes, F. G., "Summary of Measured Thermal Conductivities and Values of Viscosities," in Transport Properties in Gases (Proc. 2nd Biennial Gas Dynamics Symp., Evanston, Ill., 1957), Northwestern Univ. Press, 51–4, 1958.
[750] Keyes, F. G. and Vines, R. G., "The Thermal Conductivity of Nitrogen and Argon," Trans. Amer. Soc. Mech. Eng. (J. Heat Transfer), **87C**, 177–83, 1965.
[751] Keyes, R. W., "Laws of Corresponding States for the Thermal Conductivity of Molecular Solids," J. Chem. Phys., **31**, 452–4, 1959.
[752] Keyes, R. W., "The Thermal Conductivity of Molecular Crystals," *Organic Semiconductors*, Macmillan, New York, 123–32, 1962.
[753] Keyes, R. W., and Sladek, R. J., "Piezo-Thermal Conductivity Effect in Germanium," Phys. Rev., **125**, 478–83, 1962.
[754] Khalatnikov, I. M., "Thermal Conductivity and Absorption of Sound in Helium II," Zh. Eksp. i Teor. Fiz., **23**, 21–34, 1952.
[755] Khalileev, P. A., "Heat Conduction and Electrical Conductivity of Alkali Metals in the Solid or Liquid States," J. Exptl. Theoret. Phys. (USSR), **10**, 40–57, 1940; English translation: SNSRS–98, TT–65–28890, 35 pp., 1952.
[756] Khusainova, B. N., and Filippov, L. P., "Thermal Properties of a Molybdenum Single Crystal at High Temperatures," Teplofiz. Vys. Temp., **6**(5), 929–30, 1968; English translation: High Temp., **6**(5), 891–2, 1968.
[757] Kikoin, I. K., et al., "Electrical Conductivity and Density of a Metal Vapor," Sov. Phys.-JETP, **22**(1), 89–90, 1966.
[758] Kikuchi, R., "The Thermal and Electric Conductivities of Magnesium Alloys," Kinzoku-No-Kenkyuh, **9**(6), 239–43, 1932.
[759] King, C. R., "Compilation of Thermodynamic Properties, Transport Properties, and Theoretical Rocket Performance of Gaseous Hydrogen," NASA–TN–D–275, 1–71, 1960. [AD 235 647]
[760] King, R. W., "A Method of Measuring Heat Conductivities," Phys. Rev., **6**(6), 437–45, 1915.
[761] King, R. W., "Measurement of Heat Conductivities of Metals at High Temperatures," Phys. Rev., **11**, 149–50, 1918.
[762] Kingery, W. D., Francl, J., Cable, R. L., and Vasilos, T., "X. Data for Several Pure Oxide Materials Corrected to Zero Porosity," J. Am. Ceram. Soc., **37**, 107–10, 1954.
[763] Kirichenko, P. I., and Mikryukov, V. E., "Thermal and Electrical Properties of Some Alloys of the Rhenium-Nickel System," Teplofiz. Vys. Temp., **2**(2), 199–204, 1964; English translation: High Temp., **2**(2), 176–80, 1964.
[764] Kitrilakis, S., and Meeker, M., "Experimental Determination of the Heat Conduction of Cesium Gas," Advanced Energy Conversion, **3**, 59–68, 1963.
[765] Klein, A. H., Shanks, H. R., and Danielson, G. C.,

"Thermal Conductivity of Silicon and Iron from 300 to 1400 K," Ames Lab. Iowa State Univ., USAEC IS–835, 747–55, 1964.

[766] Klein, A. H., Shanks, H. R., and Danielson, G. C., "Thermal Diffusivity of Armco Iron by Three Methods," USAEC IS–1266, CONF–651020–3, 1–8, 1965.

[767] Klein, C. A., "STB Model and Transport Properties of Pyrolytic Graphite," IBM J. Res. Development, **8**, 274–5, 1964.

[768] Kelin, C. A., "Simple Two-Band (STB) Model and Transport Properties of Pyrolytic Graphites," J. Appl. Phys., **35**(10), 2947–57, 1964.

[769] Klein, C. A., and Holland, M. G., "Thermal Conductivity of Pyrolytic Graphite at Low Temperatures. I. Turbostratic Structures," Phys. Rev., **136**(2A), A575–90, 1964.

[770] Klemens, P. G., "The Specific Heat and Thermal Conductivity of Graphite," Australian J. Phys., **6**, 405–9, 1953.

[770a] Klemens, P. G., "The Thermal Conductivity of Monovalent Metals," Proc. Phys. Soc. (London), **A67**, 194–6, 1954.

[771] Kobushko, V. S., Merisov, B. A., and Khotkevich, V. I., "A Method of Determining the Thermal Conductivity of Metals at High Temperature," Inzh.-Fiz. Zh., **8**(1), 58–63, 1965; English translation: International Chemical Engineering, **5**(3), 485–8, 1965.

[772] Koenig, J. H. (Editor), "I. Development of Ceramic Bodies with High Thermal Conductivity. 1st Quarterly Progr. Rept.," N. J. Ceram. Res. Sta., Rutgers Univ., Signal Corps USAF, 1–33, 1953. [AD 5 552]

[773] Koenig, J. H., "I. Development of Ceramic Bodies with High Thermal Conductivity. 4th Quarterly Progr. Rept.," N. J. Ceram. Res. Sta., Rutgers Univ., Signal Corps USAF, 1–35, 1953. [AD 29 335]

[773a] Kohler, M., "Treatment of the Nonequilibrium Process with the Aid of Extreme Principle," A. Physik, **124**, 772–89, 1948.

[773b] Kohler, M., "Transport Phenomena in Electron Gas," Z. Physik, **125**, 679–93, 1949.

[774] Kohlhaas, R., and Kierspe, W., "A Method for the Continuous Measurement of Thermal Conductivity of Metals in the Temperature Region Between Liquid Air and Room Temperature," Z. Angew. Phys., **17**(5), 361–4, 1964.

[775] Kohlhaas, R., and Kierspe, W., "The Thermal Conductivity of Pure Iron and Some Ferritic and Austenitic Steels Between the Temperature of Liquid Air and Room Temperature," Arch. Eisenhüttenw, **36**(4), 301–9, 1965.

[776] Komatsu, K., "Theory of the Specific Heat of Graphite," J. Phys. Soc. Japan, **10**, 346–56, 1955.

[777] Komatsu, K., and Nagamiya, T., "Theory of the Specific Heat of Graphite," J. Phys. Soc. Japan, **6**(6), 438–44, 1951.

[778] Konno, S., "On the Variation of Thermal Conductivity During the Fusion of Metals," Sci. Repts. Tohoku Imp. Univ., **8**, 169–79, 1919.

[779] Kononenko, V. I., Yatsenko, S. P., Rubinshtein, G. M., and Privalov, I. M., "Viscosity and Electrical Resistivity of Liquid Aluminum," High Temp., **7**(2), 243–6, 1969.

[780] Kozak, M. I., "Heat Conductivity of Certain Powders at High Temperatures," Zh. Tekhn. Fiz., **22**(1), 73–6, 1952.

[781] Kozlov, F. A., and Antonov, I. N., "Relation Between Thermal Conductivity and Oxide Concentrations in Sodium," At. Energ., **19**(4), 391–2, 1965; English translation: Sov. J. At. Energy, **19**(4), 1333–4, 1965.

[782] Kraev, O. A., and Stel'makh, A. A., "Thermal Diffusivity of Tantalum, Molybdenum, and Niobium at Temperatures above 1800 K," Teplofiz. Vys. Temp., **2**(2), 302, 1964; English translation: High Temp., **2**(2), 270, 1964.

[783] Kraev, O. A., and Stel'makh, A. A., "Thermal Diffusivity and Thermal Conductivity of Metals at High Temperatures," from *High Temperature Research*, Acad. Sci. USSR—Siberian Section Novosibirsk, 55–74, 1966.

[784] Krainova, I. F., and Shpil'rain, E. E., "Experimental Determination of the Thermal Conductivity of Liquid Rubidium, Potassium, and Sodium-Potassium Alloys," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, New York, 367–72, 1969.

[785] Kramer, H., and Schmeiser, K., "Thermal Conductivity of Yellow Phosphorus in the Temperature Range Plus 16 to Plus 80 Degrees," Z. Physik Chem. (Frankfort), **35**, 1–9, 1962.

[786] Kratz, H. R., "Physical and Mechanical Properties. Metallurgy From Minutes of Metallurgy Conference, July 20–1, 1943, Chicago, Illinois," Chicago Univ. Metallurgical Lab., USAEC CT–861, 10–14, 1943.

[787] Kratz, H. R., and Raeth, C. H., "Report for Month Ending March 27, 1943. Technological Research—Metallurgy," USAEC Rept. No. CT–539, 8, 1943.

[788] Kratz, H. R., and Raeth, C. H., "The Thermal Conductivity of Uranium," Chicago Univ. Metall. Lab., USAEC CP–2315, 1–14, 1945.

[789] Krishnan, K. S., and Jain, S. C., "Determinations of Thermal Conductivity (of Metals, e. g., Platinum) at High Temperatures," Brit. J. Appl. Phys., **5**(12), 426–30, 1954.

[789a] Kroll, W., "On the Theory of Heat Conduction," Sci. Papers Inst. Phys. Chem. Res. Tokyo, **34**(756), 194–6, 1938.

[790] Krumhansl, J. A., and Brooks, H., "The Lattice Vibration Specific Heat of Graphite," J. Chem. Phys., **21**(10), 1663, 1953.

[791] Krupskii, I. N., "Thermal Conductivity of Solid Argon," Phys. Status Solidi, **24**(1), K53–6, 1967.

[792] Krupskii, I. N., and Manzhelii, V. G., "Multiphonon Interactions and the Thermal Conductivity of Crystalline Argon, Krypton and Xenon," Zh. Eksp. i Teor. Fiz., **55**(6), 2075–82, 1968; English translation: Sov. Phys.-JETP, **28**(6), 1097–1100, 1969.

[793] Krzhizhanovskii, R. E., "The Thermophysical Properties of Titanium and the Thermal Conductivity of its Alloys With Tin and Aluminum," Teplofiz. Vys. Temp., **2**(3), 392–6, 1964; English translation: High Temp., **2**(3), 359–62, 1964.

[794] Kudryavtsev, E. V., and Chakalev, K. N., "Universal Electronic Calorimeter," Inzh.—Fiz. Zh., **3**(1), 3–9, 1960; English translation: USAEC-TR–4934, 1–10, 1960.

[795] Kuhn, G., "Magnetic and Thermal Behavior in the Superconducting State of a Nb Single Crystal," Compt. Rend., **255**, 2923–5, 1962.

[796] Kuhn, G., "Irreversible Magnetic Behavior of Superconductors," Comm. Energie At. (France), Rappt. CEA–R 2808, 1–116, 1966.

[797] Kuhn, G., and Goodman, B. B., "Influence of Extensive Defects on the Superconducting Properties of Niobium," J. Physique (France), **29**(2/3), 240–52, 1968.

[798] Kulcinski, G. L., Wagner, P., and Cowder, L. R., "The Effect of Porosity and Pore Interconnection on the Thermal Conductivity and Electrical Resistivity of Tungsten," J. Less-Common Metals, **7**(5), 383–92, 1964.

[799] Kulik, P. P., Panevin, I. G., and Khvesyuk, V. I., "Theoretical Calculation of the Viscosity, Thermal Conductivity, and Prandtl Number for Argon in the Presence of Ionization," Teplofiz. Vys. Temp., **1**(1), 56–63, 1963; English translation: High Temp., **1**(1), 45–51, 1963.

[800] Kummer, D. L., Rosenthal, J. J., and Lum, D. W., "Shielded Ceramic Composite Structure. Final Rept. 1 June 1963–18 June 1965," AFML-TR-65-331, 405 pp., 1965. [AD 475 002]

[801] Kuprovskii, B. B., and Gel'd, P. V., "Heat Conductivity Isotherms of Silicon and of Its Alloys with Iron at High Temperatures," Fiz. Metal. i Metalloved., **3**, 182–3, 1956.
[802] Kuprovskii, B. B., and Gel'd, P. V., "Thermal Conductivity of α-Titanium," Tr. Ural. Politekh. Inst., Sb. No. 114, 153–4, 1961.
[803] Kurtener, A. V., and Malyshev, E. K., "Thermal Conductivity of Se and of Hutchins Alloys," J. Tech. Phys. (USSR), **13**(11), 641–4, 1943.
[804] Küster, W., Bode, K. H., and Fritz, W., "Contribution to the Measurement of the Thermal Conductivity of Metals in the Range of 0 to 500 C," Warme und Stoffübertragung, **1**(3), 129–39, 1968.
[805] Kutatelodze, S. S., Borishanskii, V. M., Novikov, I. I., and Fedynskii, O. S., "Basic Properties of Liquid Metals," From the English Translation of *Zhidkometallicheski Teplosositeli (Liquid-Metal Heat Transfer Media)*, Consultants Bureau Inc., New York, and Chapman and Hall, Ltd., London, Chapter 1, 1–12, 1958.
[806] Lafyatis, P. C., Waters, C. W., and Dull, R. B., "Development and Evaluation of Large-Scale RVA and CFZ graphite," USAF Rept., 181 pp., 1965. [AD 470 151]
[807] La Marre, D. A., Simpson, G. R., and Thorburn, M. R., "Experimental Verification of Sun Powered Laser Transmitter. Interim Engineering Rept. No. 2, Aug.–Nov. 62," USAF Rept., 1–41, 1962. [AD 437 864]
[808] Landolt, H. H., and Börnstein, R., *Landolt-Börnstein Phyikalisch-Chemische Tabellen*, Julius Springer, Berlin Tables 272–3, 1923–6.
[809] Langmuir, I., and Taylor, J. B., "The Heat Conductivity of Tungsten and the Cooling Effects of Leads on Filaments at Low Temperatures," Phys. Rev., 2, **50**(1), 68–87, 1936.
[810] Laredo, S. J., "The Thermal Conductivity of Tin at Low Temperatures," Proc. Roy. Soc. (London), **A229**, 473–92, 1955.
[811] Larsen, D. C., "Evaluation of an Apparatus for the Determination of the Thermal Conductivity of Good Conducting Solids—Results on Armco Iron From 50 to 300 C," Purdue Univ., M. S. Thesis, 135 pp., 1968.
[812] Larsen, D. C., Powell, R. W., and DeWitt, D. P., "The Thermal Conductivity and Electrical Resistivity of a Round-Robin Armco-Iron Sample, Initial Measurements from 50 to 300 C," in *Thermal Conductivity—Proceedings of the Eighth Conference*, Plenum Press, New York, 675–87, 1969.
[813] Larsen, K. B., and Koyama, K. K., "Measurement by the Flash Method of Thermal Diffusivity, Heat Capacity, and Thermal Conductivity in Two-Layer Composite Samples," J. Appl. Phys., **39**(9), 4408–16, 1968.
[814] Laubitz, M. J., "Thermal and Electric Properties of Armco Iron at High Temperatures," Can. J. Phys., **38**, 887–907, 1960.
[815] Laubitz, M. J., "The Unmatched Guard Method for Measuring Thermal Conductivity at High Temperatures," Can. J. Phys., **41**(10), 1663–78, 1963.
[816] Laubitz, M. J., "The Thermal Conductivity of Platinum from 300 to 1000 K," Div. Applied Physics, National Research Council, Ottawa, Ontario, Canada, private communication, 1965.
[817] Laubitz, M. J., "Transport Properties of Pure Metals at High Temperatures. I. Copper," Can. J. Phys., **45**(11), 3677–96, 1967.
[818] Laubitz, M. J., "Transport Properties of Pure Metals at High Temperatures. II. Silver and Gold," Can. J. Phys., **47**(23), 2633–44, 1969.
[819] Laubitz, M. J., and Chandrashekhar, G. V., Private communication of preliminary results, 3 January 1969.
[820] Laubitz, M. J., and van der Meer, M. P., "The Thermal Conductivity of Platinum between 300 and 1000 K," Can. J. Phys., **44**(12), 3173–84, 1966.
[821] Lebedev, S. V., "The Possibility of Using the Electrical Explosion of Wires for Investigation of Metals at High Temperatures," Teplofiz. Vys. Temp., **6**(1), 157–9, 1968; English translation: High Temp., **6**(1), 150–2, 1968.
[822] Lebedev, V. V., "Determination of the Thermal Conductivity of Metals at High Temperatures," Fiz. Metal. i Metalloved., Akad. Nauk SSSR, **10**(2), 187–90, 1960; English translation: Phys. Metals Metallogs., USSR, **10**(2), 31–4, 1960.
[823] Lebedev, V. V., "Thermal Conductivity Measurements of Metals at High Temperatures," Ukr. Fiz. Hr., **6**, 522–4, 1961.
[824] Lee, C. S. (Bonilla, C. F., chief investigator), "High Temperature Thermal Properties of Gases and Vapors," USAEC CU–2660–39, 1–12, 1967.
[825] Lee, C. S., and Bonilla, C. F., "Thermal Conductivity of the Alkali Metal Vapors and Argon," in *Thermal Conductivity—Proceedings of the 7th Conf.*, Gaithersburg, Maryland, NBS–SP–302, 561–78, 1968.
[826] Lee, J. A., "A Review of the Physical Metallurgy of Neptunium," in *Progress in Nuclear Energy Series V Metallurgy and Fuels*, Vol. 3, Pergamon Press, New York, 453–67, 1961.
[827] Lee, J. A., and Mardon, P. G., "Some Physical Properties of Plutonium Metal Studied at Harwell," *The Metal Plutonium*, Univ. of Chicago Press, 133–51, 1961.
[828] Lees, C. H., "On the Thermal Conductivity of Crystals and Other Bad Conductors," Phil. Trans. Roy. Soc. (London), **183**, 481–509, 1892.
[829] Lees, C. H., "X. On the Thermal Conductivities of Single and Mixed Solids and Liquids and Their Variation with Temperature," Phil. Trans. Roy. Soc. (London), **A191**, 399–440, 1898.
[830] Lees, C. H., "Bakerian Lecture—The Effects of Temperature and Pressure on the Thermal Conductivities of Solids—Part II. The Effects of Low Temperature on the Thermal and Electrical Conductivities of Certain Approximately Pure Metals and Alloys," Phil. Trans. Roy. Soc. (London), **A208**, 381–443, 1908.
[831] Legvold, S., and Spedding, F. H., "Quarterly Summary Research Report in Physics for April, May, and June 1954," Ames Lab., Ames, Iowa. (The thermal conductivity work was performed by J. E. Cranch), USAEC Rept. ISC–508, 1–13, 1954.
[832] Legvold, S., and Spedding, F. H., "Thermal Conductivity of Rare Earths," USAEC Rept. ISC–508, 11, 1954.
[833] Lehmann, H., "Thermal Conductivity of Gas Mixtures," Chem. Tech. (Berlin), **9**, 530–7, 1957.
[834] Leibfried, G., and Schlömann, E., "Heat Conduction in Electrically Insulating Crystals," Nachr. Akad. Wiss. Göttingen, Math.-Physik, Kl., **2a**(4), 71–93, 1954; English translation: USAEC–TR–5892, 1–36, 1963.
[835] Lemmon, A. W., Jr., "Engineering Properties of Potassium and Cesium. Twelfth Quarterly Rept. 1 July—30 Sept. 1963," Battelle Memorial Inst., Columbus, Ohio, BATT–4673–Q–12, NASA–CR–63582, 1–12, 1963.
[836] Lemmon, A. W., Jr., Deem, H. W., Eldridge, E. A., Hall, E. H., Matolich, J., Jr., and Walling, J. F., "Engineering Properties of Potassium," Batelle Memorial Inst., Columbus, Ohio, BATT–4673–Final, NASA–CR–54017, 1–66, 1963.
[837] Lemmon, A. W., Jr., Deem, H. W., Eldridge, E. A., Hall, E. H., Matolich, J., Jr., and Walling, J. F., "The Specific Heat, Thermal Conductivity, and Viscosity of Liquid Cesium," Battelle Memorial Institute, Columbus, Ohio, BATT–4673–T7,N64–18294, NASA–CR–54018, 1–34, 1964.
[838] LeNeindre, B., Tufeu, R., Bury, P., Johannin, P., and

Vodar, B., "The Thermal Conductivity Coefficients of Some Noble Gases," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, New York, 75–100, 1969.
[839] Lenoir, J. M., "Thermal Conductivity of Gases at Atmospheric Pressure," Univ. Arkansas, Eng. Exptl. Sta. Bull. 18, 1–48, 1953.
[840] Lepie, M. P., "The Properties of Pyrolytic ZrC," Trans. Brit. Ceram. Soc., **63**(8), 431–49, 1964.
[841] Lewis, E. J., "Some Thermal and Electrical Properties of Beryllium," Phys. Rev., **34**, 1575–87, 1929.
[842] Lifshits, E. M., and Andronikashvili, E. L., "A Supplement to Helium," Consultants Bureau Inc., N. Y., 1–167, 1959.
[843] Liley, P. E., "The Thermal Conductivity of 46 Gases at Atmospheric Pressure," in *Proceedings of the Fourth Symposium on Thermophysical Properties*, A. S. M. E., New York, 323–49, 1968.
[844] Liley, P. E., "The Thermal Conductivity of Nonmetallic Elements [in Liquid or Gaseous State at NTP] in Solid, Saturated and Atmospheric Pressure States," in *Thermal Conductivity Proceedings of the Seventh Conference*, NBS SP–302, 57, 1968.
[845] Liley, P. E., "Correlations for Thermal Conductivity and Latent Heat of Saturated Fluids Near the Critical Point," in *Proceedings of the Fifth Symposium on Thermophysical Properties*, A. S. M. E., New York, 197–9, 1970.
[846] Lindenbaum, S. D., and Quimby, S. L., "The Order Dependent Electrical and Thermal Resistivity of Cu_3Au. Final Tech. Rept., Part 2, 22 Jan. 58–21 Jan. 61," AROD Rept. 1931:2, 31 pp., 1962. [AD 272 561]
[847] Lindenfeld, P., Lynton, F. A., and Soulen, R., "Metallic Heat Conductivity Below 1 K," Phys. Letters (Netherlands), **19**(4), 265, 1965.
[848] Lindenfeld, P., and Pennebaker, W. B., "Lattice Conductivity of Copper Alloys," Phys. Rev., **127**, 1881–9, 1962.
[849] Lindenfeld, P., and Rohrer, H., "Ratio of the Lattice Thermal Conductivities of Normal and Superconducting Indium," Phys. Rev., A139(1), 206–11, 1965.
[850] Ling-Temco-Vought, Inc., "Pyrolyzed Plastic Composites," ML–TDR–64–187, 203 pp., 1964. [AD 451 206]
[851] Little, A. D., "Hydrogen Handbook. A Compilation of Properties, Handling and Testing of Procedures, Compatibility with Materials, and Behavior at Low Temperatures," AFFTC–TR–60–19, 1–246, 1960. [AD 242 285]
[852] Little, N. C., "Thermomagnetic and Galvanomagnetic Effects in Arsenic," Phys. Rev., **28**, 418–22, 1926.
[853] Löchtermann, E., "Thermal Conductivity of Liquid Neon," Cryogenics, **3**, 44, 1963; Monatsber. Deut. Akad. Wiss. Berlin, **5**, 329, 1963.
[854] Lockhart, R., Unpublished data taken from "*The Metal Beryllium*" (editors: White, D. W. and Burke, J. E.), The American Society for Metals, Cleveland, Ohio, 310, 1955.
[855] Loewen, E. G., "Thermal Properties of Titanium Alloys and Selected Tool Materials," Trans. Am. Soc. Mech. Engrs., **78**, 667–70, 1956.
[856] Lohrisch, F. W., "Heat-Transfer Coefficient for Industrial Gases," J. Appl. Chem. (London), **2**, 464–9, 1952.
[857] Long, E., and Meyer, L., "Heat Conduction by the Unsaturated Helium II Film," Phys. Rev., **87**, 153, 1952.
[858] Long, J. R., Grenier, C. G., and Reynolds, J. M., "Electron and Lattice Transport Phenomena in an Antimony Crystal at Liquid-He^4 Temperatures," Phys. Rev., **140**(1A), 187–201, 1965.
[859] Lorenz, L., "The Thermal and Electrical Conductivities of Metals," Ann. Physik, **13**(3), 582–606, 1881.
[860] Lucks, C. F., Private communication, 1964.
[861] Lucks, C. F., "Pyrometric Standard Lead as a Thermal Conductivity Reference Material," J. Appl. Phys., **38**(4), 1973–4, 1967.
[862] Lucks, C. F., and Deem, H. W., "Thermal Conductivities, Heat Capacities, and Linear Thermal Expansion of 5 Materials," WADC–TR–55–496, Series 65, 1–65, 1956. [AD 97 185]
[863] Lucks, C. F., and Deem, H. W., "Thermal Conductivities, Heat Capacities and Linear Thermal Expansion of Five Materials. Part II. Density and Thermal Conductivity of Molten Copper," WADC–TR–55–496, II, 1–14, 1957. [AD 118 168]
[864] Lucks, C. F., and Deem, H. W., "Thermal Conductivity of Uranium and UO_2 from Progress Relating to Civilian Applications During June 1958," USAEC Rept. BMI–1273, 7–9, 1958.
[865] Lucks, C. F., and Gibbs, R. L., "Correlations of Thermal and Electrical Conductivities of Two Pyrometric Standard Lead Samples," J. Appl. Phys., **41**(8), 3550–1, 1970.
[866] Lucks, C. F., Thompson, H. B., Smith, A. R., Curry, F. P., Deem, H. W., and Bing, G. F., "The Experimental Measurement of Thermal Conductivities, Specific Heats, and Densities of Metallic, Transparent, and Protective Materials. Part I," USAF–TR–6145, Pt. I, 1–127, 1951.
[867] Ludwig, H. C., "Plasma-Energy Transfer in Gas-Shielded Welding Arcs," Welding J. (N. Y.), **38**, 296S–300S, 1959.
[868] Lundin, C. E., and Klodt, D. T., "Fundamental Alloy Development. Quarterly Progress Rept., Aug. 1, 1959–Oct. 31, 1959," Denver Univ. Research Inst., Denver, Colorado, USAEC, TID–6728, 1–33, 1959.
[869] Lussana, S., "The Influence of Pressure on the Thermal and Electrical Conductivity of Metals and the Law of Wiedemann-Franz," Nuovo Cimento, **15**, 130–70, 1918.
[870] Luyckx, A., Issi, J. P., Streydio, J. M., Michenaud, J. P., and Coopmans, P., "Quenching and Post-Irradiation Studies on CdS Single Crystals. Transport Properties of Bi Rolled Thin Foils," RADC–TR–65–156, 1–56, 1965. [AD 614 485]
[871] L'vov, S. M., Mal'ko, P. I., Nevskaya, L., and Nemchenko, V. F., "Some Thermal and Electrical Properties of Porous Tungsten and Tungsten-Molybdenum Cathode Materials," Akad. Nauk Ukr. SSR, **6**(5), 89–95, 1966.
[872] Macchia, P., "Further Research on Thermal Conductivity at Low Temperature," Atti Accad. Nazl Lincei Rend. Classe Sci Fis. Mat E Nat, **16**, 507–17, 1907.
[873] MacDonald, D. K. C., White, G. K., and Woods, S. B., "Thermal and Electrical Conductivities of the Alkali Metals at Low Temperatures," Proc. Roy. Soc. (London), **A235**, 358–74, 1956.
[874] Maire, J., Gremian, R., Mereau, M., Rappeneau, J., Yvars, M., and Fillatre, A., "Preparation and Properties of a Pyrolytic Carbon Compressed at High Temperature," Carbon (Oxford), **5**, 575–82, 1967.
[875] Makinson, R. E. B., "The Thermal Conductivity of Metals," Proc. Camb. Phil. Soc., **34**(3), 474–97, 1938.
[876] Mallon, C. E., and Cutler, M., "Thermal Conductivity of Electrically Conducting Liquids," Rev. Sci. Instr., **36**(7), 1036–40, 1965.
[877] Malm, H. L., and Woods, S. B., "The Low Temperature Thermal Conductivity Electrical Resistivity and Thermoelectric Power of Dilute Silver Alloys with Manganese," Can. J. Phys., **44**(10) 2293–302, 1966.
[878] Mamiya, T., Fukuroi, S., and Tanuma, S., "Thermal Conductivity of Superconducting and Normal Lanthanum," J. Phys. Soc. Japan, **20**(9), 1559–67, 1965.
[879] Manchon, D. D., Jr., "Thermal Conductivity of Bismuth

at Liquid Helium Temperatures," Ph.D. Thesis, Univ: Microfilms Publ. 68–6538, 86 pp., 1967.

[880] Mannchen, W., "Heat Conductivity, Electrical Conductivity and the Lorenz Number for a Few Light Metal Alloys," Z. Metallk., **23**, 193–6, 1931.

[881] Manson, S. V., "Theoretical Equations for Estimating Thermal Conductivity of Liquids," USAEC Rept. Y-F8-6, 1–7, 1950.

[882] March, R. H., and Symko, O. G., "Superconducting Thermal Switches below 1 K," Bull. Inst. Intern, Froid Annexe, No. 2, 57–62, 1965.

[883] Mardon, P. G., Nichols, J. L., Pearce, J. H., and Poole, D. M., "Some Properties of Scandium Metal," Nature (London), **189**, 556–8, 1961.

[884] Mardykin, I. P., and Filippov, L. P., "Thermal Properties of Liquid Metals. I. Copper, Antimony," Fiz. Khim. Obrab. Mater., **1**, 110–2, 1968.

[885] Marsh, L. L., Jr., and Keeler, J. R., "The Technology of Thorium," USAEC Rept. BMI-76, 1–46, 1951.

[886] Martin Co., "Strontium 90 Power Project Quarterly Progr. Rept. No. 3," USAEC MND-SR-1674, 1037(283), 1–72, 1959.

[887] Martin, J. J., "Measurements of Thermal Conductivity of Silicon from 680 to 1000 K," M. S. Thesis South Dakota School of Mines and Technology, Rapid City, South Dakota, ASTIA AD 284751, 1–39, 1962.

[888] Martin, J. J., and Morris, R. G., "Thermal Conductivity Measurements on Silicon to 1000 K," From Proc. Black Hills Summer Conf. on Transport Phenomena, 21–23 Aug. 1962, South Dakota School of Mines and Technology, Rapid City, South Dakota, ASTIA and OTS, AD 289290, 24–32, 1962.

[889] Martin, J. J., and Sidles, P. H., "Thermal Diffusivity of Platinum from 300 to 1300 K," in *Proceedings of the Fourth Conference on Thermal Conductivity*, (San Francisco, Oct. 1964), Iowa State Univ., Ames Inst. for Atomic Research, and Dept. of Physics, USAEC IS-1018, 1–8, 1964.

[890] Martin, J. J., Sidles, P. H., and Danielson, G. C., "Thermal Diffusivity of Platinum," Iowa State Univ. of Science and Technology, Ames, CONF-651020-2, IS-1261, 1–11, 1965.

[891] Martin, J. J., Sidles, P. H., and Danielson, G. C., "Thermal Diffusivity of Platinum from 300° to 1200° K," J. Appl. Phys., **38**(8), 3075–8, 1967.

[892] Martinet, J., "Determination of the Thermal Conductivity and of the Factor of Total Emission of Solid Conductors at High Temperature," Journées. Intern. Transmission Chaleur Paris, 841–51, 1961.

[893] Mason, E. A., and Saxena, S. C., "An Approximate Formula for the Thermal Conductivity of Gas Mixtures," Inst. Mol. Phys., Univ. Maryland, USAEC Rept. IMP-AEC-6, 1–35, 1958.

[894] Mason, I. B., and Knibbs, R. H., "Influence of Crystallite Size on the Thermal Conductivity of Irradiated Polycrystalline Graphite," Nature (London), **198**, 850–1, 1963.

[895] Mason, I. B., and Knibbs, R. H., "The Thermal Conductivity of Artificial Graphites and Its Relationship to Electrical Resistivity," UKAEA Rept. AERE-R 3973, 1–22, 1962.

[896] Masumoto, H., "On the Thermal and Electric Conductivities of Some Aluminum Alloys," Sci. Rept. Tôhoku Impl. Univ., **13**, 229–41, 1925.

[897] Masumoto, H., "On the Magnetic, Electric and Thermal Properties of Nickel-Cobalt Alloys," Sci. Repts. Tôhoku Impl. Univ., **16**, 321–32, 1927.

[898] Masumoto, H., "On the Electrical and Thermal Conductivities of Carbon Steel and Cast Iron," Sci. Repts. Tôhoku Impl. Univ., **16**, 417–35, 1927.

[899] Masuyama, T., "Radiation Damage of Low Permeability Graphite and Hard Carbon," J. Atomic Energy Soc. (Japan), **8**(4), 185–94, 1966.

[900] Masuyama, T., "Radiation Damage of Low Permeability Graphite and Hard Carbon," NASA NSF-TR-102, 1–25, 1968.

[901] Mathur, M. P., "Thermal and Electrical Conductivity of Compensated and Non-compensated Germanium at Low Temperatures," Univ. Microfilms (Ann Arbor) Order No. 66–7452, 222 pp., 1966.

[902] Matolich, J., Jr., and Deem, H. W., (Lemmon, A. W., Jr., Compiler), "Engineering Properties of Potassium," Quarterly Report No. 8, July 1–Sept. 30, 1962, Battelle Memorial Inst., Columbus, Ohio X63-16080, NP-12305, NASA-CR-51699, N63-16080, 1–18, 1962.

[903] Matuyama, Y., "On the Electrical Resistance of Molten Metals and Alloys," Sci. Repts., Tôhoku Imp. Univ., **16**(4), 447–74, 1927.

[904a] Maxwell, C. R., "Physical Properties of Polonium. I. Melting Point, Electrical Resistance, Density, and Allotropy," J. Chem. Phys., **17**(12), 1288–92, 1949.

[904] Maurer, E., "Heat Conductivity of Chrome Steels at High Temperatures," Arch. Eisenhüttenw., **10**(4), 145–54, 1936.

[905] Maybrey, H. J., "Thermal Conductivities of some Light Alloys," Metal Ind. (London), **33**, 5–6, 1928.

[905a] McAdams, W. H., *Heat Transmission*, McGraw-Hill, N. Y., 1075 pp., 1955.

[906] McCarthy, K. A., and Ballard, S. S., "Thermal Conductivity of Germanium at Ambient Temperatures," Phys. Rev., **99**, 1104, 1955.

[907] McClelland, J. D., Rasor, N. S., Dahleen, P. C., and Zehms, E. H., "Thermal Conductivity of Liquid Copper," WADC TR 56–400. Pt. II, 1–6, 1957. [AD 118243]

[908] McCreight, L. R., "Thermal Conductivity Data for Some Nuclear Fuels," USAEC Rept. TID 10062, 1–19, 1952.

[909] McDonald, W. J., Jr., "The Thermal and Electrical Conductivities of High Purity Iron at Low Temperatures," Univ. of Texas, M. S. Thesis, 61 pp., 1962.

[910] McElroy, D. L., Kollie, T. G., Fulkerson, W., Moore, J. P., and Graves, R. S., Private Communication, 1965.

[911] McHargue, C. J., and Yakel, H. L., Jr., "Phase Transformations in Cerium," Acta. Met., **8**(9), 637–46, 1960.

[912] Meaden, G. T., *Electrical Resistance of Metals*, Plenum Press, N. Y., 218 pp., 1965.

[913] Meaden, G. T., "The Electrical Resistivity and Characteristic Temperature of Technetium," J. Less-Common Metals, **9**(5), 392, 1965.

[914] Meaden, G. T. Private communication, Jan. 23, 1969.

[915] Meaden, G. T., Rao, K. V., and Loo, H. Y., "Lorenz-function Enhancement Due to Inelastic Processes near the Néel Point of Chromium," Phys. Rev. Lett., **23**(9), 475–7, 1969.

[916] Meaden, G. T., and Sze, N. H., "The 16° K Phase Transition in Europium Metal," in *Proceedings of the Eleventh International Conference on Low Temperature Physics* (St. Andrews, Scotland, August 1968), Vol. 2, Univ. of St. Andrews Printing Dept., 1102–5, 1968.

[917] Meddins, H. R., and Parrott, J. E., "An Apparatus for the High-Temperature Measurement of Thermal Diffusivity, Electrical Conductivity, and Seebeck Coefficient," Brit. J. Appl. Phys. (J. Phys. D), **2**(5), 691–7, 1969.

[918] Meechan, C. J., and Eggleston, R. R., "Formation Energies of Vacancies in Copper and Gold," Acta Met., **2**, 680–3, 1954.

[919] Meissner, W., "On the Thermal and Electrical Conductivity of Copper Between 20 and 370 Degrees Absolute," Verh. Deut. Physik Ges., **16**, 262–72, 1914.

[920] Meissner, W., "Thermal and Electrical Conductivity of Several Metals between 20 and 373 K," Ann. Physik, **47**(4), 1001–58, 1915.

[921] Meissner, W., "Thermal and Electrical Conductivity of

Lithium between 20 and 373° K," Z. Physik, **2**, 373–9, 1920.

[922] Meissner, W., and Voight, B., "Measurements with the Aid of Liquid Helium XI: Resistance of Pure Metals at Low Temperatures," Ann. Physik., **7**(5), 892–936, 1930.

[923] Mekhtieva, S. I., Abdinov, D.Sh., and Aliev, G. M., "Thermal Conductivity of Amorphous Selenium in the Softening Region," Vysokomol. Soedin., **8**(10), 1665–8, 1966.

[924] Mekhtieva, S. I., Abdinov, D. Sh., and Aliev, G. M., "Mechanism of the Effect of Admixtures on the Thermal Conductivity, Density, and Microhardness of Selenium," Izv. Akad. Nauk SSSR, Ser. Neorg. Mater., **3**(6), 1110–11, 1967; English Translation: Inorganic Materials, **3**(6), 990–1, 1967.

[925] Mektieva, S. I., Abdinov, D. Sh., and Aliev, G. M., "Kinetics of the Crystallization of Selenium," Zh. Fiz. Khim., **42**(1), 243–4, 1968; English Translation: Russ. J. Phys. Chem., **42**(1), 127–8, 1968.

[926] Mekhtieva, S. I., Abdinov, D. Sh., and Aliev, G. M., "Kinetics of Crystallization of Selenium Studied by Measuring the Thermal and Electrical Conductivities," Izv. Akad. Nauk SSSR, Ser. Neorg. Mater., **4**(3), 312–15, 1968; English translation: Inorg. Materials, **4**(3), 259–62, 1968.

[927] Mellink, J. H., "New Measurements on the Fountain Effect and on the Heat Conductivity of Liquid Helium-II," Physica, **13**, 180–96, 1947.

[928] Mendelssohn, K., "(Studies in) Supraconductivity at the Clarendon Laboratory (Oxford, England)," U. S. Nat. Bur. Stand. Circ., **519**, 33–6, 1952.

[929] Mendelssohn, K., "Thermal Conductivity of Superconductors," Physica, **19**(9), 775–87, 1953.

[930] Mendelssohn, K., "Thermal Conductivity of Superconductors," Physica, **24**, 553–562, 1958.

[931] Mendelssohn, K., and Montgomery, H. C., "Scattering of Phonons and Electrons by Imperfections in a Metals," Phil. Mag., Ser. 8, **1**(8), 718–21, 1956.

[932] Mendelssohn, K., and Olsen, V. L., "Anomalous Heat Flow in Superconductors," Phys. Rev., **80**, 859–62, 1950.

[933] Mendelssohn, K., and Olsen, V. L., "Heat Transport in Superconductors," Proc. Phys. Soc. (London), **A63**, 2–13, 1950.

[934] Mendelssohn, K., and Olsen, J. L., "Heat Flow in Superconductive Alloys," Proc. Phys. Soc. (London), **A63**, 1182–3, 1950.

[935] Mendelssohn, K., and Renton, C. A., "Heat Conductivities of Superconductive Tin, Indium, Thallium, Tantalum, Niobium, and Alunimum Below 1 K," Phil. Mag., **44**, 776–81, 1953.

[936] Mendelssohn, K., and Renton, C. A., "The Heat Conductivity of Superconductors Below 1 Degree K," Proc. Roy. Soc. (London), **A230**, 157–69, 1955.

[937] Mendelssohn, K., and Rosenberg, H. M., "The Thermal Conductivity of Metals at Low Temperatures, I: The Elements of Groups 1, 2, and 3, II: The Transition Elements," Proc. Phys. Soc. (London), **A65**, 385–94, 1952.

[938] Mendelssohn, K., and Rosenberg, H. M., "The Thermal Conductivity of Metals in High Magnetic Fields at Low Temperatures," Proc. Roy. Soc. (London), **A218**, 190–205, 1953.

[939] Mendelssohn, K., Sharma, J. K. N., and Yoshida, I., "Heat Conductivity of Pure Metals Below 1 K," Bull. Inst. Intern. Froid. Annexe, No. 2, 49–56, 1965.

[940] Méndez-Peñalosa, R., "Contribution to the Study of the Thermal Properties of Uranium Carbide and the Nitrides of the Transition Elements at Elevated Temperatures," Univ. of Madrid, Ph.D. Thesis, 196 pp., 1967.

[941] Merisov, B. A., Khotkevich, V. I., Zlobintsev, G. M., and Kozinei, V. V., "Thermal Conductivity of some Metals and Alloys at 4.2–273° K," Inzh.-Fiz. Zh., **12**(5), 675–7, 1967.

[942] Merisov, B. A., and Khotkevich, V. I., "Lattice Component of the Thermal Conductivity of Technically Pure Niobium," Metal. Metalloved., **26**(2), 369–71, 1968; English Translation: Phys. Metals Metallog., **26**(2), 182–4, 1968.

[943] Metallurgia Editor, "Ultra-Pure Nickel Prepared (News Note)," Metallurgia, Ser. 85, **72**(430), 1965.

[944] Mette, H., Gärtner, W. W., and Loscoe, C., "Nernst and Ettingshausen Effects in Germanium between 300 and 750° K," Phys. Rev., **115**, 537–542, 1959.

[945] Mette, H., Gärtner, W. W., and Loscoe, C., "Nernst and Ettingshausen Effects in Silicon Between 300° K and 800° K," Phys. Rev., **117**(6), 1491–3, 1960.

[946] Meyer, L., and Mellink, J. H., "The Thermomechanical Effects on Helium-II," Physica, **13**, 197–215, 1947.

[947] Meyer, R. A., Paper presented in the Carbon Conference 1965; Private communication, 1967.

[948] Meyer, R. A., and Koyama, K. K., "Method of Measuring the Thermal Conductivity of Graphite from 50 to 2200 C," USAEC Rept. GA–4621, 1–12, 1963.

[949] Meyer, R. A., and Schweitzer, D. G., "Post-irradiation Measurements of Thermal Conductivity between 200 and 600° for Low Permeability Graphite," in *Proceedings of the 5th Conference on Carbon*, Univ. Park, Pa., No. 1, 328–34, 1961.

[950] Meyers, C., "Evaluation of VCC Grade TS–814 (AGOT–NP) Graphite Log," USAEC, GAMD–8737, 1–34, 1968.

[951] Meyers, C., and Koyama, K. K., "Evaluation of Candidate Graphites (and carbon) for PSC Core-support Applications," USAEC, GAMD–8371, 1–135, 1968.

[952] Mezhov-Deglin, L. P., "Influence of Dimensions on the Thermal Conductivity of Crystalline He^4 Samples," Zh. Eksp. i. Teor. Fiz., **52**(4), 866–70, 1967; English translation: Sov. Phys.-JETP, **25**(4), 568–71, 1967.

[953] Mezhov-Deglin, L. P., "The Heat Conductivity of Solid Helium 4," Zh i Teor. Fiz., **46**(5), 1926–7, 1964; English Translation: Sov. Phys.-JETP, **19**(5), 1297–8, 1964.

[954] Mezhov-Deglin, L. P., "Measurement of the Thermal Conductivity of Crystalline He^4," Zh. Eksp. i Teor. Fiz., **49**(1), 66–79, 1965; English translation: Sov. Phys.-JETP, **22**(1), 47–56, 1966.

[955] Mezhov-Deglin, L. P., "Influence of Dimensions on the Thermal Conductivity of Crystalline He^4 Samples," Zh. Eksp. i Teor. Fiz., **52**(4), 866–70, 1967; English translation: Sov. Phys.-JETP, **25**(4), 568–71, 1967.

[956] Michels, A., and Botzen, A., "The Thermal Conductivity of Nitrogen at Pressures up to 2500 Atmosphere," Physica, **19**, 585–98, 1953.

[957] Michels, A., Botzen, A., Friedman, A. S., and Sengers, J. V., "The Thermal Conductivity of Argon Between 0° and 75° at Pressures up to 2500 Atmosphere," Physica, **22**, 121–8, 1956.

[958] Michels, W. C., and Cox, M., "The Thermal Conductivity of Tungsten," Physics, **7**(4), 153–5, 1936.

[959] Michels, A., Sengers, J. V., et al., "The Thermal Conductivity of Argon at Elevated Densities," Physica, **29**, 149–60, 1963.

[960] Micinski, E., Unpublished data, National Carbon Company, as quoted in Ref. 307.

[961] Mikol, E. P., "The Thermal Conductivity of Molybdenum over the Temperature Range 1000–2100 F (540–1150 C)," ORNL–1131, 1–7, 1952.

[962] Mikryukov, V. E., "Thermal and Electrical Properties of Copper Alloys," Vestnik Moskov Univ. Ser. Mat. Mekh. Astron. Fiz i Khim, **11**(2), 53–70, 1956.

[963] Mikryukov, V. E., "Temperature Dependence of the Heat Conductivity and Electrical Resistance of Ti, Zr, and Zr Alloys," Vestnik Moskov Univ., Ser. Mat. Mekh. Astron. Fiz. Khim., **12**(5), 73–80, 1957.

[964] Mikryukov, V. E., "Thermal and Electrical Properties of Copper, Silver, Gold, Aluminum, and Copper-Beryllium Alloys," Vestnik Moskov, Univ., Ser. Mat., Mekh., Astron., Fiz. i Khim., **12**(6), 57–67, 1957; English Translation: SLA, TT–65–63678, 1–16, 1965.

[965] Mikryukov, V. E., "Thermal and Electrical Conductivity of Metals and Alloys," Moscow Metallurgizdat, 1–260, 1959.

[966] Mikryukov, V. E., "Thermal and Electrical Properties of Copper, Silver, Gold, Aluminum, and Alloys with a Copper Base," FTS–9848/1+2+4, N64–17072, 707–21, 1963. [AD 418 153]

[967] Mikryukov, V. E., and Chou, S. C., "Heat, Electrical, and Mechanical Properties of the Alloys Copper-Beryllium-Manganese," Vestnik Moskov. Univ., Ser. Mat., Mekh., Astron., Fiz. i Khim, **13**(3), 129–38, 1958.

[968] Mikryukov, V. E., and Karagezyan, A. G., "Thermal and Electrical Properties of Alloys of the Systems Al-Mg and Al-Cu," Inzh.-Fiz. Zh., Akad. Nauk Belorussk. SSR, **4**(12), 90–3, 1961.

[969] Mikryukov, V. E., and Rabotnov, S. N., "Thermal and Electrical Conductivities of Mono- and Polycrystalline Substances from 100 C to the Melting Point," Uch. Zap. Mosk. Ordena Lenina Gosudarst Univ. Mv Lomonosova Fiz., **74**, 167–79, 1944.

[970] Mikryukov, V. E., and Tyapunia, N. A., "Investigation of Temperature Dependence of Thermal Conductivity, Electric Conductivity, and Heat Capacity of Bismuth, Lead, and Bismuth Lead Alloys," Fiz. Metal i Metalloved., **3**, 31–41, 1956.

[971] Mikryukov, V. E., Tyapunina, N. A., and Cherpakov, V. P., "Thermal Conductivity and Electrical Conductivity of Alloys of Bismuth with Cadmium," Vestnik Moskov Univ. Ser. Mat., Mekh, Astron, Fiz., Khim., **11**(1), 127–36, 1956.

[972] Miller, V. S., "Results of the Experimental Investigation of Contact Heat-exchange between Plane Metal Surfaces," Akad. Nauk Ukr. RSR, Inst. Teploenerg. Zb. Prats., No. 20, 44–53, 1960; English translation: MOA–TIL/T. 5407, N64–27040, 9 pp., 1964. [AD 442 269]

[973] Mills, J. J., Morant, R. A., and Wright, D. A., "Thermomagnetic Effects in Pyrolytic Graphite," Brit. J. Appl. Phys., 479–85, 1965.

[974] Mil'vidskii, M. G., and Evemeev, V. V., "On the Estimation of Heat Conductivity Coefficients in Solids and Melts near the Melting Point," Fiz. Tverd. Tela, **6**(7), 1962–66, 1964; English translation: Sov. Phys.-Solid State, **6**(7), 1949–52, 1965.

[975] Minges, M. L., "The Temperature Dependence of the Thermal Contact Resistance across Nonmetallic Interfaces," Ph.D. Thesis, Univ. Microfilm Publ., AFML–TR–69–1, 186 pp., 1968. [AD 697 988]

[976] Mizushina, T., Iuchi, S., Sasano, T., and Tamura, H., "Thermal Contact Resistance Between Mercury and a Metal Surface," Int. J. Heat Mass Transfer, **1**(2/3), 139–146, 1960.

[977] Moak, D. P. (compiler), "Thermal-Energy-Storage Supporting Research," Final Tech. Rept. NASA–CR–80058, N67–12043, 1–300, 1966.

[978] Moeller, C. E., and Wilson, D. R., "Determination of the Thermal Properties of Materials at Elevated Temperatures," MRI–2059–E, 1–95, 1960.

[979] Mogilevskiy, B. M., and Chudnovskiy, A. F., "Measurement of Thermal Conductivity of Semiconductors by the Transient Probe Method," Inzh.-Fiz. Zh. Akad. Nauk Belorussk, SSR, **7**(12), 23–31, 1964; English translation: J. Engineering Physics, **7**(12), 1–15, 1966.

[980] Mokrovskii, N. P., and Regel, A. R., "The Electrical Conductivity of Copper, Nickel, Cobalt, Iron, and Manganese in the Solid and Liquid States," Zh. Tekhn. Fiz., **23**(12), 2121–5, 1953.

[981] Montgomery, H. C., "The Thermal Conductivity of Lead at Low Temperatures," Proc. Roy. Soc. (London), **A244**, 85–100, 1958.

[982] Moore, J. P., Fulkerson, W., and Graves, R. S., "Physical Properties of Tungsten," ORNL–3870, Part 1, 45–8, 1965.

[983] Moore, J. P., Fulkerson, W., and McElroy, D. L., "Comparison of the Thermal Conductivity, Electrical Resistivity, and Seebeck Coefficient of a High-Purity Iron and Armco Iron to 1000° C," ORNL–P–149, CONF–638–1, 1–30, 1964.

[984] Moore, J. P., Fulkerson, W., McElroy, D. L., and Kollie, T. G., Private communication, 1964.

[985] Moore, J. P., Godfrey, T. G., and McElroy, D. L., "Thermal Properties of Grade CGB Graphite," ORNL–P–150 ,Contr. [W–7405–eng–26], Conf. -638–2, 1–10, 1964.

[986] Moore, J. P., Graves, R. S., Fulkerson, W., and McElroy, D. L., "The Physical Properties of Tungsten," Metals and Ceramics Division, Oak Ridge National Laboratory, Private communication, 1965.

[987] Moore, J. P., McElroy, D. L., and Barisoni, M., "Thermal Conductivity Measurements between 78 and 340° K on Al, Iron, Platinum, and Tungsten," in *Proceedings of 6th Conf. on Thermal Conductivity*, Dayton, Ohio, Oct. 1966.

[988] Moore, J. P., McElroy, D. L., and Graves, R. S., "Thermal Conductivity and Electrical Resistivity of High-Purity Copper from 78 to 400° K," Can. J. Phys., **45**(12), 3849–65, 1967.

[989] Moore, J. P., Williams, R. K., and McElroy, D. L., "Physical Properties of Chromium from 77 to 400° K," in *Proceedings of the Seventh Conference on Thermal Conductivity*, Gaithersburg, Maryland, 297–310, 1968.

[990] Moore, J. P., Williams, R. K., and McElroy, D. L., "Further Comments on Transport Properties of Chromium," in *Proceedings of the Eighth Conference on Thermal Conductivity* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N. Y., 303–13, 1969.

[991] Morris, R. G., "High-Temperature Thermal Conductivity Measurements in Semiconductors," South Dakota School of Mines and Technology, Rapid City, South Dakota, DDC,ONR,1–8, 1965. [AD 622 246]

[992] Morris, R. G., and Delinger, W. G., "Series Comparative Measurements of Thermal Conductivity with Thermistors," J. Sci. Instrum., **42**(12), 910–911, 1965.

[993] Morris, R. G., and Hust, J. G., "Thermal Conductivity Measurements of Silicon from 30 to 425 C," Phys. Rev., **124**(5), 1426–30, 1961.

[994] Morris, R. G., and Martin, J. J., "Thermal Conductivity Measurements of Silicon from 680 to 1000 K," J. Appl. Phys., **34**(8), 2388–9, 1963.

[995] Morrison, B. H., "Thermal Diffusion of SX–5 Graphite from 800° to 2800° C," LA–DC–9969, N69–17143, CONF–681009–9, 1–19, 1968.

[996] Morrison, B. H., "Thermal Diffusivity of SX–5 Graphite from 800 to 2800 C," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N. Y., 1031–49, 1969.

[997] Morrison, B. H., "Thermal Diffusivity of ATJ–S Graphite from 100 to 3000 K," in *Proceedings of the Ninth Conference on Thermal Conductivity*, USAEC Rept. CONF–691002, 366–92, 1970.

[998] Moser, J. B., and Kruger, O. L., "Development of Thermal Diffusivity for Ceramic Materials," *From Argonne National Laboratory Annual Progress Report for 1964*, USAEC ANL–7000, 106–10, 1964.

[999] Moser, J. B., and Kruger, O. L., "Heat Pulse Measurements on Uranium Compounds," J. Nucl. Mater., **17**(2), 153–8, 1965.

[1000] Moss, M., "An Apparatus for Measuring the Thermal

Conductivity of Metals in Vacuum at High Temperatures," Rev. Sci. Instr., **26**, 276–80, 1955.

[1001] Moss, M., "Thermal Conductivity of Plastically Deformed Crystals," Univ. Microfilms Publ. 63-4825, 1-125, 1963.

[1002] Mott, N. F., "Electrons in Disordered Structures," Advances in Phys., **16**(61), 49–144, 1967.

[1003] Mottershead, D., and James, A., "Effects of Fast-Neutron Irradiation on the Thermal Conductivity of a Reactor Graphite," in *Second Conference on Carbon and Graphite* (London, 1965), 553–8, 1966.

[1004] Moyer, D. F., "Thermal Conductivity of Silicon from 20 K to 40 K," M. S. Thesis, Miami Univ., 56 pp., 1962.

[1005] Mrozowski, S., Andrew, J. F., Juul, N., Okada, J., Strauss, H. E., and Wobschall, D. C., "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies," Buffalo Univ., N. Y., Carbon Research Lab., WADD ASTIA WADC TR 58-360, Part 2, 1–84, 1960. [AD 236 663]

[1006] Mrozowski, S., Andrew, J. F., Juul, N., Sato, S., Strauss, H. E., and Tsuzuku, T., "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies," State of New York at Buffalo, USAF, WADC-TR-58-360, Part 5, 1–68, 1963.

[1007] Mrozowski, S., Andrew, J. F., Juul, N., Strauss, H. E., Tsuzuku, T., and Wobschall, D. C., "Investigation of Elastic and Thermal Properties of Carbon-Base-Bodies," Buffalo Univ., Carbon Research Lab., WADC TR 58-360 (Pt. 4) ASTIA OTS USAF, Part 4, 1–45, 1962. [AD 282 006]

[1008] Mrozowski, S., Andrew, J. F., Juul, N., Strauss, H. E., and Wobschall, D. C., "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies," Univ. of Buffalo Carbon Research Lab., Buffalo, N. Y., USAF, WADC TR 58-360 (Pt. 3), 1–54, 1961. [AD 258 531]

[1009] Mrozowski, S., Andrew, J. F., Repetski, J., Strauss, H. E., and Wobschall, D. C., "Investigation of Elastic and Thermal Properties of Carbon-Base Bodies," Univ. Buffalo, N. Y., USAF, WADC-TR-58-369, Part 1, 1–59, 1958. [AD 206 664]

[1010] Muto, Y., Noto, K., and Mamiya, T., "The Thermal Conductivity in a Pure Type-II Superconductor near Liquid Helium Temperatures," J. Phys. Soc. Japan, **23**(1), 130–1, 1967.

[1011] Nakamura, T., "Thermal and Electrical Conductivities of Sintered Powders of Iron, Silicon, and PbTe," Nippon Kagaku Zasshi, **86**(5), 491–7, 1965.

[1012] Natarajan, N. S., and Chari, M. S. R., "Thermal Conductivity of Rhodium at Helium Temperatures and in Magnetic Fields," in *Proceedings of the Ninth Conference on Thermal Conductivity*, USAEC Rept. CONF-69 1002, 208–16, 1970.

[1013] National Carbon Co., "Summary Report Phase I. Graphite-Matrix Nuclear Fuel Elements. Vol. I," National Carbon Co., Cleveland, Ohio, USAEC ORO-240 (Vol. 1), 1–128, 1959.

[1014] National Defense Research Committee, "Appendix A. Data on Air and Its Components. Improved Equipment for Oxygen Production, Vol. I, Oxygen Research, Summary Technical Report," OSRD PR 32.413 STR DIV II V I, 343–94, 1946.

[1015] National Physical Laboratory, "The Thermal Conductivity of Iron," in *National Physical Laboratory Report for 1964, Basic Physics Division*, 128–30, 1965.

[1016] National Research Council and the National Academy of Science, *International Critical Tables of Numerical Data, Physics, Chemistry, and Technology*, McGraw-Hill Book Co., N. Y., Vol. I-VII, 1926–30, 1936.

[1017] Neel, D. S., and Pears, C. D., "Measurement of High-Temperature Behavior up to 5000° F," Prog. Intern. Res. Thermodyn. Transport Properties, 2nd Symp. Thermophys. Prop., 500–11, 1962.

[1018] Neel, D. S., Pears. C. D., and Oglesby, S., Jr., "The Thermal Properties of Thirteen Solid Materials to 5000 F or their Destruction Temperatures," Final Tech. Documentary Rept. Covering Period 15 Mar. 1959 to 14 Nov. 1960, Southern Res. Inst., Birmingham, Ala., USAF WADD-TR-60-924, N62-12987, 1-216, 1962. [AD 275 536]

[1019] Neimark, B. E., and Bykova, T. I., "Thermal Conductivity of Nickel Pipes with Thin Walls," Inzh.-Fiz. Zh., **8**(3), 1965; English translation: J. Engineering Physics SSR, **8**(3), 250–2, 1965.

[1020] Neimark, B. E., and Voronin, L. K., "Thermal Conductivity, Electric Resistivity, and Total Hemispherical Emissivity of Refractory Metals at High Temperatures," Teplofiz. Vys. Temp., **6**(6), 1044–56, 1968; English Translation: High Temp. **6**(6), 999–1010, 1968.

[1021] Nellis, W. J., and Legvold, S., "Thermal Conductivities and Lorenz Function of Gadolinium, Terbium, and Holmium Single Crystals," Phys. Rev., **180**(2), 581–90, 1969.

[1022] Nettleton, H. R., "III. On the Thermal Conductivity of Mercury by the Impressed Velocity Method," Proc. Phys. Soc. (London), **26**, 28–42, 1913.

[1023] Nettleton, H. R., "The Vacuum Guard Ring and Its Application to the Determination of the Thermal Conductivity of Mercury," Proc. Phys. Soc. (London), **27**, 129–48, 1915.

[1024] Neubert, T. J., Argonne National Laboratory, Private communication, as quoted in Ref. 307.

[1025] Neubert, T. J., Royal, J., and Van Dyken, A. R., "The Structure and Properties of Artificial and Natural Graphite," USAEC Rept. ANL-5524, 1–44, 1956.

[1025a] Neumann, F., "Experiments on the Thermal Conductivity of Solids," Ann. Chim. Phys., 3, **66**, 183–7, 1862; English translation: Phil. Mag., **25**, 63–5, 1863.

[1026] Newman, B. O., "Physical Properties of Heat Transfer Fluids," General Electric Rept. GI-401, 1–29, 1947. [AD 64 951]

[1027] Nguyen, V. D., "The Effect of Fast Neutrons on the Thermoelectric Properties of Semiconductors," Onde Electric, **43**, 1260–6, 1963.

[1028] Nguyen, V. D., "Effect of Fast Neutrons on Thermal Conductivity of Germanium Measured at Low Temperatures," Compt. Rend., **259**(6), 1091–4, 1964.

[1029] Nguyen, V. D., "Effect of Fast Neutrons on the Thermal Conductivity and Thermoelectric Power of Germanium. Measurements at Low Temperatures," J. Phys. (France), **27**(3/4), 128–32, 1966.

[1030] Nguyen, V. D., Pham, N. T., and Vandevyver, M., "The Effect of Fast Neutrons on the Thermal Conductivity of Germanium," Compt. Rend., **256**(8), 1722–5, 1963.

[1031] Nguyen, V. D., Vandevyver, M., and Pham, N. T., "Effect of Fast Neutrons on the Thermal Conductivity of Germanium and Silicon," J. Phys. (France), **24**(7), 464–6, 1963.

[1032] Nichols, J. L., "Orientation and Temperature Effects on the Electrical Resistivity of High-Purity Magnesium," J. Appl. Phys., **26**(4), 471–2, 1955.

[1033] Nicol, J., "Thermal Conduction in Metals Below 1 K," Univ. Microfilms Publ., **25460**, 1–165, 1952.

[1034] Nicol, J., and Tseng, T. P., "Thermal Conductivity of Copper between 0.25 K and 4.2 K," Phys. Rev., **92**, 1062–3, 1953.

[1035] Nikol'skii, N. A., "Heat Transfer and Thermal Stimulation," (In Russian), Izd. AN SSSR, 1959.

[1036] Nikol'skii, N. A., Kalakutskaya, N. A., Pchelkin, I. M., Klassen, T. V., and Vel'tishcheva, V. A., "Thermophysical Properties of Some Metals and Alloys in a Molten State," Voprosy Teploobmena, Akad. Nauk SSSR, Energet. Inst. im. G. M. Krzhizhanovoskogo, 11–45, 1959; English translation: USAEC-TR-4511, MCL-714/1 61-27826, OTS SLA DDC, 1–36, 1962. [AD 261 775]

[1037] Nishioka, S., "Thermal Conductivities of Single and Polycrystalline Bismuth," Mem. Coll. Sci. Univ. Kyoto, **A25**, 147–54, 1949.

[1038] Nitti, D. A., "A Method for Determining the Thermal Conductivity of Solids at High Temperatures," Univ. of Cincinnati, M. S. Thesis, 146 pp., 1961.

[1039] Niven, C., and Geddes, A. E. M., "On a Method of Finding the Conductivity for Heat," Proc. Roy. Soc. (London), **A87**, 535–9, 1912.

[1040] Noguchi, T., and Miyazaki, Y., "Measurement of Thermal Conductivity of Carbon Products at Room Temperature," Tanso, **5**, 36–9, 1956.

[1041] Northdurft, W., "The Absolute Measurement of the Heat Conductivities of Gases," Ann. Physik, **28**, 137–56, 1937.

[1042] Noto, K., "Thermal Conductivity in a Pure Type II Superconductor Near the Upper Critical Field," J. Phys. Soc. Japan, **26**(3), 710–6, 1969.

[1043] Novikov, I. I., Gruzdev, V. A., Kraev, O. A., Odintzov, A. A., and Roshchunkin, V. V., "Experimental Investigations of Thermophysical Properties of Liquid Alkali Metals at High Temperatures," Teplofiz. Vys. Temp., **7**(1), 71–4, 1969; English Translation: High Temp., **7**(1), 65–8, 1969.

[1044] Novikov, I. I., Solovyev, A. N., Khabakhpasheva, E. M., Gruzdev, V. A., Pridantsev, A. I., and Vasenina, M. Ya., "Heat Transfer and Thermophysical Properties of Molten Alkali Metals," Sov. J. At. Energy, **4**, 545–60, 1956.

[1045] Null, M. R., and Lozier, W. W., "Measurement of Thermal Diffusivity by the Phase Shift Method," in *Thermal Conductivity—Proceedings of the Eighth Conference,* (Ho, C. Y., and Taylor, R. E.), Plenum Press, N. Y., 837–56, 1969.

[1046] Nuttall, R. L., and Ginnings, D. C., "Thermal Conductivity of Nitrogen from 50° to 500° and 1 to 100 atm," J. Research NBS, **58**, 271–8, 1957.

[1047] Oak Ridge National Laboratory, "Gas-Cooled Reactor Project," Quarterly Progress Report for Period Ending June 30, 1960, Oak Ridge National Laboratory Staff, Tenn., USAEC ORNL–2964, 1–255, 1960.

[1048] O'Day, M. D., "A New Application of the Bar Method for the Measurement of Thermal Conductivity," Phys. Rev., **23**, 245–54, 1924.

[1049] O'Hagan, M. E., "Measurements of the Thermal Conductivity and Electrical Resistivity of Platinum from 373–1373° K," The George Washington University, Ph.D. Dissertation, 1–175, 1966.

[1050] O'Hagan, M. E., Heller, R. B., and Flynn, D. R., "Measurements of the Thermal Conductivity and Electrical Resistivity of Pt from 373 to 1373 K," USAFOSR 66–2484, 1–8, 1966. [AD 642 245]

[1051] Ohyama, M., "Thermal Conductivity in Antimony-Arsenic System," J. Phys. Soc. Japan, **23**(3), 522–5, 1967.

[1052] Olsen, J. L., and Renton, C. A., "Heat Conductivity of Superconductive Lead below 1 K," Phil. Mag., **43**, 946–8, 1952.

[1053] Olsen, J. L., and Wyder, P., "A Direct Comparison of the Mean Free Paths for Electrical and Thermal Conduction in Indium at Low Temperatures," in *Proceedings of the Seventh International Conference on Low Temperature Physics* (Toronto, 1960), 266–7, 1961.

[1054] Orthmann, H. J., and Ueberreiter, K., "Thermal Conductivity of Glassy Selenium," Kolloid-Z., **147**, 129–31, 1956.

[1055] Osborn, R. H., "The Thermal Conductivity and Thompson Effect in Tungsten and Molybdenum at Incandescent Temperatures," Univ. of Pittsburg, Ph.D. Thesis, Pittsburg, Penn., 1–20, 1938.

[1056] Osborn, R. H., "Thermal Conductivities of Tungsten and Molybdenum at Incandescent Temperatures," J. Optical Soc. Am., **31**, 428–32, 1941.

[1057] Oskotskii, V. S., Pogarskii, A. M., Timchenko, I. N., and Shalyt, S. S., "Effect of Isotope Content on Lattice Thermal Conductivity and Thermoelectromotive Force of Tellurium," Fiz. Tverd. Tela, **10**(11), 3247–53, 1968; English translation: Sov. Phys.-Solid State, **10**(11), 2569–73, 1969.

[1058] Owens, E. J., and Thodos, G., "Thermal Conductivity Reduced State Correlation for the Inert Gases," AIChE Journal, **3**, 454–61, 1957.

[1059] Paine, R. M., Stonehouse, A. J., and Beaver, W. W., "An Investigation of Intermetallic Compounds for Very High Temperature Applications," WADC TR 59–29 (Pt. 2), 1–119, 1959. [AD 244 758]

[1060] Pak, M. I., and Osipova, V. A., "Quasi-Steady-State Method for a Complex Determination of Thermophysical Properties of Solid Bodies over a Wide Temperature Range," Teploenergetika, **14**(6), 73–6, 1967; English translation: Thermal Eng., **14**(6), 100–6, 1967.

[1061] Pandorf, R. C., Chen, C. Y. C., and Daunt, J. G., "Heat Transport through Carbon Radio Resistors at Low Temperatures and their Use in Conjunction with Superconducting Thermal Valves," Tech. Rept. No. 6, Ohio State Univ. Res. Foundation, 7 pp., 1962. [AD 275 287]

[1062] Pankove, J. I., "Pulsed Measurement of the Variation of Thermal Conductivity of Ge with Temperature," Rev. Sci. Instr., **30**(6), 495–6, 1959.

[1063] Panteleimonov, L. A., and Nesterova, O. P., "Electrical and Thermal Conductivity of Ruthenium," Vestn. Mosk. Univ., Ser. II, Khim., **21**(2), 49–50, 1966.

[1064] Pappis, J., and Blum, S. L., "Properties of Pyrolytic Graphite," J. Am. Ceram. Soc., **44**(12), 592–7, 1961.

[1065] Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L., "Flash Method of Determining Thermal Diffusivity, Heat Capacity, and Thermal Conductivity," J. Appl. Phys., **32**, 1679–84, 1961.

[1066] Pashaev, B. P., "On the Changes in the Thermal Conductivity of Tin, Bismuth and Gallium on Melting," Fiz. Tverd. Tela, **3**(2), 416–9, 1961; English translation: Sov. Phys.-Solid State, **3**(2), 303–5, 1961.

[1067] Pashaev, B. P., "Determination of the Thermal Conductivity of Some Metals and Alloys during Fusion," Teplo. i Massoperenos Pervoe Vses Soveshch Minsk, **1**, 126–30, 1962.

[1068] Pears, C. D., Private communication, October 7, 1965.

[1069] Pears, C. D., and Neel, D. S., "The Thermal Properties of Twenty-Six Solid Materials to 5000 F or their Destruction Temperatures," ASD–TDR–62–765, 1–420, 1962. [AD 298 061]

[1070] Pearson, G. J., Davey, P. O., and Danielson, G. C., "Thermal Conductivity of Nickel and Uranium," Proc. Iowa Acad. Sci., **64**, 461–5, 1957.

[1071] Pearson, G. J., Ulbrich, C. W., Gueths, J. E., Mitchell, M. A., and Reynolds, C. A., "Superconducting- and Normal-State Thermal Conductivity of Impure Tin," Phys. Rev., Ser. 2, **154**(2), 329–37, 1967.

[1072] Peczalski, T., "A Contribution to the Study of Thermal Conductivity of Solids," Ann. Physik, **7**, 185–224, 1917.

[1073] Peletskii, V. E., and Filippov, L. P., "New Experimental Apparatus for an Investigation into the Coefficient of Thermal Conductivity of Electrically Conductive Materials in the Temperature Range 500–3000° K," Teplofiz. Vys. Temp., **6**(6), 1100–7, 1968; English translation: High Temp., **6**(6), 1054–60, 1968.

[1074] Peletskii, V. E., and Sobol, Y. G., "On the Problem of Practical Realization of the Method of Longitudinal Thermal Current in Studies of the Coefficient of Thermal Conductivity of Metals and Alloys at Temperatures above 1000° C," in *Thermal Conductivity—Proceedings* *of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, N.Y., 381–88, 1969.

[1075] Peletskii, V. E., Sobol, Y. G., and Drujinin, V. P., "Experimental Study of Thermal and Electrical Conductivities of Single Crystals of Tungsten at High Temperatures," in *Proceedings of the Ninth Conference on Thermal Conductivity*, (1969), USAEC Rept. CONF-691002, 318–25, 1970.

[1076] Peletzskii, V. E., and Voskresenskii, V. Yu., "Tantalum Thermophysical Properties at Temperatures above 1000 K," Teplofiz. Vys. Temp., **4**(3), 336–42, 1966; English translation: High Temp., **4**(3), 329–33, 1966.

[1077] Pereira, A. N. G., and Raw, C. J. G., "Heat Conductivities of Polyatomic Gases and their Binary Mixtures," Phys. Fluids, **6**, 1091–6, 1963.

[1078] Perlitz, H., "On an Apparent Relation between the Rate in the Change of the Electric Resistance at Fusion and the Crystal Lattice of Metallic Elements," Phil. Mag., Ser. 7, **2**, 1148–52, 1926.

[1079] Perova, V. I., and Knoroz, L. I., "Heat and Electric Conductivity of Certain Heat-Resistant Materials at High Temperatures," Tsentral. Nauch.-Issledovatel. Inst. Teknol. i Mashinostroen, **79**, 159–74, 1957.

[1080] Perron, J. C., "Measurement of Thermal Conductivity in the Unsteady State," Compt. Rend. (France), **252**(19), 2867–9, 1961.

[1081] Peshkov, V. P., and Parshin, A. Ya., "The Efficiency of Superconducting Thermal Switches," in *Proceedings of the 9th International Conference on Low Temperature Physics* (Columbus, Ohio, Aug. 31–Sept. 4, 1964), Plenum Press, N. Y., LC–65–14085, 517–20, 1965.

[1082] Peshkov, V. P., and Parshin, A. Ya., "On Superconducting Thermal Switches," Zh. Eksp. i Teor. Fiz. (USSR), **48**(2), 393–403, 1965; English translation: Sov. Phys.-JETP, **21**(2), 258–65, 1965.

[1083] Petersen, H., "The Properties of Helium: Density, Specific Heats, Viscosity and Thermal Conductivity at Pressures from 1 to 100 bar and from Room Temperature to about 1800 K," Danish Atomic Energy Commission Rept. 224, 1–42, Sept. 1970.

[1084] Petersen, J. R., and Bonilla, C. F., "The Development of a Frequency Response Analysis Technique for Thermal Conductivity Measurements and its Application to Gases at High Temperatures," in *Proceedings of the 3rd Symposium on Thermophysical Properties*, ASME, Purdue Univ., Lafayette, Indiana, 264–76, 1965.

[1085] Petrov, A. V., Germaidze, M. S., Golikova, O. A., Kiskachi, A. Yu., and Matreev, V. N., "The Relationship between the Thermal Conductivity and Crystal Structure of Beta-Rhombohedral Boron," Fiz. Tverd. Tela, **11**(4), 907–10, 1969; English translation: Sov. Phys.-Solid State, **11**(4), 741–4, 1969.

[1086] Pigal'skaya, L. A., Filippov, L. P., and Borisov, V. D., "Thermal Conductivity of Tungsten at High Temperatures," Teplofiz. Vys. Temp., Akad. Nauk SSSR, **4**(2), 293–5, 1966; English translation: High Temp., **4**(2), 290–2, 1966.

[1087] Pigal'skaya, L. A., Yurchak, R. P., Makarenko, I. N., and Filippov, L. P., "Thermal Properties of Molybdenum at High Temperatures," Teplofiz. Vys. Temp., **4**(1), 144–7, 1966; English translation: High Temp., **4**(1), 135–7, 1966.

[1088] Pike, J. N., "Measurements of Thermal Conductivity and Electrical Resistivity of a Highly Anisotropic ZT-Type Graphite at High Temperatures," Union Carbide Corp., Parma Research Lab, Ohio, ARPA DDC C–16, NP–12796, 1–36, 1963. [AD 404 453]

[1089] Pike, J. N., "Some Physical Measurements on Hot-Pressed Hafnium Carbide," Union Carbide Res. Inst., 1–14, 1965. [AD 468 829]

[1090] Pindroh, A. L., "Transport Properties of Argon in Ionization Equilibrium," Boeing Aircraft Co. Rept. D2–11253, 1–63, 1961. [AD 434 829]

[1091] Platunov, E. S., and Federov, V. B., "Use of Photographic Pyrometry in Thermal Studies," Teplofiz. Vys. Temp., **2**(4), 628–33, 1964; English translation: High Temp., **2**, 568–72, 1964.

[1092] Plott, R. F., and Raeth, C. H., "Determination of the Thermal Conductivity and Density of Uranium and Some of its Components," Chicago University Metallurgical Lab, USAEC OTS CP–228, 1–7, 1942.

[1093] Plott, R. F., and Raeth, C. H., "Thermal Conductivity of Eight Specimens of X-Metal and X-metal Alloys," Chicago Univ. Metallurgical Lab., N–1936. MUC–RJM–2, 1–4, 1945.

[1094] Plumb, H. H., "The Thermal Conductivity of Gallium at Low Temperatures," Univ. Microfilms Publ. 9268, 1–71, 1954.

[1095] Pochettino, A., and Fulcheris, G., "On the Electrical and Thermal Properties of Iodine," Atti. Accad. Sci. Torino. Pt. I. Classe Sci. Fis. Mat. E Nat., **58**(14a), 311–20, 1923.

[1096] Poltz, H., "Thermal Conductivity of Pure Platinum and Gold Between 0 and 500 C," PTB Mitteilungen, **80**(4), 259–61, 1970.

[1097] Pott, F. P., "A Method for the Determination of the Thermal Conductivity of Small Probes at High Temperatures," Z. Naturforsch, **A13**(2), 116–25, 1958.

[1098] Reference withdrawn.

[1099] Powell, R. F., "Lorenz Number of Plutonium Metal," Nature (London), **207**, 965, 1965.

[1100] Powell, R. L., Hall, W. J., and Roder, H. M., "Low-Temperature Transport Properties of Commercial Metals and Alloys. II. Aluminums," J. Appl. Phys., **31**(3), 496–503, 1960.

[1101] Powell, R. L., Harden, J. L., and Gibson, E. F., "Low Temperature Transport Properties of Commercial Metals and Alloys. IV. Reactor-Grade Be, Mo, and W," J. Appl. Phys., **31**, 1221–4, 1960.

[1102] Powell, R. L., Roder, H. M., and Hall, W. J., "Low-Temperature Transport Properties of Copper and Its Dilute Alloys: Pure Copper, Annealed and Cold-Drawn," Phys. Rev., **115**(2), 314–23, 1959.

[1103] Powell, R. L., Roder, H. M., and Rogers, W. M., "Low-Temperature Thermal Conductivity of Some Commercial Coppers," J. Appl. Phys., **28**, 1282–8, 1957.

[1104] Powell, R. L., Rogers, W. M., and Coffin, D. O., "An Apparatus for Measurement of Thermal Conductivity of Solids at Low Temperatures," J. Res. Natl. Bur. Stand., **59**(5), 349–55, 1957.

[1105] Powell, R. L., Rogers, W. M., and Roder, H. M., "Thermal Conductivity of Copper and Cu Alloys," in *Proc. 2nd Cryogenic Conf.* (Boulder, Colorado, 1956), 166–71, 1957.

[1106] Powell, R. W., "The Thermal and Electrical Conductivities of Metals and Alloys. Part I, Iron from 0 to 800 C," Proc. Phys. Soc. (London), **46**, 659–79, 1934.

[1107] Powell, R. W., "The Thermal and Electrical Conductivities of a Sample of Acheson Graphite from 0 to 800 C," Proc. Phys. Soc. (London), **49**(4), 419–25, 1937.

[1108] Powell, R. W., "The Thermal and Electrical Conductivities of Metals and Alloys," Univ. of London, Ph. D. Thesis, 1–79, 1938.

[1109] Powell, R. W., "Further Measurements of the Thermal and Electrical Conductivity of Iron at High Temperatures," Proc. Phys. Soc. (London), **51**, 407–18, 1939.

[1110] Powell, R. W., "The Thermal and Electrical Conductivities of Some Magnesium Alloys," Phil. Mag., 7, **27**, 677–86, 1939.

[1111] Powell, R. W., "Note on Existing Data for the Thermal Conductivities of Certain Metals, "Gt. Brit. National Physical Lab., DSIR Rept. BR–669, 1–13, 1945.

[1112] Powell, R. W., "Some Anisotropic Properties of Gallium, "Nature (London), **164**, 153, 1949.

[1113] Powell, R. W., "The Electrical Resistivity of Gallium and Some Other Anisotropic Properties of This Metal," Proc. Roy. Soc. (London), **A209**, 524–41, 1951.

[1114] Powell, R. W., "The Thermal and Electrical Conductivities of Beryllium," Phil. Mag., **44**, 645–63, 1953.

[1115] Powell, R. W., "The Electrical Resistivity of Liquid Iron," Phil. Mag., 7, **44**, 772–5, 1953.

[1116] Powell, R. W., "Discussion on the Metallurgy of Niobium," J. Inst. Metals, **85**, 553–4, 1957.

[1117] Powell, R. W., "The Thermal Conductivities of Carbons and Graphites at High Temperatures," in *Proceeding Conf. Ind. Carbon and Graphite* (London, 1957), 46–51, 1958.

[1118] Powell, R. W., "Armco Iron as a Thermal Conductivity Standard. Review of Published Data," Progress in Inter. Res. on Thermodynamic and Transport Properties, in *Proceedings of the 2nd Symposium on Thermodynamic Properties*, ASME, 454–65, 1962.

[1119] Powell, R. W., "Some Preliminary Measurements of the Thermal Conductivity and Electrical Resistivity of Cobalt," Cobalt, **24**, 145–50, 1964.

[1120] Powell, R. W., "Correlation of Metallic Thermal and Electrical Conductivities for Both Solid and Liquid Phases," Intern. J. Heat Mass Transfer, **8**(7), 1033–45, 1965.

[1121] Powell, R. W., "Room Temperature Thermal Conductivity of the Rare Earth Metals Gadolinium, Terbium, and Dysprosium," J. Appl. Phys., **37**, 2518–9, 1966.

[1122] Powell, R. W., "The Thermal and Electrical Conductivities of Molten Metals," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Plenum Press, New York, 357–65, 1969.

[1123] Powell, R. W., Groot, H., and Taylor, R. E., "The Electrical Resistivity and Thermal Conductivity of Ruthenium," *Proceedings of the Ninth Conference on Thermal Conductivity*, USAEC Rept. CONF–691002, 352–62, 1970.

[1124] Powell, R. W., Hickman, M. J., and Tye, R. P., "The Thermal and Electrical Conductivity of Magnesium and Some Magnesium Alloys," Metallurgia, **70**(420), 159–163, 1964.

[1125] Powell, R. W., Hickman, M. J., Tye, R. P., and Woodman, M. J., "Armco Iron as a Thermal Conductivity Standard: New Determinations at the National Physical Laboratory," in *Progress in International Research on Thermodynamic and Transport Properties*, 2nd Symposium on Thermophysical Properties, ASME, 466–73, 1962.

[1126] Powell, R. W., Ho, C. Y., and Liley, P. E., "Thermal Conductivity of Selected Materials," National Standard Reference Data Series—Natl. Bur. Stand., NSRDS–NBS 8, 1–168, 1966.

[1127] Powell, R. W., and Jolliffe, B. W., "The Thermal Conductivities of Scandium and Some Rare Earth Metals," Phys. Letters (Netherlands), **14**(3), 171–2, 1965.

[1128] Powell, R. W., and Schofield, F. H., "The Thermal and Electrical Conductivities of Carbon and Graphite to High Temperatures," Proc. Phys. Soc. (London), **51**(1), 153–72, 1939.

[1129] Powell, R. W., and Tye, R. P., "Thermal Conductivity Measurements Down to Minus 190 Degrees. Iridium and Rhodium," Congr. Intern. Froid 9E Paris 1955 Compt. Rend. Trav. Comm., **1**, 2083–7, 1955.

[1130] Powell, R. W., and Tye, R. P., "The Influence of Heat-Treatment on the Electrical Resistivity and the Thermal Conductivity of Electrodeposited Chromium," J. Inst. Metals, **85**, 185–95, 1957.

[1131] Powell, R. W., and Tye, R. P., "Experimental Determinations of the Thermal and Electric Conductivities of Molten Metals," in Proc. Conf. Thermodynamic and Transport Properties of Fluids, Inst. Mech. Engrs., (London, 1957), 182–7, 1958.

[1132] Powell, R. W., and Tye, R. P., "Thermal and Electrical Conductivities of Molten Metals," Brit. Chem. Eng., **2**, 596, 1957.

[1133] Powell, R. W., and Tye, R. P., "The Thermal and Electrical Conductivity of Liquid Mercury," in *International Development in Heat Transfer*, Part IV, ASME Symposium, 856–62, 1961.

[1134] Powell, R. W., and Tye, R. P., "The Thermal and Electrical Conductivities of Zirconium and of Some Zr Alloys," J. Less-Common Metals, **3**, 202–15, 1961.

[1135] Powell, R. W., and Tye, R. P., "The Thermal and Electrical Conductivity of Titanium and Its Alloys," J. Less-Common Metals, **3**, 226–33, 1961.

[1136] Powell, R. W., and Tye, R. P., "The Promise of Platinum as a High-Temperature Thermal Conductivity Reference Material," Brit. J. Appl. Phys., **14**(10), 662–6, 1963.

[1137] Powell, R. W., and Tye, R. P., "New Measurements on Thermal Conductivity Reference Materials," Intern. J. Heat Mass Transfer, **10**(5), 581–96, 1967; Correction: Laubitz, M. J., 11/5/933–4, 1968; Reply: Powell, R. W., Tye, R. P., 11/5/934–5, 1968.

[1138] Powell, R. W., Tye, R. P., and Hickman, M. J., "The Thermal Conductivity of Nickel," Intern. J. Heat Mass Transfer, **8**(5), 679–87, 1965.

[1139] Powell, R. W., Tye, R. P., and Jolliffe, B., "Heat Transfer at the Interface of Dissimilar Materials: Evidence of Thermal-Comparator Experiments," Intern. J. Heat Mass Transfer, **5**, 897–902, 1962.

[1140] Powell, R. W., Tye, R. P., and Metcalf, S. C., "The Thermal Conductivity of Pure and Alloyed Aluminum: II. Molten Aluminum and Aluminum Alloys," in *Advances in Thermophysical Properties at Extreme Temperatures and Pressures,* 3rd Symposium on Thermophysical Properties, ASME, 289–95, 1965.

[1141] Powell, R. W., Tye, R. P., and Woodman, M. J., "Thermal Conductivities and Electrical Resistivities of the Platinum Metals," Platinum Metals Rev., **6**(4), 138–43, 1962.

[1142] Powell, R. W., Tye, R. P., and Woodman, M. J., "The Thermal Conductivity and Electrical Resistivity of Rhenium," J. Less-Common Metals, **5**, 49–56, 1963.

[1143] Powell, R. W., Tye, R. P., and Woodman, M. J., "The Thermal Conductivity of Pure and Alloyed Aluminum: I. Solid Aluminum as a Reference Material," in *Advances in Thermophysical Properties at Extreme Temperatures and Pressures,* 3rd Symposium on Thermophysical Properties, ASME, 277–88, 1965.

[1144] Powell, R. W., Tye, R. P., and Woodman, M. J., "The Thermal Conductivity and Electrical Resistivity of Platinum," Platinum Met. Rev., **10**(4), 132, 1966.

[1145] Powell, R. W., Tye, R. P., and Woodman, M. J., "The Thermal Conductivity and Electrical Resistivity of Polycrystalline Metals of the Platinum Group and of Single Crystals of Ruthenium," J. Less-Common Metals, **12**(1), 1–10, 1967.

[1146] Powell, R. W., Woodman, M. J., and Tye, R. P., "The Thermal Conductivity and Electrical Resistivity of Indium," Phil. Mag., **7**, 1183–6, 1962.

[1147] Powell, R. W., Woodman, M. J., and Tye, R. P., "Further Measurements Relating to the Anisotropic Thermal Conductivity of Gallium," Brit. J. Appl. Phys., **14**(7), 432–5, 1963.

[1148] Powers, R. W., and Hansen, R. H., (Johnston, H. R., Editor), "Liquid Hydrogen Propellant for Aircraft and Rockets. 25th Bimonthly Progr. Rept.," Res. Foundation, OSU, USAF, ATI–58926, No. 25, 1–3, 1949.

[1149] Powers, R. W., Johnston, H. L., and Mattox, R. W., "The Thermal Conductivity of Liquid Nitrogen Between 65 and 90 K," in *Proc. Eighth Int. Congr. Refrig.* (London), 186–94, 1951.

[1150] Powers, R. W., Mattox, R. W., and Johnston, H. L., "Thermal Conductivities of Condensed Gases. I. The Thermal Conductivity of Liquid N between 65 and 90 K," J. Am. Chem. Soc., **76**, 5968–71, 1954.

[1151] Powers, R. W., Mattox, R. W., and Johnston, H. L., "Thermal Conductivities of Condensed Gases. II. The Thermal Conductivities of Liquid Normal and Liquid Para Hydrogen from 15 to 27 K," J. Am. Chem. Soc., **76**, 5972–3, 1954.

[1152] Powers, R. W., Mattox, R. W., and Johnston, H. L., "Thermal Conductivities of Condensed Gases. III. The Thermal Conductivity of Liquid Deuterium from 19 to 25 K," J. Am. Chem. Soc., **76**, 5974, 1954.

[1153] Powers, R. W., and Schwartz, D., "Liquid Hydrogen-Propellant for Aircraft and Rockets," Res. Foundation, Ohio State University, USAF Rept. ATI-52496, 1–61, 1949.

[1154] Powers, R. W., Schwartz, D., and Johnston, H. L., "The Thermal Conductivity of Metals and Alloys at Low Temperatures. I. Apparatus for Measurements between 25 and 300 K. Data on Pure Aluminum, OFHC Copper and L Nickel," Ohio State Univ. Columbus Cryogenic Lab., USAF TR-264-5, 1–19, 1950.

[1155] Powers, R. W., Ziegler, J. B., and Johnston, H. L., "The Thermal Conductivity of Metals and Alloys at Low Temperatures. II. Data On Iron and Several Steels between 25 and 300 K. Influence of Alloying Constituents," Ohio State Univ. Columbus Cryogenic Lab., USAF TR-264-6, 1–14, 1951.

[1156] Powers, R. W., Ziegler, J. B., and Johnston, H. L., "The Thermal Conductivity of Metals and Alloys at Low Temperature. III. Data for Aluminum Alloys between 25 and 300 K," Ohio State Univ. Columbus Cryogenic Lab., USAF TR-264-7, ATI 105-924, 1–13, 1951.

[1157] Pozdnyak, N. Z., and Akhmetzyanov, K. G., "Heat Conductivity and Electrical Conductivity of Tantalum and Niobium," Teplofiz. Vys. Temp., **1**(2), 316–8, 1963; English translation: High Temp., **1**(2), 280–2, 1963.

[1158] Probert, S. D., "Heat and Mass Transfers in Solid Helium," Int. J. Heat Mass Transfer, **12**(7), 825–8, 1969.

[1159] Prosad, S., "Thermal Conductivity of Liquid Nitrogen," Current Sci. (India), **20**, 264, 1951.

[1160] Prosad, S., "Thermal Conductivity of Liquid Oxygen," Brit. J. Appl. Phys., **3**, 58–9, 1952.

[1161] Pustovalov, V. V., "High-Temperature Measurements (up to 2400 Degrees) in Vacuum of the Thermal Conductivities of Refractory Materials," Ukr. Nauchn.-Issled. Inst. Ogneuporov., No. 5, 324–35, 1961.

[1162] Quick, R. W., and Lanphear, B. S., "Thermal Conductivity of Copper. Part II. Conductivity at Low Temperatures," Phys. Rev., **3**(1), 1–20, 1895.

[1163] Raag, V., and Kowger, H. V., "Thermoelectric Properties of Niobium in the Temperature Range 300–1200 K," J. Appl. Phys., **36**(6), 2045–8, 1965.

[1164] Rademakers, A., "The Thermal Conductivity of Lead and Tin in the Superconducting and in the Normal State," Physica, **15**, 849–59, 1949.

[1165] Radhakrishna, P., and Nielsen, M., "Thermal Conductivity of Niobium-Zirconium Alloys at Low Temperatures," Phys. Letters (Netherlands), **6**(1), 36–8, 1963.

[1166] Radhakrishna, P., and Nielsen, M., "Transport Properties of Cobalt at Low Temperatures," Phys. Status Solidi, **11**(1), 111–15, 1965.

[1167] Raeth, C. H., "The Thermal Conductivity of Some Project Materials," USAEC, CP-2332, 1–25, 1944.

[1168] Rafalowicz, J., "Integral Method of Thermal Conductivity Measurements of Cylindrical Semiconductor Specimens Immersed in a Helium Bath," Acta Phys. Pol., **30**(2), 205–22, 1966.

[1169] Ranque, G., Henry, P., and Chaussian, M., "An Industrial Apparatus for Determining the Thermal Conductivity of Metals Up to 900 C," Congres. Internat. Mines Met. Geol. Section de Metallurgie, **2**, 303–9, 1936.

[1170] Rao, K. V., "Thermal Conductivity of Dysprosium Between 1 and 4 K," Phys. Letters (Netherlands), **A24**(1), 39–40, 1967.

[1171] Rao, K. V., "Thermal Conductivity of Metals at Low Temperatures," University of Oxford, Ph.D. Thesis, 147 pp., 1967.

[1172] Rao, K. V., "Nuclear Hyperfine Contribution to Thermal Conductivity of Holmium," Phys. Rev. Lett., **22**(18), 943–5, 1969.

[1173] Rao, K. V., Loo, H. Y., and Meaden, G. T., Private communication, 22 January, 1969.

[1174] Rao, K. V., Loo, H. Y., and Meaden, G. T., "Lattice Contribution to Thermal Conductivity of Some Rare Earth Ferromagnets," in *Proceedings of the Ninth Conference on Thermal Conductivity* (Iowa State Univ., Oct. 6–8, 1969), USAEC Rept. CONF-691002, 181–207, 1970.

[1175] Rappeneau, J., Bocquet, M., Micaud, G., and Fillatre, A., "Effects of Irradiation on the Physical Properties of Graphite," Carbon (Oxford), **1**, 97–109, 1964.

[1176] Rasor, N. S., "Technique for the Measurement of Changes in Thermal and Electrical Properties of Pulse-Annealed Irradiated Graphite," USAEC Rept. NAA-SR-43, 1–36, 1950.

[1177] Rasor, N. S., "Low Temperature Thermal and Electrical Conductivity and Thermoelectric Power of Graphite," USAEC Rept. NAA-SR-1061, 1–23, 1955.

[1178] Rasor, N. S., and McClelland, J. D., "Thermal Properties of Materials. Part 1. Properties of Graphite, Molybdenum and Tantalum to Their Destruction Temperatures," WADC-TR-56-400, 1–53, 1957. [AD 118 144]

[1179] Rasor, N. S., and McClelland, J. D., "Thermal Properties of Graphite, Molybdenum, and Tantalum to Their Destruction Temperatures," J. Phys. Chem. Solids, **15**, 17–26, 1960.

[1180] Rasor, N. S., and Smith, A. W., "Low Temperature Thermal and Electrical Conductivities of Normal and Neutron Irradiated Graphite," North American Aviation Inc., Downey, Univ. of Calif., NAA-SR-862, 1–37, 1954. [AD 85 006]

[1181] Ratnalingam, R., Univ. of Oxford, Ph.D. Thesis, 1970; results transmitted by R. Berman in a private communication, February 10, 1970.

[1182] Ratnalingam, R., and Sousa, J. B., "Thermal Conductivity of Holmium at Low Temperatures," Phys. Letters (Netherlands), **30A**(1), 8–9, 1969.

[1183] Ratnalingam, R., and Sousa, J. B., "Thermal Conductivity and Lorenz Number of Gadolinium at Low Temperatures. (0.4 to 4.2 K)," Phys. Letters (Netherlands), **29A**(7), 367–8, 1969.

[1184] Rausch, V. K., "Investigations on Antimony Single Crystals in the Transverse Magnetic Field," Ann. Physik, 6, **1**, 190–206, 1947.

[1185] Raytheon Company, "Summary Report on Pyrolytic Material," 1–56, 1963. [AD 819 227]

[1186] Reddemann, H., "Thermal Conductivity, Wiedemann-Franz-Lorenz Ratio and the Thermal Forces of Single Crystals of Mercury," Ann. Physik, **14**, 139–63, 1932.

[1187] Reddemann, H., "Changes in the Thermal and Electrical Conductivity of a Single Crystal of Bismuth in a Magnetic Field," Ann. Physik, **20**(5), 441–48, 1934.

[1188] Reddemann, H., "The Wiedemann-Franz Number of Beta-Manganese at Minus 190 C," Ann. Physik, **22**(5), 28–30, 1935.

[1189] Red'ko, N. A., Bresler, M. S., and Shalyt, S. S., "Carrier

Scattering Mechanism in Antimony," Fiz. Tverd. Tela, **11**(10), 3005–7, 1969; English translation: Sov. Phys.-Solid State, **11**(10), 2435–6, 1970.

[1190] Reese, W., and Steyert, W. A., Jr., "Properties of Lead Thermal Switches at Low Temperatures," Rev. Sci. Instr., **33**(1), 43–7, 1962.

[1191] Reppy, J. D., and Reynolds, C. A., "Thermal Gradient in Channels of Helium-II," ASTIA, 1–18, 1956. [AD 103 530]

[1192] Revel, G., "Aluminum of High Purity Obtained by Zone Melting," Compt. Rend., **259**, 4031–3, 1964.

[1192a] Reynolds, W. N., *Physical Properties of Graphite*, Elsevier Publ. Co., Amsterdam, 193 pp., 1968.

[1192b] Rhys. D. W., "The Fabrication and Properties of Ruthenium," J. Less-Common Metals, **1**, 269–91, 1951.

[1193] Rice, M. J., "Itinerant Electron Correlation and the Ideal Lorenz Number of Transition Metals," Phys. Letters (Netherlands), **26A**(2), 86–7, 1967.

[1194] Richter, F., "Thermal Conductivity of Pure Iron Between −180 and 1000 C with Special Consideration of Phase Changes," Cologne Univ., W. Germany, Ph.D. Dissertation, 1–109, 1964.

[1195] Richter, F., and Kohlhaas, R., "Thermal Conductivity of Pure Iron at Curie Temperature," Z. Naturf. **A19**(13), 1632–4, 1964.

[1196] Richter, F., and Kohlhaas, R., "Heat Conductivity of Pure Iron Between −180 and 1000 Degrees with Special Reference to Phase Transformations," Arch. Eisenhuettenw., **36**(11), 827–33, 1965.

[1197] Richter, W., Lippmann, S., and Wahn, G., "Determination of the Thermal Diffusivity and Thermal Conductivity at Moderate and Elevated Temperatures. Part 3. Thermal Conductivity," Neue Hutte, **8**(7), 406–10, 1963.

[1198] Richter, W., and Wahn, G., "Determination of the Thermal Conductivity of Metals by the Cylinder Method at Normal and Medium Temperatures," Wiss. Z. Hochsch. Maschinenbau Karl-Marx-Stadt (Germany), **4**(4), 385–9, 1962.

[1199] Rienda, J. M. B., "Dependence of the Thermal Conductivity on Temperatures for Polyatomic Polar Gases," Univ. of Madrid, Spain, Ph.D. Thesis, 1963. [AD 254 599]

[1200] Rigney, C. J., and Bockstahler, L. I., "The Thermal Conductivity of Titanium Between 20 and 273 Degrees Kelvin," Phys. Rev., **83**, 220, 1951.

[1201] Rigney, D. V., Kapelner, S. M., and Cleary, R. E., "The Electrical Resistivity of Lithium and Columbium (Niobium) −1 Zirconium Alloy to 1430," Pratt and Whitney Aircraft-Canel, Middletown, Conn., USAEC, TIM–854, N–65–35548, 1–14, 1965.

[1202] Rinck, E., "The Allotropic Transformations of Strontium," Compt. Rend. Acad. Sci. (Paris), **234**, 845–7, 1952.

[1203] Ristikivi, J., "Viscosity and Thermal Conductivity of Gas Mixtures," Tek. Tidskr., **89**, 1325–6, 1959.

[1204] Robertson, R., Fox, J. G., and Martin, A. E., "Two Types of Diamond," Phil. Trans. Roy. Soc., **A232**, 463–536, 1934.

[1205] Robinson, H. E., "Apparatus for Measuring the Thermal Conductivities of Metals," USAEC Rept. ANL–5611, 1–15, 1959.

[1206] Roder, H. M., "The Thermal Conductivity of Solid Nitrogen," Cryogenics, **2**, 302–4, 1962.

[1207] Roder, H. M., and Diller, D. E., "Thermal Conductivity of Gaseous and Liquid Hydrogen," J. Chem. Phys., **52**(11), 5928–49, 1970.

[1208] Roder, H. M., Powell, R. L., and Hall, W. J., "Thermal and Electrical Conductivity of Pure Copper," in *Proceedings of the Fifth International Conference on Low Temperature Physics and Chemistry*, 364–66, 1958.

[1209] Rodine, M. T., "Thermal Conductivities of Bismuth Single Crystals as Influenced by a Magnetic Field," Phys. Rev., **46**(2), 910–16, 1934.

[1210] Rodine, M. T., "Pt. 1. Thermal Conductivities of Bismuth Single Crystals as Influenced by a Magnetic Field. Pt. II. The Effect of Carbon Tetrachloride on the Dielectric Strength of Air," Univ. of Wisconsin, 1–33, 1934.

[1211] Roehlich, F., Jr., "The Electrical Resistivity and the Thermal Conductivity of Liquid Alkali Metals to 2000 F," Electrochem. Soc. 126th Meeting, CONF–641018–1, 1–21, 1964.

[1212] Roehlich, F., Jr., and Tepper, F., "Electrical and Thermal Conductance of Alkali Metals at Elevated Temperatures," Electrochem. Technol., **3**(9/10), 234–9, 1965.

[1213] Rogers, J. D., Zeigler, R. K., and McWilliams, P., "Hydrogen Transport Property Correlations, Part II," USAEC LA–2719, NASA–N16081, 1–40, 1962.

[1214] Rogers, K. W., "Experimental Investigations of Solid Nitrogen Formed by Cryopumping," NASA–CR–553, N66–33982, 1–40, 1966.

[1215] Roizin, N. M., Mostovlyanskii, N. S., and Strod, R. K., "Heat Conductivity of Indium," Fiz. Metal. i Metalloved., **15**(5), 800, 1963; English translation: Phys. Metals Metallography (GB), **15**(5), 139, 1964.

[1216] Roizin, N. M., Mostovlyanskii, N. S., and Strod, R. K., "Thermal Conductivity of Indium," Fiz. Tverd. Tela (USSR), **5**(4), 1216, 1963; English translation: Sov. Phys.-Solid State, **5**(4), 887, 1963.

[1217] Roll, A., and Motz, H., "The Electrical Resistivity of Molten Metals," Z. Metallk., **48**(5), 272–80, 1957.

[1218] Rosenberg, H. M., "The Thermal Conductivity of Germanium and Silicon at Low Temperatures," Proc. Phys. Soc. (London), **A67**, 837–40, 1954.

[1219] Rosenberg, H. M., "The Thermal and Electrical Conductivity of Magnesium at Low Temperatures," Phil. Mag., **45**, 73–9, 1954.

[1220] Rosenberg, H. M., "The Thermal Conductivity of Metals at Low Temperatures," Phil. Trans. Roy. Soc. (London), **A247**, 441–97, 1955.

[1221] Rosenberg, H. M., "The Thermal and Electrical Conductivity of Lithium at Low Temperatures," Phil. Mag., **1**(8), 738–46, 1956.

[1222] Rosenberg, H. M., "The Thermal Conductivity of Metals at Low Temperatures. Deviations from Ideal Behavior," Phil. Mag. 8, **2**, 541–7, 1957.

[1223] Rosenthal, M. W., "Measurement of the Thermal Conductivity of Molten Lead," Massachusetts Inst. of Tech., Cambridge, Mass., Ph.D. Thesis, 1–200, 1953.

[1224] Rosner, D. E., "Properties of Equilibrium Dissociating Hydrogen for Predicting Convective Heating in Nuclear-Thermal Rockets," Aerochem. Res. Lab. Rept. TP 27, 1–27, 1961. [AD 257 863]

[1225] Rothman, A. J., "Thermal Conductivity of Gases at High Temperatures," USAEC Rept. UCRL–2339, 1–115, 1953.

[1226] Rothman, A. J., and Bromley, LeR. A., "High Temperature Thermal Conductivity of Gases," Ind. Eng. Chem., **47**, 899–906, 1955.

[1227] Rowe, V. A., "Phonon Drag Thermopower in Cadmium, Zinc, and Magnesium," Univ. of Michigan, Ph.D. Thesis, Univ. Microfilms Publ. 68–7957, 1–104, 1967.

[1228] Rowell, P. M., "Thermal Conductivity of Some Superconductors," Proc. Roy. Soc. (London), **A254**, 542–50, 1960.

[1229] Rudkin, R. L., Parker, W. J., and Jenkins, R. J., "Measurements of the Thermal Properties of Metals at Elevated Temperatures," Temp. Meas. Control Sci. Ind., Pt. 2, **3**, 523–34, 1962.

[1230] Rudkin, R. L., Parker, W. J., and Jenkins, R. J., "Thermal Diffusivity Measurements on Metals and Ceramics at High Temperatures," ASD–TDR–62–24, 1–20, 1963.

[1231] Rudkin, R. L., Parker, W. J., and Westover, R. W., "Measurements of the Thermal Properties of Metals at Elevated Temperatures," USNRDL-TR-419, 1-27, 1960. [AD 240 185-L]

[1232] Rudnev, I. I., Lyashenko, V. S., and Abramovich, M. D., "The Thermal Diffusivity of Sodium and Lithium," At. Energy (USSR), **11**, 230-2, 1961; English translation: Sov. J. At. Energy, **11**(3), 877-80, 1962.

[1233] Ruh, E., "Improved Method of Measuring Thermal Conductivity of Dense Ceramics," J. Am. Ceram. Soc., **37**, 224-9, 1954.

[1234] Sager, G. F., "Investigation of the Thermal Conductivity of the System Copper-Nickel," Rensselaer Polytech. Inst. Bull. 27, 3-48, 1930.

[1235] Salceanu, C., and Bojin, S., "The Thermal Conductivity of Gases and Vapors," Compt. Rend., **243**, 237-9, 1956.

[1236] Saller, H. A., Dickerson, R. F., Bauer, A. A., and Daniel, N. E., "Properties of a Fissium-Type Alloy," USAEC, BMI-1123, 1-32, 1956.

[1237] Saller, H. A., Rough, F. A., and Chubb, W., "The Properties of Uranium Containing Minor Additions of Chromium, Silicon, or Titanium," USAEC, BMI-1068, 1-32, 1956.

[1238] Reference withdrawn.

[1239] Samsonov, G. V. (Editor), *Handbook of the Physicochemical Properties of the Elements*, IFI/Plenum Data Corp., New York, 941 pp., 1968.

[1240] Sandenaw, T. A., and Gibney, R. B., "The Electrical Resistivity and Thermal Conductivity of Plutonium Metal," Los Alamos Sci. Lab. of Univ. California, LADC 3052, 1-19, 1957.

[1241] Sandenaw, T. A., and Gibney, R. B., "The Electrical Resistivity and Thermal Conductivity of Plutonium Metal," J. Phys. Chem. Solids, **6**(1), 81-8, 1958.

[1242] Sanunu, J. H., "Experimental Measurement of the Thermal Conductivity of Cesium Vapor," Massachusetts Inst. of Tech., M. S. Thesis, 38 pp., 1963.

[1243] Sasaki, K., and Sekito, S., "Three Crystalline Modifications of Electrolytic Chromium," Trans. Electrochem. Soc. (USA), **59**, 437-60, 1931.

[1244] Satterthwaite, C. B., "Thermal Conductivity of Normal and Superconducting Aluminum," Phys. Rev., **125**, 873-6, 1962.

[1245] Saunders, N. H., Private communication, April 16, 1969.

[1246] Sawin, F., "Thermal Conductivity of Silicon and Germanium at Low Temperatures," Univ. of Texas, M.S. Thesis, 61 pp., 1962.

[1247] Sawyer, R. B., "The Investigation of Thermal and Electrical Properties of Metals at High Temperatures," Inst. Res. LeHigh Univ., 1-38, 1955. [AD 81 977]

[1248] Sawyer, et al., Unpublished data taken from *The Metal Beryllium* (Editors: White, D. W., and Burke, J. E.), The American Society for Metals, Cleveland, Ohio, 310 pp., 1955.

[1249] Saxena, S. C., "Transport Coefficients and Force Between Unlike Molecules," Indian J. Phys., **31**, 146-55, 1957.

[1250] Saxena, S. C., "Thermal Conductivity of Binary and Ternary Mixtures of Helium, Argon, and Xenon," Indian J. Phys., **31**, 597-606, 1957.

[1251] Saxena, V. K., and Saxena, S. C., "Thermal Conductivity of Krypton and Xenon in the Temperature Range 350 to 1500 K," Univ. Illinois at Chicago, Energy Engineering Rept. IITRI-E 21, 1-16, 1968.

[1252] Saxena, V. K., and Saxena, S. C., "Measurement of the Thermal Conductivity of Neon Using Hot-Wire-Type Thermal Diffusion Columns," J. Chem. Phys., **48**(12), 5662-7, 1968.

[1253] Sayce, E. D., "Some Determinations of the Heat Conductivity of Selenium," J. Proc. Roy. Soc. N.S. Wales, **51**, 356-63, 1917.

[1254] Schäfer, K., and Reiter, F. W., "Determination of the Absolute Thermal Conductivity of Gases up to 1100 Degrees," Naturwissenschaften, **43**, 296-7, 1956.

[1255] Schäfer, K., and Reiter, F. W., "Method for the Measurement of Heat Conductivity at 1100 Degrees," Z. Elektrochem., **61**, 1230-5, 1957.

[1256] Schaefer, C. A., and Thodos, G., "Reduced Thermal Conductivity Correlation. Gaseous and Liquid Hydrogen," Ind. Eng. Chem., **50**, 1585-8, 1958.

[1257] Schaefer, C. A., and Thodos, G., "Thermal Conductivity of Diatomic Gases: Liquid and Gaseous States," A. I. Ch. E. Journal, **5**, 367-72, 1959.

[1258] Schaufelberger, W., "Thermal Conductivity of Copper Determined from Stationary and Variable Temperature and Heat Flow in a Heat Conductor with Interfaces Cooled by Water," Ann. Physik, **7**, 589-630, 1902.

[1259] Schettler, H. G., "Thermal Conductivity of Thorium," Iowa State Univ., M. S. Thesis, 46 pp., 1969.

[1260] Schettler, H. G., Martin, J. J., Schmidt, F. A., and Danielson, G. C., "Thermal Conductivity of High-Purity Thorium," Phys. Rev., **187**(3), 801-4, 1969.

[1261] Schlegel, R., "Conductivity Measurements," Chicago Univ. Metallurgical Lab., USAEC N-1880, 1, 1945.

[1262] Schleiermacher, A., "The Thermal Conductivity of Mercury Vapor," Ann. Physik, **36**, 346-57, 1889.

[1263] Schleiermacher, A., "On the Thermal Conduction of Gases," Ann. Physik, **34**, 623-46, 1888.

[1264] Schmidt, P. H., "Purification and Crystal Growth of Gold," J. Electrochemical Soc., **112**(6), 631-2, 1965.

[1265] Schmitz, G., and Patt, H. J., "The Determination of Material Functions of a Nitrogen Plasma at Atmospheric Pressure Up to 15 000 K," Z. Phys., **171**, 449-62, 1963.

[1266] Schneider, E., "Correction on My Work 'On the Thermal Conductivity of Air and Hydrogen'," Ann. Physik, **79**, 177-203, 1926.

[1267] Schofield, F. H., "The Thermal and Electrical Conductivities of Some Pure Metals," Proc. Roy. Soc. (London), **A107**, 206-27, 1925.

[1268] Schott, R. (Revised by Eucken, A.), "The Thermal Conductivity of Some Metals at Low Temperatures—Remark by Meissner, W. (p. 240-4)," Verh. Deut. Physik Ges., **18**, 27-34, 1916.

[1269] Schottky, W. F., "Measurement of the Thermal Conductivity of Gases at Higher Temperatures," Z. Elektrochem., **56**, 889-92, 1952.

[1270] Schramm, B., "Thermal Conductivity of Gas Mixtures at High Temperatures and a New Formula for Their Calculations," Allgem. Wärmetech., **12**(6/7), 125-9, 1966.

[1271] Schriempf, J. T., "Thermal Conductivity of High-Purity Rhenium at 2 Degrees K to 20 K, from Rept. of NRL Progress," PB 173 549, N67 19963, 1-6, 1966.

[1272] Schriempf, J. T., "Thermal Conductivity Measurements Using Au-Fe vs. Ag-Au Thermocouples at Temperatures from 2-20 K," in *Proceedings of the Sixth Conference on Thermal Conductivity, Dayton, Ohio, Oct. 19-21, 1966*, Air Force Materials Lab., 615-25, 1966.

[1273] Schriempf, J. T., "Lorenz Number of Pure Palladium at Low Temperatures," Phys. Rev. Letters, **19**(19), 1131-3, 1967.

[1274] Schriempf, J. T., "Thermal and Electrical Resistivities of Rhenium from 2 K to 20 K," J. Phys. Chem. Solids, **28**(12), 2581-7, 1967.

[1275] Schriempf, J. T., "Three-Term Analysis of the Ideal Thermal and Electrical Resistivities of Transition Metals," Phys. Rev. Lett., **20**(19), 1034-6, 1968.

[1276] Schriempf, J. T., "Deviations from Mattiessen's Rule in the Low Temperature Thermal and Electrical Resistivities of Very Pure Copper," in *Thermal Conductivity—Proceedings of the Seventh Conference*, NBS Sp-302, 249-52, 1968.

[1277] Schriempf, J. T., "Thermal and Electrical Resistivities of Osmium from 2 to 20 K," Solid State Commun., **6**(12), 873–6, 1968.

[1278] Schriempf, J. T., Schindler, A. I., and Mills, D. L., "Electron-Electron Scattering Effects in the Low-Temperature Lorenz Numbers of Dilute Pd-Ni Alloys," NRL–6949, 1–32, 1969. [AD 694 453]

[1279] Schulze, A., "Temperature Measurement in the Metals Industry. 1. Direct Method," Z. Metallk., **13**, 234–8, 1921.

[1280] Schulze, F. A., "The Thermal Conductivity of Several Series of Noble Metal Alloys," Physik Z., **12**, 1028–31, 1911.

[1281] Schweitzer, D. G., and Singer, R., "Thermal Conductivity of Radiation Damaged AGOT Graphite from the Graphite Research Reactor," USAEC Rept. BNL–696 (S–59), 56–8, 1962.

[1282] Sedstrom, E., "Peltierwarme Samt Thermischer und Elektrischer Leitfahigkeit Einiger Festen Metallischen Losungen," Ann. Physik, 4, **59**, 134–44, 1919.

[1283] Sedstrom, E., "To the Knowledge of Gold-Copper Alloys," Ann. Physik, **75**, 549–55, 1924.

[1284] Semchyshen, M., and Barr, R. Q., "Summary Report. Arc-Cast Molybdenum Base Alloys," Climax Molybdenum Co. of Michigan, 1–428, 1955. [AD 90 229]

[1285] Senftleben, H., "A Simple Method of Determining Simultaneously the Specific Heat, Viscosity, and Heat Conduction of Gases," Z. Angew. Phys., **5**, 33–9, 1953.

[1286] Sengers, J. V., "Triple Collision Effects in the Thermal Conductivity and Viscosity of Moderately Dense Gases," USAEDC–TR–69–68, 1–166, 1969. [AD 684 179]

[1287] Sengers, J. V., Bolk, W. T., Stigter, C. F., "The Thermal Conductivity of Neon Between 25 and 75 Degrees at Pressures Up to 2000 Atmospheres," Physica, **30**(5), 1018–26, 1964.

[1288] Serlemitsos, A. T., and Bhagat, S. M., "Thermal Conductivity of Mercury at Liquid Helium Temperatures," Univ. Maryland Techn. Rept. No. 879, 1–72, 1968.

[1289] Serlemitsos, A. T., and Bhagat, S. M., "Thermal Conductivity in Mercury at Liquid Helium Temperatures," in *Proceedings of the Eighth Conference on Thermal Conductivity*, Purdue University, Plenum Press, N. Y., 165–73, 1969.

[1290] Seward, W. D., Lazarus, D., and Fain, S. C., Jr., "Thermal Conductivity of Hexagonal Close-Packed Solid Helium Four at High Densities," Phys. Rev., **178**(1), 343–55, 1969.

[1291] Seyfert, P., "Influence of Neutron Irradiation on the Thermal Conductivity of Silicon at 80 K Temperature," Compt. Rend., **265B**(10), 609–12, 1967.

[1292] Shadrichev, E. V., and Smirnov, I. A., "Thermal Conductivity of Tellurium in the Solid and Liquid States," Fiz. i Tekh. Poluprov, **1**(4), 501–8, 1967.

[1293] Shadrichev, E. V., Smirnov, I. A., and Kutasov, V. A., "Thermal Conductivity of Bismuth Telluride and Tellurium Melts," Fiz. Tverd. Tela, **11**(7), 1935–9, 1969; English translation: Sov. Phys.-Solid State, **11**(7), 1557–60, 1970.

[1294] Shalyt, S. S., "Thermal Conductivity of Bi at Low Temperatures," J. Phys. (USSR), **8**, 315–16, 1944.

[1295] Shanks, H. R., Burns, M. M., and Danielson, G. C., "The Thermal Diffusivity of Gold," in *Proceedings of the Seventh Conference on Thermal Conductivity*, Gaithersburg, Maryland, 331–6, 1967.

[1296] Shanks, H. R., Klein, A. H., and Danielson, G. C., "Thermal Properties of Armco Iron," J. Appl. Phys., **38**(7), 2885–92, 1967.

[1297] Shanks, H. R., Maycock, P. D., Sidles, P. H., and Danielson, G. C., "Thermal Conductivity of Silicon from 300 to 1400 K," Phys. Rev., **130**, 1743–8, 1963.

[1298] Sharkoff, E. G., "Impurity Effects on the Thermal Conductivity of Magnesium at Low Temperature," Massachusetts Inst. Tech., Ph.D. Thesis, 78 pp., 1953.

[1299] Sharma, J. K. N., "Heat Conductivities Below 1 K. I," Cryogenics, **7**(3), 141–56, 1967.

[1300] Shashkov, Yu. M., and Grishin, V. P., "Thermal Conductivity of Silicon in the Solid and Liquid States Near the Melting Point," Fiz. Tverd. Tela, **8**(2), 567–9, 1966; English translation: Sov. Phys.-Solid State, **8**(2), 447–8, 1966.

[1301] Shelton, S. M., "Thermal Conductivity of Some Irons and Steels Over the Temperature Range 100 to 500 C," J. Research Natl. Bur. Stds., **12**, 441–50, 1934.

[1302] Shelton, S. M., and Swanger, W. H., "Thermal Conductivity of Irons and Steels and Some Other Metals in the Temperature Range 0–600 Degrees," Trans. Am. Soc. Steel Treating, **21**, 1061–77, 1933.

[1303] Sherman, M. P., "Calculation of Transport Properties of Mixtures of Helium and Partly-Ionized Argon," Aeronaut. Engng. Lab. Rept. 673, Princeton Univ., 1–74, 1963.

[1304] Shimada, T., and Kikuchi, T., "Irradiation Effects in Glassy Carbon," Session VI, Paper 3 of *Symposium on Carbon*, Tokyo, 1–4, 1964.

[1305] Shpil'rain, E. E., and Krainova, I. F., "Experimental Investigation of the Thermal Conductivity of Liquid Cesium," Teplofiz. Vys. Temp., **5**(1), 58–65, 1967; English translation: High Temp. (USSR), **5**(1), 50–5, 1967.

[1306] Shpil'rain, E. E., and Krainova, I. F., "Thermal Conductivity of Liquid Rubidium," Teplofiz. Vys. Temp., **6**(3), 451–4, 1968; English translation: High Temp., **6**(3), 432–5, 1968.

[1307] Shpil'rain, E. E., and Krainova, I. F., "Experimental Study of the Thermal Conductivity of Potassium and K-Na Alloys," Teplofiz. Vys. Temp., **7**(1), 172–5, 1969; English translation: High Temp., **7**(1), 159–62, 1969.

[1308] Shpil'rain, E. E., and Krainova, I. F., Private communication from E. E. Shpil'rain, May 14, 1969.

[1309] Shpil'rain, E. E., and Savehenko, V. A., "Experimental Investigation of the Electrical Conductivity of Lithium and Cesium in the Condensed Phase at Temperatures Up to 1200 K," Teplofiz. Vys. Temp., **6**(2), 254–60, 1968.

[1310] Sibley, L. B., Allen, C. M., Zielenbach, W. J., Peterson, C. L., and Goldthwaite, W. H., "A Study of Refractory Materials for Seal and Bearing Applications in Aircraft Accessory Units and Rocket Motors," WADC–TR–58–299, 1–52, 1958. [AD 203 787]

[1311] Sidles, P. H., and Danielson, G. C., "Thermal Conductivity of Metals at High Temperatures," J. Appl. Phys., **25**(1), 58–66, 1951.

[1312] Sidles, P. H., and Danielson, G. C., "Thermal Diffusivity of Metals at High Temperatures," USAEC OTS, ISC198, 1–24, 1951.

[1313] Sidles, P. H., and Danielson, G. C., "Thermal Conductivity of Metals at High Temperature," J. Appl. Phys., **25**(1), 58–66, 1954.

[1314] Sidles, P. H., and Danielson, G. C., "Thermal Diffusivity Measurements at High Temperatures," in Proc. Thermoelectricity Conf. (1958), Iowa State Univ., 270–87, 1960.

[1315] Silverman, L., "Thermal Conductivity Data Presented for Various Metals and Alloys Up to 900 Degrees," J. Metals, **5**, 631–2, 1953.

[1316] Simonova, L. K., "Determination of Thermal Constant of Samples of Activated Carbon and Silica Gels," J. Applied Chem. (USSR), **16**, 87–94, 1943; English translation: SLA 61–16958, 1–5, 1961.

[1317] Simonova, Yu, N., and Filippov, L. P., "Thermal Conductivity of Tungsten at High Temperatures," Zh. Prikl.

Mekhan. i Tekhn. Fiz., **1**, 111–2, 1965; English translation: J. Appl. Mech. Tech. Phys., **1**, 102–3, 1965.
[1318] Slack, G. A., "Anisotropic Thermal Conductivity of Pyrolytic Graphite," Phys. Rev., **127**, 694–701, 1962.
[1319] Slack, G. A., "Platinum as a Thermal Conductivity Standard," J. Appl. Phys., **35**, 339–44, 1964.
[1320] Slack, G. A., "Thermal Conductivity of Pure and Impure Silicon, Silicon Carbide, and Diamond," J. Appl. Phys., **35**(12), 3460, 1964.
[1321] Slack, G. A., "Thermal Conductivity of Elements with Complex Lattices: B, P, S," Phys. Rev., **139**(2A), A507–15, 1965.
[1322] Slack, G. A., and Glassbrenner, C. J., "Thermal Conductivity of Germanium from 3 to 1020 K," Phys. Rev., **120**(3), 782–9, 1960.
[1323] Sladek, R. J., "Thermal Conductivity of Indium-Thallium Alloys at Low Temperatures," Phys. Rev., **97**, 902–15, 1955.
[1324] Smart, D., "Method Suitable for the Measurement of the Thermal Diffusivity of Irradiated Materials," J. Nucl. Mater., **2**(4), 341–9, 1960.
[1325] Smirnov, E. V., Muchnik, G. F., and Shklyarevskii, E. E., "Determination of the Coefficient of Thermal Conductivity of Deposited Metal Layers," Teplofiz. Vys. Temp., **5**(3), 445–49, 1967; English translation: High Temp., **5**(3), 398–402, 1967.
[1326] Smirnov, I. A., and Shadrichev, E. V., "Thermal Conductivity of Tellurium Single Crystals in the Temperature Range 80–650 K," Fiz. Tverd. Tela, **4**(7), 1960–3, 1962; English translation: Sov. Phys.-Solid State, **4**(7), 1435–6, 1963.
[1327] Smith, A. W., "The Thermal Conductivities of Alloys," Ohio State Univ. Studies Eng. Exp. Sta. Bull., No. 31, 1–61, 1925.
[1328] Smith, A. W., "Low Temperature Thermal Conductivity of a Canadian Natural Graphite," Phys. Rev., **95**, 1095–6, 1954.
[1329] Smith, A. W., and Rasor, N. S., "Observed Dependence of the Low-Temperature Thermal and Electrical Conductivity of Graphite on Temperature, Type, Neutron Irradiation, and Bromination," USAEC Rept. NAA–SR–1590, 1–25, 1956. [AD 106 065]
[1330] Smith, A. W., and Rasor, N. S., "Observed Dependence of the Low-Temperature Thermal and Electrical Conductivity of Graphite on Temperature, Type, Neutron Irradiation, and Bromination," Phys. Rev., **104**(4), 885–91, 1956.
[1331] Smith, C. S., "Thermal Conductivity of Copper Alloys. II. Copper-Tin Alloys. III. Copper-Phosphorus Alloys," AIMME Tech. Publ. No. 360, 1–11, 1930.
[1332] Smith, C. S., and Palmer, E. W., "Thermal and Electrical Conductivities of Copper Alloys," AIMME Tech. Publ. No. 648, 1–19, 1935.
[1333] Smith, J. F., Carlson, O. N., and Vest, R. W., "Allotropic Modifications of Calcium," J. Electrochem. Soc., **103**(-7), 409–13, 1965.
[1334] Smith, K. F., and Chiswik, H. H., "High Temperature Strength Zirconium and Titanium Base Alloys for Fuel Element Jacketing," Argonne Natl. Lab., Lemont, Ill., ANL–5339, 1–15, 1956.
[1335] Smith, M. G., "CMF–13 Research on Carbon and Graphite. Summary Rept. No. 7," Aug. 1–Oct. 31, 1968, LA–4057, 1–35, 1968.
[1336] Smith, N. D., Fun, F., and Visokey, R. M., "A Rapid, Simple Method for the Determination of the Thermal Conductivity of Solids," Amer. Chem. Soc., Div. Fuel Chem. Preprints, **11**(4), 365–74, 1967.
[1337] Smoke, E. J., Illyn, A. V., Eichbaum, B. R., Snyder, N. H., Lass, G., and Nussbaum, T., "Development of Ceramic Bodies with High Thermal Conductivity. Progress Rept. No. 3," New Jersey Ceramic Res. Sta., Rutgers Univ., New Brunswick Signal Corps, 1–62, 1955. [AD 74 093]
[1338] Snyder, N. H., Smoke, E. J., Wisley, H. R., and Ruh, E., "Low Loss Ceramics, Progr. Rept. No. 3," PB 162 945, 1–87, 1949. [AD 89 089]
[1339] Snyder, T. M., and Kamm, R. L., "Measurements of Some Physical Properties of Technologically Important Substances," USAEC Rept. C–96, 1–2, 1942.
[1340] Snyder, T. M., and Kamm, R. L., "Some Physical Constants Important in the Design of an Atomic Power Plant," USAEC–C–192, 1–56, 1955.
[1341] Sochtig, H., "Investigations on Pure Chromium in the Anomolous Region (Electrical and Thermal Resistance, Thermoelectric Power, Heat Content, Magnetic Susceptibility, and Lattice Structure)," Ann. Phyik, **38**(5), 97–120, 1940.
[1342] Solomon, P. R., and Otter, F. A., Jr., "Thermomagnetic Effects in Superconductors," Phys. Rev., **164**(2), 608–18, 1967.
[1342a] Sondheimer, E. H., "The Theory of the Transport Phenomena in Metals," Proc. Roy. Soc. (London), **A203**(1072), 75–98, 1950.
[1342b] Sondheimer, E. H., "A Note on the Theory of Conduction in Metals," Proc. Phys. Soc. (London), **A65**, 561–2, 1952.
[1342c] Sondheimer, E. H., "The Thermal Conductivity of Metals at Low Temperatures," Proc. Phys. Soc. (London), **A65**, 562–4, 1952.
[1343] Sorokin, A. G., Trukhanova, L. N., and Filippov, L. P., "Thermal Conductivity, Electrical Conductivity, and Radiative Characteristics of Rhodium at High Temperatures," Teplofiz. Vys. Temp., **7**(2), 372–4, 1969; English translation: High Temp., **7**(2), 342–3, 1969.
[1344] Sousa, J. B., "Lattice Thermal Conductivity of Ta-Nb and Nb-Mo Solid Solution Alloys in Normal and Superconducting States," J. Phys. C., Solid State Phys., **2**(4), 629–39, 1969.
[1345] Southern Research Inst., "The Mechanical and Thermal Properties of Tungsten and TZM Sheet Produced in the Refractory Metal Sheet Rolling Program, Part I," DDC N–67–10380, 1–200, 1966. [AD 638 631]
[1346] Southern Research Inst. (Arthur D. Little, Inc.), "Deviation of High Temperature Thermal Conductivity Standards," AFML–TR–69–2, N69–39266, 1–372, 1969. [AD 689 851]
[1347] Sparrell, J. K., Coumou, K. G., and Plunkett, J. D., "An Instrument for Measuring the Thermal Conductance of High-Temperature Structural Materials," Dynatech. Corp., Cambridge, Mass., ASD–TDR–63–359, 1–46, 1963. [AD 421 886]
[1347a] Spedding, F. H., and Daane, A. H. (Editors), *The Rare Earths*, John Wiley and Sons, New York, 641 pp., 1961.
[1348] Spedding, F. H., Hanak, J. J., and Daane, A. H., "The Preparation and Properties of Europium," Trans. AIMME, **212**, 379–83, 1958.
[1349] Speer Carbon Company, Inc., Data Sheet "Characteristics of Speer Grade 875S," 1966.
[1350] Speer Carbon Company, Inc., Data Sheet "Characteristics of Speer Grade 890S," 1966.
[1351] Spohr, D. A., and Webber, R. T., "Resistance Minimum of Magnesium, Electrical and Thermal Resistivities," Phys. Rev., **105**, 1427–33, 1957.
[1352] Spyra, W., "A Method for the Absolute Measurement of Thermal Conductivity," DEW Tech. Ber., **2**(4), 166–73, 1962.
[1353] Spyra, W., "The Development of a Method for Absolute Measurement of Thermal Conductivity," BISI–3260, 1–16, 1963.
[1354] Srivastava, B. N., and das Gupta, A., "Thermal Conductivity of Binary Mixtures of Ammonia and Inert Gases," Brit. J. Appl. Phys., **18**(7), 945–51, 1967.

[1355] Srivastava, B. N., and Madan, M. P., "Thermal Conductivity of Argon-Neon Mixtures," Proc. Natl. Inst. Sci., India, **20A**, 587–97, 1954.

[1356] Srivastava, B. N., and Saxena, S. C., "Thermal Conductivity of Binary and Ternary Rare Gas Mixtures," Proc. Phys. Soc., (London), **70B**, 369–78, 1957.

[1357] Srivastava, B. N., and Srivastava, R. C., "Thermal Conductivity and Eucken Correction for Diatomic Gases and Binary Gas Mistures," J. Chem. Phys., **30**, 1200–5, 1959.

[1358] Staebler, J., "Electrical and Thermal Conductivity and the Number of Wiedemann-Franz of Light Metals and Magnesium Alloys," Technischen Hochschule zu Breslau, Ph.D. Dissertation, 35 pp., 1929.

[1359] Starr, C., "Thermal Diffusivity of Nickel," Phys. Rev., 2, **51**(5), 376, 1937.

[1360] Stauder, R. F., and Mielczarek, E. V., "Measurements of the Thermal Conductivity of Single Crystals of Potassium Between 2.5 and 40 K," Phys. Rev., **158**(3), 630–6, 1967.

[1361] Steele, M. C., and Rosi, F. D., "Thermal Conductivity and Thermoelectric Power of Germanium-Silicon Alloys," J. Appl. Phys., **29**(11), 1517–20, 1958.

[1362] Stefanov, B. I., Timrot, D. L., Totskii, E. E., and Chu, W. H., Viscosity and Thermal Conductivity of the Vapors of Sodium and Potassium," Teplofiz. Vys. Temp., **4**(1), 141–2, 1966; English translation: High Temp., **4**(1), 131–2, 1966.

[1363] Stephenson, A. E., "The Design, Construction, and Calibration of an Apparatus to Determine the Thermal Conductivity of Solids," Univ. of Missouri, Rolla, Missouri, Masters Thesis, 1–37, 1963.

[1364] Stewart, R. W., "X. The Absolute Thermal Conductivity of Iron and Copper," Phil. Trans. Roy. Soc. (London), **184A**, 569–90, 1893.

[1365] Stiel, L. I., and Thodos, G., "The Prediction of the Transport Properties of Pure Gaseous and Liquid Substances," Progr. Int. Res. Thermodyn. Transport Properties, ASME, New York, 352–65, 1962.

[1366] Stolyarov, E. N., Ipat'ev, V. V., and Teodorovich, V. P., "Transfer Phenomena in Compressed Gases. I. Determination of the Heat-Conduction Coefficient of Compressed Gases (H, N, air, methane, and carbon dioxide)," Zh. Fiz. Khim., **24**, 166–76, 1950; English translation: TIB/T4445, [AD 92 320]

[1367] Stops, D. W., "Effect of Temperature Upon the Thermal Conductivity of Gases Between 0 and 100 C," Univ. of London, Ph.D. Thesis, 1948.

[1368] Stops, D. W., "Effect of Temperature on the Thermal Conductivity of Gases," Nature (London), **164**, 966–7, 1949.

[1369] Störmer, R., "A Method for Measuring the Thermal Conductivity and the Temperature Coefficient of the Thermal Conductivity of Electrical Conducting Bodies," Wiss. veroffentl. Siemens-Konzern, **13**, 30–40, 1934.

[1370] Strauss, H. E., "Thermal Conductivity of Carbon at High Temperature," in *Proceedings of the Fifth Conference on Carbon* (Univ. Park, Pa., 1961), Vol. 2, 647–54, 1962.

[1371] Strelkov, P. G., "Optical Dewar Vessel and Some Observations on Thermal Conductivity in Helium-II," J. Exptl. Theor. Phys. (USSR), **10**, 1225–8, 1940.

[1372] Strickler, H. S., "Thermal Conductivity of Gases and Aggregate Matter," J. Chem. Phys., **17**, 427–8, 1949.

[1373] Stuckes, A. D., "The Thermal Conductivity of Germanium, Silicon, and Indium Arsenide from 40 Degrees to 425 Degrees," Phil. Mag., **5**(8), 84–99, 1960.

[1374] Stuckes, A. D., and Chasmar, R. P., "Measurement of the Thermal Conductivity of Semiconductors," Rept. Meeting on Semiconductors, Rugby, 119–25, 1956.

[1375] Sugawara, A., "Thermal Conductivity of Sulfur Accompanying Crystal Transition and Phase Change," J. Appl. Phys., **36**(8), 2375–7, 1965.

[1376] Sugawara, A., "The Precise Determination of Thermal Conductivity of Pure Fused Quartz," J. Appl. Phys., **39**(13), 5994–7, 1968.

[1377] Süsman, H., "Thermal Conductivity of Tellurium," Wiss. Z. Martin-Luther-Univ. Halle-Wittenberg Math-Nat Reihe, **10**(1), 33–9, 1961.

[1378] Sutter, P. H., and Gallo, C., "The Thermoelectric Properties of a Tellurium Single Crystal Parallel to the "C" Axis," WRL–RM–929–8900–M11, 1–4, 1961.

[1379] Sutton, W. H., "Apparatus for Measuring Thermal Conductivity of Ceramic and Metallic Materials to 1200 C," J. Am. Ceram. Soc., **43**(2), 81–6, 1960.

[1380] Suzuki, H., Kuwayama, N., and Yamauchi, T., "An Improved Apparatus for Measuring Thermal Conductivity of Highly Conductive Hard Ceramics," Yogyo Kyokai Shi, **64**, 161–6, 1956.

[1381] Svehla, R. A., "Estimated Viscosities and Thermal Conductivities of Gases at High Temperatures," NASA–TR–R–132, 1–140, 1962.

[1382] Swift, D. L., "The Thermal Conductivity of Spherical Metal Powders Including the Effect of an Oxide Coating," Int. J. Heat Mass Transfer, **9**(10), 1061–74, 1966.

[1383] Sybert, J. R., "Transport Phenomena in a Single Crystal of Bismuth at Liquid Helium Temperatures," Louisiana State Univ., Ph.D. Thesis, Univ. Microfilms Publ. 62–63, 119 pp., 1961.

[1384] Taga, M., "A Method of Measuring Thermal Conductivity by Revolving Ring," Bull. JSME, **3**(11), 346–52, 1960.

[1385] Tainsh, R. J., and White, G. K., "Resistivity of Ruthenium," Can. J. Phys., **42**(1), 208–9, 1964.

[1386] Talley, C. P., "Thermal Conductivity of Polycrystalline Boron," J. Phys. Chem., **63**, 311, 1959.

[1387] Tamarin, P. V., Chuprikov, G. E., and Shalyt, S. S., "Investigation of the Phenomena of Charge and Heat Transfer in Yttrium Single Crystals at Low Temperatures," Zh. Eksp i Teor. Fiz., **55**(5), 1595–7, 1968; English translation: Sov. Phys.-JETP, **28**(5), 836–7, 1969.

[1388] Taylor, G., and Christian, J. W., "The Effect of High-Vacuum Purification on the Mechanical Properties of Niobium Single Crystals," Acta Met., **13**, 1217, 1965.

[1389] Taylor, R., "An Investigation of the Heat-Pulse Method for Measuring Thermal Diffusivity," Brit. J. Appl. Phys., **16**, 509–15, 1965.

[1390] Taylor, R., "The Thermal Conductivity of Pyrolytic Graphite," Phil. Mag., 8, **13**(121), 157–66, 1966.

[1391] Taylor, J. B., Bennett, S. L., and Heyding, R. D., "Physical Properties of α and γ Arsenic," J. Phys. Chem. Solids, **26**(1), 69–74, 1965.

[1392] Taylor, R., Gilchrist, K. E., and Poston, L. J., "Thermal Conductivity of Polycrystalline Graphite," NASA N68–10943, 1–14, 1967.

[1393] Taylor, R., Kelly, B. T., and Gilchrist, K. E., "The Thermal Conductivity of Fast Neutron Irradiated Graphite," UKAEA TRG Rept. 1602(c), 1–34, 1968.

[1394] Taylor, R., Kelly, B. T., and Gilchrist, K. E., "The Thermal Conductivity of Fast Neutron Irradiated Graphite," J. Phys. Chem. Solids, **30**, 2251–67, 1969.

[1395] Taylor, R. E., "A High Temperature Thermal Conductivity Apparatus," Atomics International, Canoga Park, Calif., USAF ASD–TDR–62–348, 1–22, 1962. [AD 275 417]

[1396] Taylor, R. E., Davis, F. E., Powell, R. W., and Kimbrough, W. D., "Determination of Thermal and Electrical Conductivity, Emittance and Thomson Coefficient at High Temperatures by Direct Heating Methods," Progr. Rept., TPRC, Purdue Univ., AFML–TR–69–39–277, 1–90, 1969. [AD 697 761]

[1397] Taylor, T. S., "Thermal Conductivity of Insulating Materials," Mech. Engineering, **42**, 8–10, 1920.

[1398] Tepper, F., Murchison, A., Zelenak, J., and Roehlich, F., "Thermophysical Properties of Rubidium and Cesium.

Quarterly Progress Rept. No. 7, July–Sept. 63," MSA Res. Corp., Callery, Pa., USAF, 1–18, 1963. [AD 442 718]

[1399] Tepper, F., Murchison, A., Zelenak, J. S., and Roehlich, F., "Thermophysical Properties of Rubidium and Cesium," MSA Res. Corp., Callery, Pa., USAF ML–TDR–64–42, 1–64, 1964. [AD 448 772]

[1400] Tepper, F., and Roehlich, F., "Thermophysical and Transport Properties of Liquid Metals," AFML–TR–66–206, 1–67, 1966. [AD 487 987L]

[1401] Tepper, F., Zelenak, J., Roehlich, F., and May, V., "Thermophysical and Transport Properties of Liquid Metals," AFML–TR–65–99, 1–103, 1965. [AD 464 138]

[1402] Tewfik, O. E., Eckert, E. R. G., and Jurewicz, L. S., "Measurement of Heat Transfer from a Circular Cylinder to an Axial Stream with Air Injection into a Turbulent Boundary Layer," Minnesota Univ. Heat Transfer Lab., HTL–TR–38, 1–57, 1961. [AD 266 568]

[1403] Thielke, N. R. (compiler), "Thermoelectric Materials. Bimonthly Progress Rept. No. 1. 28 Jan.–28 Mar. 59," National Carbon Co., Parma, Ohio, 1–29, 1959. [AD 220 537]

[1404] Thielke, N. R. (compiler), "Thermoelectric Materials. Bimonthly Progress Rept. No. 3, 28 May 59–28 July 59," National Carbon Co., Parma, Ohio, 1–35, 1959. [AD 231 571]

[1405] Thomas, L. B., and Golike, R. C., "A Comparative Study of Accommodation Coefficient by the Temperature-Jump and Low-Pressure Methods and Thermal Conductivity of Helium, Neon, and Carbon Dioxide," J. Chem. Phys., **22**, 300–5, 1954.

[1406] Thomlinson, W. C., "Evidence for Anomalous Phonon Excitation in Solid He^3," Phys. Rev. Letters, **23**(23), 1330–2, 1969.

[1407] Thompson, J. C., and McDonald, W. J., Jr., "Low Temperature Thermal Conductivity of Boron," Phys. Rev., **132**(1), 82–4, 1963.

[1408] Thompson, J. C., and Younglove, B. A., "Thermal Conductivity of Silicon at Low Temperatures," Phys. and Chem. Solids, **20**, 146–9, 1961.

[1409] Timchenko, I. N., and Shalyt, S. S., "Thermoelectric Properties of Tellurium at Low Temperatures," Fiz. Tverd. Tela, **4**(4), 934–45, 1962; English translation: Sov. Phys.-Solid State, **4**(4), 685–92, 1962.

[1410] Timrot, D. L., and Peletskii, V. E., "Use of Heating by Electron Bombardment to Investigate the Coefficient of Heat Conductivity in High-Melting-Point Alloys and Compounds," Teplofiz. Vys. Temp., **1**(2), 168–72, 1963; English translation: High Temp. USSR, **1**(2), 147–51, 1963.

[1411] Timrot, D. L., and Peletskii, V. E., "The Thermal Conductivity and Integral Blackness of Zirconium," Teplofiz. Vys. Temp., **3**(2), 223–7, 1965; English translation: High Temp., **3**(2), 199–202, 1965.

[1412] Timrot, D. L., Peletskii, V. E., and Voskresenskii, V. Yu., "Thermal Conductivity and Degree of Blackness of Iodide Hafnium," Teplofiz. Vys. Temp., **4**(6), 874–5, 1966; English translation: High Temp., **4**(6), 808–9, 1966.

[1413] Timrot, D. L., Peletskii, V. E., and Voskresenskii, V. Yu., "Experimental Investigation of Integral Hemispherical Degree of Blackness, Electrical Conductivity, and Coefficient of Thermal Conductivity of a Series of Refractory Metals in the Temperature Range 1300–3000 K," Symposium on M. G. D., in Salzburg, 1966, in press (private communication from Prof. A. E. Sheindlin, Feb. 13, 1967).

[1414] Timrot, D. L., and Totskii, E. E., "Experimental Studies of Thermal Conductivity of Sodium and K Vapors as a Function of the Temperature and Pressure," Teplofiz. Vys. Temp., **5**, 793–801, 1967; English translation: High Temp., **5**(5), 708–14, 1967.

[1415] Todd, G. W., "Thermal Conductivity of Air and Other Gases," Proc. Roy. Soc. (London), **A83**, 19–39, 1909.

[1416] Todd, G. W., "A Method of Comparing the Thermal Conductivities of Metal Rods," J. Sci. Instrum., **4**(4), 97–99, 1927.

[1417] Tödheide, K., Hensel, F., and Franck, E. U., "Thermal Conductivity of Gases," *Eigenschaften der Materie in Ihren Aggregatzuständen. Transport phonomene II. Kinetik Homogene gosgleichge wichte (Landolt-Bornstein)*, Springer-Verlag, **5**(6), 39–71 and 385–92, 1968.

[1418] Tottle, C. R., "The Physical and Mechanical Properties of Niobium," J. Inst. Metals, **85**, 375–8, 1957.

[1419] Touloukian, Y. S. (Editor), *Thermophysical Properties of High Temperature Solid Materials, Vol. 1: Elements*, MacMillan Co., New York, 1270 pp., 1967.

[1420] Touloukian, Y. S., Liley, P. E., and Saxena, S. C., *Thermal Conductivity—Nonmetallic Liquids and Gases*, Vol. 3 of *Thermophysical Properties of Matter—The TPRC Data Series*, IFI/Plenum Data Corp., New York, 707 pp., 1970.

[1421] Touloukian, Y. S., Powell, R. W., Ho, C. Y., and Klemens, P. G., *Thermal Conductivity—Metallic Elements and Alloys*, Vol. 1 of *Thermophysical Properties of Matter—The TPRC Data Series*, IFI/Plenum Data Corp., New York, 1595 pp., 1970.

[1422] Touloukian, Y. S., Powell, R. W., Ho, C. Y., and Klemens, P. G., *Thermal Conductivity—Nonmetallic Solids*, Vol. 2 of *Thermophysical Properties of Matter—The TPRC Data Series*, IFI/Plenum Data Corp., New York, 1302 pp., 1970.

[1423] Toxen, A. M., "Thermal Conductivity of Alloys of Germanium with Silicon," Univ. Microfilms Publ. 59–1007, 1–100, 1958.

[1424] Toxen, A. M., Chang, G. K., and Jones, R. E., "Thermal Conductivity of Dilute Indium-Mercury Alloys," Phys. Rev., **126**, 919–22, 1962.

[1425] Toy, S. M., and Vetrano, J. B., "Properties of Zirconium Hydride and Zirconium-Uranium Alloy Hydrides," NAA–SR–4244 DEL, 1–18, 1960.

[1426] Treco, R. M., "Some Properties of High-Purity Zirconium and Dilute Alloys with Oxygen," USAEC, MIT–1056, 1–39, 1950.

[1427] Treco, R. M., "Some Properties of High-Purity Zirconium and Dilute Alloys with Oxygen," Trans. Am. Soc. Metals, **45**, 872–92, 1953.

[1428] Tsederberg, N. V., "Thermal Conductivity of Compressed Gases," Teploenergetica, **4**(1), 45–8, 1957.

[1429] Tsederberg, N. V., "Thermal Conductivity of Gases and Liquids," MIT Press, 246 pp., 1965.

[1430] Tsederberg, N. V., Popov, V. N., and Morozova, V. A., "Thermodynamic and Thermophysical Properties of Helium," Atomizdat, Moscow, 1969, and Dept. of Commerce USA translation, TT–70–50096, 255 pp., 1971.

[1431] Tsederberg, N. V., and Timrot, D. L., "Experimental Determination of the Thermal Conductivity of Liquid Oxygen," Zh. Tekhn. Fiz., **26**, 1849–56, 1956; English translation: Sov. Phys.-Tech. Phys., **1**, 1791–7, 1957.

[1432] Tseng, T. P., "Properties of Matter at Very Low Temperatures," Ohio State Univ., Ph.D. Dissertation, Univ. Microfilms 59–6644, 124 pp., 1960.

[1433] Turnbull, A. G., "Thermal Conductivity of Molten Salts and Other Liquids," Imperial College of Science and Tech. (London), Ph.D. Thesis, 146 pp., 1959.

[1434] Turnbull, A. G., "Thermal Conductivity of Liquid and Solid α-Phosphorus," Z. Phys. Chem. (Frankfort), **42**(3/4), 243–6, 1964.

[1435] Turner, J. H., and Carter, M. B., "Research and Development on Advanced Graphite Materials. Vol. XXXIII.

Investigation of hot-worked Recrystallized Graphites," WADD–TR–61–72, 1–59, 1964. [AD 604 683]

[1436] Tyagi, R. C., and Mathur, R. S., "A Method of Measuring High-Temperature Thermal Conductivity of Metals," J. Phys. D. (Applied Phys.), **3**(2), 1338, 1970.

[1437] Tye, R. P., "Preliminary Measurements of the Thermal and Electrical Conductivities of Molybdenum, Niobium, Tantalum, and Tungsten," J. Less-Common Metals, **3**(1), 13–18, 1961.

[1438] Tye, R. P., "Thermophysical Properties of Hot Pressed Beryllium," Dynatech. Rept. 796, NASA–CR–96217, 1–33, 1968.

[1439] Tye, R. P., and Quinn, J. E., "Thermal Conductivity of Hot Pressed Beryllium Block," in *Proceedings of the 4th Symposium on Thermophysical Properties*, (Moszynski, J. R., Editor), April 1–4, 1968, Univ. Maryland, 144–9, 1968.

[1440] Tye, R. P., and Woodman, M. J., "Thermal Conductivity of Compacted Powder Carbons and Mixtures of Carbon Powders with Uranium Carbide Particles," Carbon, **4**(2), 167–76, 1966.

[1441] Tyler, W. W., and Wilson, A. C., Jr., "Measurements of Thermal Conductivity, Electrical Resistivity, and Thermoelectric Power of Graphite," USAEC Rept. KAPL–789, 1–44, 1952.

[1442] Tyler, W. W., and Wilson, A. C., Jr., "Thermal Conductivity, Electrical Resistivity, and Thermoelectric Power of Graphite," USAEC Rept. KAPL–789, 1–44, 1952.

[1443] Tyler, W. W., and Wilson, A. C., Jr., "Thermal Conductivity, Electrical Resistivity, and Thermoelectric Power of Graphite," Phys. Rev., **89**(4), 870–5, 1953.

[1444] Tyler, W. W., Wilson, A. C., Jr., and Wolga, G. J., "Thermal Conductivity, Electrical Resistivity, and Thermoelectric Power of Uranium," USAEC Rept. KAPL–802, 1–25, 1952.

[1445] Ubbink, J. B., "Thermal Conductivity of Gaseous Hydrogen and of Gaseous Deuterium," Physica, **14**, 165–74, 1948.

[1446] Ubbink, J. B., and deHaas, W. J., "Thermal Conductivity of Gaseous He," Physica, **10**, 465–70, 1943.

[1447] Uhlir, A., Jr., "Thermal Conductivity of Fluid Argon and Nitrogen," J. Chem. Phys., **20**, 463–72, 1952.

[1448] Umanskii, A. S., and Timrot, D. L., "Measurement of the Thermal Conductivity of Krypton Up to 2000 K," in *Proceedings of the Eighth Conference on Thermal Conductivity,* Plenum Press, New York, 151–7, 1969.

[1448a] Umeda, K., and Yamamoto, T., "Kroll's Expression for the Heat Resistance of the Monovalent Metals," J. Fac. Sci. Hokkaido Univ., 2, **3**, 249–54, 1949.

[1449] Union Carbide Corp., "Research and Development Program for Fabrication and Testing 103 in. Diameter Grade CFW Graphite," 1–70, 1964. [AD 460 423]

[1450] Union Carbide Corp., "Research Program to Obtain Comprehensive Design Criteria for Grade CFW Graphite," USAF, 1–34, 1964. [AD 448 242]

[1451] Union Carbide Corp., *The Industrial Graphite Engineering Handbook,* Union Carbide Corp., Carbon Products Div., 1965.

[1452] Unvala, B. A., and Goel, T. C., "Thermal Conductivity, Electrical Resistivity, and Total Emittance of Titanium at High Temperatures," Rev. Int. Hautes Tempér. et Réfract., **7**(4), 341–5, 1970.

[1453] van Baarle, C., and Huebener, R. P., "Lattice Heat Conductivity in Annealed and Quenched Gold-Platinum Alloys," Phys. Rev., **172**(3), 699–704, 1968.

[1454] van Baarle, C., Roest, G. J., Roest-Young, M. K., and Gorter, F. W., "Thermal Conductivity and Thermopower of Silver and Silver-Base Alloys at Low Temperatures," Physica, **32**(10), 1700–8, 1966.

[1455] van Cleave, A. B., and Maass, O., "The Thermal Conductivity of Deuterium," Can. J. Research, **12**, 372–6, 1935.

[1456] van der Hoeven, B. J. C., and Keesom, P. H., "Specific Heat of Various Graphites Between 0.4 and 2.0 K," Phys. Rev., **130**(4), 1318–21, 1963.

[1457] Vanderslice, J. T., Weissman, S., Mason, E. A., and Fallon, R. J., "High-Temperature Transport Properties of Dissociating Hydrogen," Phys. Fluids, **5**, 155–64, 1962.

[1458] van de Velde, J., Ockfen, H., and Noek, T., "An Apparatus to Measure the Thermal Conductivity of Graphite Near Room Temperature," USAEC n–68–24359, EUR–3909.e, 1–20, 1968.

[1459] Vandevyver, M., "Study of the Effect of Neutron and Electron Irradiations on the Low Temperature Thermal Conductivity of Germanium and Silicon," Univ. Paris, Ph.D. Thesis, AEC–N–68–37136, CEA–R–3387, 74 pp., 1968.

[1460] Vandevyver, M., and Albany, H. J., "Thermal Conductivity at Low Temperature of Germanium and Silicon Irradiated by Fast Neutrons," Phys. Letters (Netherlands), **19**(5), 376–8, 1965.

[1461] Vandevyver, M., and Albany, H. J., "Diffusion of Phonons at Low Temperatures in Irradiated Silicon," Phys. Letters (Netherlands), **25A**(2), 115–7, 1967.

[1462] Vandevyver, M., Roubeau, P., and Albany, H. J., "Cryostat with Adjustable Temperature Between 4 and 300 K and Measurement of the Thermal Conductivity," Revue Phys. Appl., **1**(1), 25–31, 1966.

[1463] van Dusen, M. S., "A Simple Apparatus for Comparing the Thermal Conductivity of Metals and Very Thin Specimens of Poor Conductors," J. Opt. Soc. Am., **6**, 739–43, 1922.

[1464] van Dusen, J. S., and Shelton, S. M., "Apparatus for Measuring Thermal Conductivity of Metals Up to 600 C," J. Research Nat. Bur. Stand., **12**, 429–40, 1934.

[1465] van Sant, J. H., "An Apparatus for Measuring the Thermal Conductivity of Graphite at Temperatures Above 2000 F," General Atomic Div., General Dynamics Corp., San Diego, Calif., USAEC Rept. GAMD–2089, 1–21, 1961.

[1466] van Torne, L.I., "The Electrical Transport and Mechanical Properties of Ta-Mo Alloy Single Crystals," Univ. of Calif. (Berkeley), Ph.D. Thesis, 1965; also USAEC Rept. UCRL–11752, 1965.

[1467] van Witzenburg, W., and Laubitz, M.J., "Magnetoresistances and the Phonon Conductivity of Metals," Can. J. Phys., **46**(17), 1887–94, 1968.

[1468] Vardi, J., and Lemlich, R., "Radiation from and Conduction within a Finite Cylinder with a Distributed Electromagnetic Heat Source," Chem. Eng. Prog. Symp. Series, **64**(82), 255–68, 1968.

[1469] Vargaftik, N. B., "The Dependence of the Coefficient of Thermal Conductivity of Gases on the Pressure," Tech. Phys. (USSR), **4**, 341–60, 1937.

[1470] Vargaftik, N. B., "Thermal Conductivity of Steam," in Proc. Fifth Intern. Properties Steam (London, 1955), 12 pp., 1955.

[1471] Vargaftik, N. B., *Handbook of Thermophysical Properties of Substances,* Moscow and Leningrad, 1–368, 1956.

[1472] Vargaftik, N. B., "Thermophysical Properties of Substances," (English translation of *Teplofizicheskiye Svoystvo Veshchestv,* Gosudarstvennoe Energeticheskoe Izdatel'stvo, Moscow/Leningrad, 368 pp., 1956); F–TS–9537/V, 485 pp., 1959. [AD 709 136]

[1473] Vargaftik, N. B., *Handbook of Thermophysical Properties of Gases and Liquids* (in Russian), Gosudarst. Izdatel. Fiz. Mat. i Lit., Moscow, 1–708, 1963.

[1474] Vargaftik, N. B., Filippov, L. P., Tarzimanov, A. A., and Yurchak, R. P., "Thermal Conductivity of Gases and

Liquids," Governmental Service of Standards and References, Moscow, USSR, 155 pp., 1970.

[1475] Vargaftik, N. B., and Smirnova, E. V., "Temperature Dependence of the Thermal Conductivity of Water Vapor," Zh. Tekhn. Fiz., **26**, 1251–61, 1956; English translation: Sov. Phys.-Tech. Phys., **1**, 1221–31, 1957.

[1476] Vargaftik, N. B., and Voshchinin, A., "Experimental Studies of the Thermal Conductivity of Sodium and Potassium as Vapors," Teplofiz. Vys. Temp., **5**(5), 802–11, 1967; English translation: High Temp., **5**(5), 715–22, 1967.

[1477] Vargaftik, N. B., and Yakush, L. V., "Experimental Investigation of the Thermal Conductivity of Neon, Krypton and Xenon," in *Thermophysical Properties of Gases*, (N. B. Vargarftik, Editor), Nauka, Moscow, 216 pp., 1970.

[1478] Vargaftik, N. B., and Zimina, N. Kh., "Heat Conductivity of Argon at High Temperatures," Teplofiz. Vysok. Temp., **2**(5), 716–24, 1964; English translation: High Temp., **2**(5), 645–51, 1964.

[1479] Vargaftik, N. B., and Zimina, N. Kh., "Thermal Conductivity of Nitrogen at High Temperatures," Teplofiz. Vys. Temp., **2**, 869–78, 1964; English translation: High Temp., **2**, 782–90, 1964.

[1480] Vargaftik, N. B., and Zimina, N. Kh., "Thermal Conductivity of Helium at 0–1000 Degrees and 1–200 Atmospheres," At. Energy (USSR), **19**(3), 300–3, 1965; English translation: Sov. J. At. Energy, **19**(3), 1221–5, 1965.

[1481] Vasserman, A. A., and Rabinovich, V. A., *Thermophysical Properties of Liquified Air and its Components*, (English translation of *Teplofizicheskie Svoistva Zhidkogo Vozdukha i ego Komponentov*., 239 pp., 1968); TT–69–55092, 235 pp., 1970.

[1482] Veliev, M. I., Kerimov, I. G., Aliev, G. M., and Aliev, M. I., "Effect of Crystallization on Thermal Conductivity of Selenium," Izv. Akad. Nauk Azerb. SSR, 4, 33–6, 1963.

[1483] Vel'tischeva, V. A., Kalakutskaya, N. A., and Nikol'skii, N. A., "The Heat Conductivity of Mercury," Teploenergetika, **10**, 80–2, 1958.

[1484] Vernotte, P., "Apparatus for Measuring the Thermal Conductivity of Metals in the Form of Wire or Ribbons," Chimie and Industrie Special No., 393–6, 1932.

[1485] Vianey, L. R., "Thermal Conductivity of 347 Stainless Steel and Zirconium," PB 123–175, 1–6, 1951. [AD 140 931]

[1486] Vines, R. G., "Measurement of the Thermal Conductivity of Gases at High Temperatures," Trans. ASME, **82**, 48–52, 1960.

[1487] Voigt, W., *Lehrbuch der Kristallphysik*, Teubner, Leipzig, 959 pp., 1928.

[1488] von Lohberg, K., and Motz, J., "Conductivities of Some Ferrous Alloys," Giesserei, **44**, 305–8, 1957.

[1489] von Rudiger, O., and Dietze, H. D., "Measurement of Thermal Conductivity According to Diesselhorst," Tech. Mitt, Krupp., **13**(3), 56–61, 1955; English translation: TT–67–59052, 1–18, 1967.

[1490] von Ubisch, H., "Conduction of Heat in Rarified Gases and Its Manometric Application," Appl. Sci. Res., **A2**, 364–402, 1951.

[1490a] von Ubisch, H., "The Thermal Conductivity of Mixtures of Rare Gases at 29 C and at 520 C," Arkiv. Fysik., **16**, 93–100, 1959.

[1491] Vook, F. L., "Thermal Conductivity of Electron-Irradiated Germanium," Phys. Rev., **A138**(4), 1234–41, 1965.

[1492] Vook, F. L., "Thermal Conductivity of Electron Irradiated Silicon," Phys. Rev., **A140**(6), 2014–19, 1965.

[1493] Voskresenskii, V. Yu., Peletskii, V. E., and Timrot, D. L., "Thermal Conductivity and Emissivity of Niobium," Teplofiz. Vys. Temp., **4**(1), 46–9, 1966; High Temp., **4**(1), 39–42, 1966.

[1494] Wachsmuth, J., "About Heat Conduction in Mixtures of Argon and Helium," Physik Z., **9**, 235, 1908.

[1495] Wagner, P., and Dauelsberg, L. B., "Thermal Conductivity of ZTA Graphite," in *Proceedings of the Sixth Conference on Thermal Conductivity*, Wright-Patterson AFB, LA–DC–8163, N67–17568, Conf. 661013–1, 1–20, 1966.

[1496] Wagner, P., and Dauelsberg, L. B., "Thermal Conductivity of SX–5 Graphite," Carbon (Oxford), **6**(3), 373–80, 1968.

[1497] Wagner, P., and Dauelsberg, L. B., "Some Thermal Properties of a Poly(furfuryl alcohol)-Bonded Graphite," Carbon (Oxford), **7**(2), 273–8, 1969.

[1498] Wagner, P., Driesner, A. R., and Kmetko, E. A., "Some Mechanical Properties of Graphite in the Temperature Range 20 to 3000 C. Second U.N. Intern. Conf. on the Peaceful Uses of Atomic Energy," OTS A–Conf–15–P–702, 1–28, 1958.

[1499] Waldmann, L. (Edited by Flügge, S.), "Transport Phenomena in Gases at Medium Pressure," *Handbuch der Physik*, Springer-Verlag, Berlin, **12**, 295–507, 1958.

[1500] Waldron, M. B., Garstone, J., Lee, J. A., Mardon, P. G., Marples, J. A. C., Poole, D. M., and Williamson, G. K., "Physical Metallurgy of Plutonium," from *Basic Metallurgy and Fabrication of Fuels*, in Proceedings of the Second United Nations Intern. Conf. on Peaceful Uses of At. Energy, (U.N. Geneva, Switzerland), **6**, 162–9, 1958.

[1501] Walton, A. J., "The Thermal and Electric Resistance of Tin in the Intermediate State," Proc. Roy. Soc. (London), **A289**(1418), 377–401, 1966.

[1502] Wassiljewa, A., "Conduction of Heat in Gas Mixtures. I. Theory of Heat Conduction in Application to Gas Mixtures," Physik. Z., **5**, 737–42, 1904.

[1503] Waterman, T. E., "Thermodynamic and Transport Properties of Gases, Liquids, and Solids. Thermal Conductivity of Liquid Ozone," in *Proceedings of the Symposium on Thermal Properties*, ASME, 301–3, 1959.

[1504] Waterman, T.E., Kirsh, D.P., and Brabets, R.I., "Thermal Conductivity of Liquid Ozone," J. Chem. Phys., **29**, 905–8, 1958.

[1505] Watson, J. H. P., "The Thermal Conductivity of Lead and Mercury Close to Their Superconducting Transition Temperatures," Toronto Univ. of Toronto, 1–99, 1963.

[1506] Watson, J. H. P., and Graham, G. M., "Thermal Conductivity of Pb and Hg Near T_c," Can. J. Phys., **41**(10), 1738–43, 1963.

[1507] Watson, T. W., Flynn, D. R., and Robinson, H. E., "Thermal Conductivity and Electrical Resistivity of Armco Iron," J. Res. Natl. Bur. Stand., **71**(4), 285–91, 1967.

[1508] Watson, T. W., and Robinson, H. E., "Thermal Conductivity of a Specimen of Electroformed Nickel," Natl. Bur. Stand. 8345, 1–12, 1964.

[1509] Weatherford, W. D., Jr., Tyler, J. C., and Ku, P. M., "Properties of Inorganic Energy-Conversion and Heat-Transfer Fluids for Space Applications," WADC–TR–61–96, 1–470, 1961. [AD 267 541]

[1510] Webber, H. A., Goldstein, D., and Fellinger, R. C., "Determination of the Thermal Conductivity of Molten Lithium," Trans. Am. Soc. Mech. Engrs., **77**, 97–102, 1955.

[1511] Webber, R. T., and Spohr, D. A., "Thermal Conductivity of Superconducting Lead in the Intermediate State," Phys. Rev., **84**, 384–5, 1951.

[1512] Webber, R. T., and Spohr, D. A., "Thermal Conductivities of Pure Metals at Low Temperatures. Mercury," Phys. Rev., **106**, 927–33, 1957.

[1513] Weber, H. F., "VII. Investigation of Heat Conduction in Liquids," Ann. Physik, **10**(3), 472–500, 1880.

[1514] Weber, R., "Heat Conduction in Liquids," Ann. Physik, 4, **11**, 1047–70, 1903.

[1515] Weber, S., "Investigation on the Thermal Conductivity of Gases. II," Ann. Physik, **54**(4), 437–62, 1917.

[1516] Weber, S., "The Method of Martin Knudsen for Determining Relationships of Thermal and Electrical Conductivity of Metals Including Some Physical Constants of Tungsten," Ann. Physik, **54**, 165–81, 1917.

[1517] Weber, S., "Theoretical and Experimental Investigations of the Thermal Conductivity of Gas Mixtures," Ann. Physik, **54**, 325–56 and 481–502, 1917.

[1517a] Weber, S., "Investigations of the Thermal Conductivity of Gases. II," Ann. Physik, 4, **54**(22), 437–62, 1917.

[1518] Weber, S., "The Thermal Conductivity of Neon," Commun. Kamerlingh Onnes Lab., Univ. Leiden, **14**, Suppl. 42B, 23–41, 1919.

[1519] Reference withdrawn.

[1520] Wechsler, A. E., "Development of High Temperature Thermal Conductivity Standards," Wright-Patterson AFB, Ohio, AFML-TR-66-415, N67-38507, 1–143, 1967. [AD 657 024]

[1521] Weeks, C. C., and Nakata, M. M., "Development of High Temperature Thermal Conductivity Standards," AFML-TR-69-2, N69-39266, 1–372, 1969. [AD 689 851]

[1522] Weeks, J. L., "Thermal Conductivity of Uranium and Several Uranium Alloys," J. Metals (Trans. AIME 203), **7**, 192, 1955.

[1523] Weeks, J. L., and Seifert, R. L., "The Thermal Conductivity of Synthetic Sapphire," J. Am. Ceram. Soc., **35**(1), 15, 1952.

[1524] Weeks, J. L., and Seifert, R. L., "Apparatus for the Measurement of the Thermal Conductivity of Solids," USAEC Publ. ANL-4938, 1–14, 1952.

[1525] Weeks, J. L., and Seifert, R. L., "Apparatus for the Measurement of the Thermal Conductivity of Solids," Rev. Sci. Instr., **24**(10), 1054–7, 1953.

[1526] Weeks, J. L., and Smith, K. F., "Thermal Conductivity of Vanadium and Certain Vanadium Alloys," Trans. AIMME, **203**, 1010, 1955.

[1527] Weeks, J. L., and Smith, K. F., "Thermal Conductivity of Vanadium and Certain Vanadium Alloys," J. Metals, **7**, 1010, 1955.

[1528] Weill, G., "Apparatus for the Measurement of Thermal Conductivity of Semiconductors. I. Generalities; Methods of Fluxmeters," J. Phys. Radium, **23**(3), 15a–20a, 1962.

[1529] Westenberg, A. A., and deHaas, N., "Gas-Thermal Conductivity Studies at High Temperatures; Line-Source Technique and Results for N_2, CO_2, N_2-CO_2 Mixtures," Phys. Fluids, **5**, 266–73, 1962.

[1530] Westenberg, A. A., and deHaas, N., "Gas Thermal Conductivity Studies at High Temperatures. II. Results for O_2 and O_2-H_2O Mixtures," Phys. Fluids, **6**, 617–20, 1963.

[1531] Westphal, R. L., "Thermal Conductivity of Reactor Fuel Element Materials," USAEC, WAPD-MM-538, 1–4, 1954.

[1532] Wheeler, H. L., Jr., "A Study of the Temperature Drop Across a Sweat-Cooled Wall. Progress Rept.," Jet Propulsion Lab., Calif. Inst. of Tech., JPL-PR-4-71, 1–12, 1948.

[1533] Wheeler, M. J., "Thermal Diffusivity at Incandescent Temperatures by a Modulated Electron Beam Technique," Brit. J. Appl. Phys., **16**(3), 365–76, 1965.

[1534] Wheeler, M. J., "Thermal Diffusivity Measurement by the Modulated Electron Beam Method. Thermal Diffusivity of Iron between 280 C and 1100 C," High Temp.—High Pressures, **1**(1), 13–20, 1969.

[1535] White, D., Gonzales, O. D., and Johnston, H. L., "Heat Conduction of the Boundary Layer in Liquid Helium-II," Phys. Rev., **89**, 593–4, 1953.

[1536] White, G. K., "The Thermal Conductivity of Gold at Low Temperatures," Proc. Phys. Soc. (London), **A66**, 559–64, 1953.

[1537] White, G. K., "Thermal Conductivity of Silver at Low Temperatures," Proc. Phys. Soc. (London), **A66**, 844–5, 1953.

[1538] White, G. K., "The Thermal and Electrical Conductivity of Copper at Low Temperatures," Austral. J. Phys., **6**, 397–404, 1953.

[1539] White, G. K., Private communication, CSRIO, National Standards Laboratory, Australia, 1965.

[1540] White, G. K., and Tainsh, R. J., "Lorenz Number for High-Purity Copper," Phys. Rev., **119**, 1869–71, 1960.

[1541] White, G. K., and Tainsh, R. J., "Electron Scattering in Nickel at Low Temperatures," Phys. Rev. Lett. **19**(4), 165–6, 1967.

[1542] White, G. K., and Woods, S. B., "The Lattice Thermal Conductivity of Dilute Copper Alloys at Low Temperatures," Phil. Mag., **45**, 1343–5, 1954.

[1543] White, G. K., and Woods, S. B., "Thermal and Electrical Conductivities of Solids at Low Temperatures," Can. J. Phys., **33**, 58–73, 1955.

[1544] White, G. K., and Woods, S. B., "Thermal Conductivity of Germanium and Silicon at Low Temperatures," Phys. Rev., **103**, 569–71, 1956.

[1545] White, G. K., and Woods, S. B., "Thermal and Electrical Conductivity of Rhodium, Iridium, and Platinum," Can. J. Phys., **35**, 248–57, 1957.

[1546] White, G. K., and Woods, S. B., "Conductivity of Alpha-Manganese," Can. J. Phys., **35**, 346–8, 1957.

[1547] White, G. K., and Woods, S. B., "Low Temperature Resistivity of the Transition Elements. Cobalt, Tungsten, Rhenium," Can. J. Phys., **35**, 656–65, 1957.

[1548] White, G. K., and Woods, S. B., "Low Temperature Resistivity of Transition Elements, Vanadium, Niobium, and Hafnium," Can. J. Phys., **35**(8), 892–900, 1957.

[1549] White, G. K., and Woods, S. B., "Thermal and Electrical Resistivity at Low Temperatures," in Proc. Intern. Conf. on Low Temp. Phys. and Chem., (Wisconsin, 1957), 367–70, 1957.

[1550] White, G. K., and Woods, S. B., "Conductivity of Metallic Cryogenic Materials," in Proceedings of the Cryogenic Engineering Conference, 120–4, 1957.

[1551] White, G. K., and Woods, S. B., "The Thermal and Electrical Resistivity of Bismuth and Antimony at Low Temperatures," Phil. Mag., 8, **3**(28), 342–59, 1958.

[1552] White, G. K., and Woods, S. B., "Thermal Conductivity of the Solidified Inert Gases. Argon, Neon, and Krypton," Phil. Mag., **3**(32), 785–97, 1958.

[1553] White, G. K., and Woods, S. B., "Low Temperature Resistivity of the Transition Elements. Ruthenium and Osmium," Can. J. Phys., **36**, 875–83, 1958.

[1554] White, G. K., and Woods, S. B. "Electrical and Thermal Resistivity of the Transition Elements at Low Temperatures," Phil. Trans. Roy. Soc. (London), **A251**, 273–302, 1959.

[1555] White, G. K., Woods, S. B., and Elford, M. T., "Thermal Conductivity of Selenium at Low Temperatures," Phys. Rev., 2, **112**(1), 111–3, 1958.

[1556] White, J. L., and Koyama, K., "Graphite Materials Hot-Worked with a Dispersed Liquid Carbide: Thermal and Electrical Conductivity," J. Am. Ceram. Soc., **51**(7), 394–8, 1968.

[1556a] Wiedemann, G., and Franz, R., "The Thermal Conductivity of Metals," Ann. Physik, **89**, 497–531, 1853.

[1557] Wilkes, K. E., "Thermal Conductivity Measurements Between 77 K and 373 K on Iron, Cobalt, Aluminum, and Zinc," Purdue Univ., M.S. Thesis, 93 pp., 1968.

[1558] Wilkes, K. E., and Powell, R. W., "Thermal Conductivity of Aluminum between About 78 and 373 K," in *Thermal Conductivity—Proceedings of the Seventh Conference*, Gaithersburg, Maryland, 293–6, 1967.

[1559] Wilkes, K. E., Powell, R. W., and DeWitt, D. P., "Thermal Conductivity Measurements on Cobalt and Zinc between 78 and 373 K," in *Thermal Conductivity—Proceedings of the Eighth Conference* (Ho, C. Y., and Taylor, R. E., Editors), Purdue Univ., Plenum Press, N. Y., 3–7, 1968.

[1560] Wilkinson, K. R., and Wilks, J., "Some Measurements of Heat Flow Along Technical Materials in the Region 4 to 20 K," J. Sci, Instr. and Phys. in Industry, **26**, 19–20, 1949.

[1561] Wilks, J., "The Thermal Conductivity of Condensed Helium," Nuovo Cimento Supplemento, **9**, 84–94, 1958.

[1562] Williams, D. R., "The Thermal Conductivities of Several Metals: An Evaluation of a Method Employed by the NBS," Southern Methodist Univ., M.S. Thesis, NASA–CR–82479, N67–19030, 182 pp., 1966.

[1563] Williams, D. R., and Blum, H. A., "The Thermal Conductivities of Several Metals: An Evaluation of a Method Employed by the National Bureau of Standards," in *Thermal Conductivity—Proceedings of the Seventh Conference*, Gaithersburg, Maryland, 349–54, 1968.

[1564] Williams, H. M., and Bihlman, V. W., "Thermal Conductivity of Some Industrial Alloys," Trans. Am. Inst. Mining Met. Engrs., **69**, 1065–9, 1923.

[1565] Williams, R. K., and McElroy, D. L., "Estimated Thermal Conductivity Values for Solid and Liquid Promethium," USAEC ORNL–TM–1424, 1–34, 1966.

[1566] Williams, T. L., and Pate, J. L., "Automation of a Longitudinal Comparison Thermal Conductivity Apparatus," USAEC–Y–1607, 1–53, 1968.

[1567] Willott, W. B., "The Wiedemann-Franz Ratio and Anomalous Lattice Conductivity of Pure Aluminium," Phil. Mag., **16**(142), 691–702, 1967.

[1568] Wilson, A. H., "The Second Order Electrical Effects in Metals," Proc. Camb. Phil. Soc., **33**(2), 371–9, 1937.

[1569] Wilson, A. H., *The Theory of Metals*, 2nd Ed., Cambridge Univ. Press, 346 pp., 1953.

[1570] Winkelmann, A., "The Heat Conduction of Gases," Ann. Physik, **156**, 497–531, 1875.

[1571] Winkelmann, A., "On the Thermal Conduction of Gases," Wied. Ann., **44**, 429–56, 1891.

[1572] Wirth, H., and Klemenc, A., "The Thermal Conductivity of Gases at Low Pressure," Monatsh., **83**, 879–82, 1952.

[1573] Wold, P. I., "The Hall Effect and Allied Phenomena in Tellurium," Phys. Rev., **7**, 169–93, 1916.

[1574] Wolff, C. L., "Thermal Conductivity of Lead at Low Temperature," OOR Rept. No. 2771–2, 1–58, 1961. [AD 253 117]

[1575] Wood, W. A., "Transition from Hexagonal to Cubic Electrodeposited Chromium," Phil. Mag., 7, **24**(161), 511–8, 1937.

[1576] Woodall, N. D., Moore, J. P., and McElroy, D. L., "Physical Properties of Tungsten and Tungsten Alloys," NASA–N68–20428, 1–92, 1967.

[1577] Woolley, H. W., Scott, R. B., and Brickwedde, F. G., "Compilation of Thermal Properties of Hydrogen in its Various Isotopic and Ortho-Para Modifications," J. Res. Natl. Bur. Stand., **41**, 379–475, 1948.

[1578] Worth, K., "Techniques and Procedures for Evaluating Low-Permeability Graphite Properties for Reactor Application," USAEC GA–3559, 1–39, 1963.

[1579] Worthing, A. G., "The Thermal Conductivities of Tungsten, Tantalum, and Carbon at Incandescent Temperatures by an Optical Pyrometer Method," Phys. Rev., **4**, 535–43, 1914.

[1580] Wright, W. H., "Thermal Conductivity of Metals and Alloys at Low Temperatures, Part I. A Survey of Existing Data, Part II. The Thermal Conductivity of a Yellow Brass and of Cadmium," Georgia Institute of Technology. M.S. Thesis, 225 pp., 1960.

[1581] Wyder, P., "Mean Free Paths in the Normal and Superconducting States," Phys. Letters (Netherlands), **5**(5), 301–2, 1963.

[1582] Wyder, P., "Mean Free Paths in the Normal and the Superconducting State," Rev. Mod. Phys., **36**, 116–8, 1964.

[1583] Yaggee, F. L., and Untermyer, S., "The Relative Thermal Conductivities of Liquid Lithium, Sodium, and Eutectic NaK, and the Specific Heat of Liquid Lithium," USAEC ANL–4458, 1–27, 1950.

[1584] Yans, F. M., and Gardner, N. R., "Beryllium—The Metal and Its Design Potential," Electrical Manufacturing, **64**, 181–7, 1959.

[1585] Yim, W. M., and Stofko, E. J., "Preparation and Properties of Eutectic Bi-MnBi Single Crystals," J. Appl. Phys., **38**(13), 5211–6, 1967.

[1586] Yos, J. M., "Transport Properties of Nitrogen, Hydrogen, Oxygen, and Air to 30,000 K," AVCO Research and Advanced Development Div., Tech. Memo, RAD–TM–63–7, March 1963.

[1587] Yoshizawa, Y., Sugawara, A., and Yamada, E., "Thermal Conductivity of Alpha-Sulfur," J. Appl. Phys., **35**(4), 1354–5, 1964.

[1588] Yoshikawa, H. H., "High Temperature Radiation Effects in Lampblack-Based Graphites," Carbon (Oxford), **1**(2), 201–7, 1964.

[1589] Younglove, B. A., "Thermal Conductivity of Silicon at Low Temperatures," Univ. Texas, Austin, Ph.D. Thesis, Univ. Microfilms Publ. 61–1381, 59 pp., 1961.

[1590] Yun, K.-S., Weisman, S., et al., "High-Temperature Transport Properties of Dissociating Nitrogen and Dissociating Oxygen," Phys. Fluids, **5**, 672–7, 1962.

[1591] Yurchak, R. P., and Filippov, L. P., "Measuring the Thermal Diffusivity of Molten Metals," Teplofiz. Vys. Temp., **2**(5), 696–704, 1964; English translation: High Temp., **2**(5), 628–35, 1964.

[1592] Yurchak, R. P., and Filippov, L. P., "Thermal Properties of Liquid Tin and Lead," Teplofiz. Vys. Temp., **3**(2), 323–5, 1965; English translation: High Temp., **3**(2), 290–1, 1965.

[1593] Yurchak, R. P., and Smirnov, B. P., "Thermal Conductivity and Lorenz Number of Solid and Liquid Gallium," Fiz. Tverd. Tela, **10**(5), 1340–2, 1968: English translation: Sov. Phys.-Solid State, **10**(5), 1065–6, 1968.

[1594] Yurchak, R. P., and Smirnov, B. P., "Apparatus for Measuring the Thermal Conductivity of Conducting Materials," Zavod. Lab., **34**(2), 240–2, 1968.

[1595] Yurchak, R. P., and Smirnov, B. P., "Thermal Conductivity and Lorenz Number of Indium in the Solid and Liquid States," Teplofiz. Vys. Temp., **7**(1), 176–7, 1969; English translation: High Temp., **7**(1), 163–4, 1969.

[1596] Yurchak, R. P., Smirnov, B. P., and Kanevskaya, L. C., "Thermal Conductivity of Solid and Molten Tellurium," Fiz. i Tekh. Poluprov., **3**(7), 1092–5, 1969.

[1597] Zaitseva, L. S., "An Experimental Investigation of the Heat Conductivity of Monatomic Gases over Wide Temperature intervals," Zh. Tekhn. Fiz., **29**, 497–505, 1959: English translation: Sov. Phys.—Tech. Phys., **4**(4), 444–50, 1959.

[1598] Zavaritskii, N. V., "The Thermal Properties of Superconductors. I. Tin (to 0.15 K)," Zh. Eksp. i Teor. Fiz., **33**, 1085–98, 1957; English translation: Sov. Phys. JETP, **6**, 837–47, 1958.

[1599] Zavaritskii, N. V., "Investigation of Thermal Properties of Superconductors II," Zh. Eksp. i Teor. Fiz., **34**, 1116–24, 1958: English translation: Sov. Phys. JETP, **7**, 773–9, 1958.

[1600] Zavaritskii, N. V., "Investigation of the Thermal Properties of Superconductors. III. Anisotropy of the Thermal Conductivity of Gallium," Zh. Eksp. i Teor. Fiz., **37**, 1506–16, 1959; English translation: Sov. Phys.-JETP, **10**(6), 1069–76, 1960.

[1601] Zavaritskii, N. V., "Measurement of Heat Conductive Anisotropy of Zn and Cd in the Superconducting State," Zh. Eksp. i Teor. Fiz., **39**, 1193–7, 1960; English translation: Sov. Phys. JETP, **12**(5), 831–3, 1961.

[1602] Zavaritskii, N. V., "The Thermal Conductivity of High Purity Thallium and Tin," J. Exp. Theor. Phys. (USSR), **39**, 1571–7, 1960; English translation: Sov. Phys.—JETP, **12**(6), 1093–7, 1961.

[1603] Zavaritskii, N. V., "The Thermal Conductivity of Superconductors in the Intermediate State," Zh. Eksp. i Teoret. Fiz., **38**, 1673–84, 1960; English translation: Sov. Phys.—JETP, **11**(6), 1207–14, 1960.

[1604] Zavaritskii, N. V., "Concerning the Quantization of the Energy Levels of Electronic Excitations in the Immediate State of a Superconductor," Zh. Eksp. Teor. Fiz., Akad Nauk SSSR, **2**(4), 168–70, 1965; English translation: JETP Letters, **2**(4), 106–8, 1965.

[1605] Zavaritskii, N. V., and Zeldovich, A., "Thermal Conductivity of Technical Materials at Low Temperatures," Zh. Tekhn. Fiz., **26**, 2032–6, 1956; English translation: Sov. Phys.-Tech. Phys., **1**, 1970–4, 1956.

[1606] Zegler, S. T., and Nevitt, M. V., "Apparatus for Measuring the Thermal Conductivities of Metals," USAEC ANL–5611, 1–15, 1959.

[1607] Zegler, S. T., and Nevitt, M. V., "Structures and Properties of Uranium-Fissium Alloys," USAEC ANL–6116, 1–50, 1961.

[1608] Zeigarnik, V. A., Peletskii, V. E., and Tarabanov, A. S., "Thermal Conductivity of RV and N Graphites at 400–1400 Degrees," Khim. Tverd. Topl., No. 3, 144–5, 1968.

[1609] Zhuze, V. P., Golubkov, A. V., Goncharova, E. V., and Sergeeva, V. M., "Electrical Properties of Rare-Earth Monochalcogenides (Cerium Subgroup)," Fiz. Tverd. Tela, **6**, 257–67, 1964; English translation: Sov. Phys.-Solid State, **6**(1), 205–12, 1964.

[1610] Ziebland, H., "The Thermal Conductivity of N_2, O_2, and Ar in the Liquid and Gaseous State," Dechema Monograph, **32**, 74–82, 1959.

[1611] Ziebland, H., and Burton, J. T. A., "The Thermal Conductivity of Liquid and Gaseous Oxygen," Brit. J. Appl. Phys., **6**, 416–20, 1955.

[1612] Ziebland, H., and Burton, J. T. A., "The Thermal Conductivity of Nitrogen and Argon in the Liquid and Gaseous States," Brit. J. Appl. Phys., **9**, 52–9, 1958.

[1612a] Ziman, J. M., "The Electrical and Thermal Conductivities of Monovalent Metals," Proc. Roy. Soc. (London), **A226**, 436–54, 1954.

[1612b] Ziman, J. M., *Electrons and Phonons—The Theory of Transport Phenomena in Solids*, Oxford University Press, 554 pp., 1960.

[1613] Zimmerman, J. E., "Heat Conduction in Alloys and Semiconductors at Low Temperatures," Carnegie Inst. of Tech., Ph.D. Thesis, 54 pp., 1951.

[1614] Zimmerman, J. E., and Esterman, I., "Effect of Lattice Defects on the Thermal Conductivity of Certain Alloys at Low Temperatures," Bull. Intern. Inst. Refrig., Annexe, 35–42, 1952–1.

[1615] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Conductivity of Iron at High Temperatures," Fiz. Metal. i Metalloved., **26**(4), 743–5, 1968; English translation: Phys. Metals Metallog., **26** (4), 767–9, 1968.

[1616] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Conductivity and Thermal Diffusivity of Nickel at High Temperatures," Fiz. Metal. i Metalloved, **25**(6), 1137–9, 1968; English translation: Phys. Metal Metallog., **25**(6), 188–90, 1968.

[1617] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Thermal Conductivity of Titanium at Low Temperatures," Teplofiz. Vys. Temp., **6**(5), 927–8, 1968; English translation: High Temp., **6**(5), 888–90, 1968.

[1618] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Conductivity and Thermal Diffusivity of Platinum at High Temperatures," Fiz. Tverd. Tela, **10**(9), 2826–8, 1968; English translation: Sov. Phys.-Solid State, **10**(9), 2228–30, 1969.

[1619] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Thermal Conductivity of Palladium at High Temperatures," Fiz. Tverd. Tela, **11**(3), 834–6, 1969; English translation: Sov. Phys-Solid State, **11**(3), 685–7, 1970.

[1620] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Thermal Conductivity of Chromium at High Temperatures," Fiz. Tverd. Tela, **11**(7), 2012–14, 1969; English translation: Sov. Phys.-Solid State, **11**(7), 1623–5, 1970.

[1621] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Thermal Conductivity Palladium at High Temperatures," Fiz. Tverd. Tela, **11**(3), 834–6, 1969; English translation: Sov. Phys.-Solid State, **11**(3), 685–7, 1970.

[1622] Zinov'ev, V. E., Krentsis, R. P., and Gel'd, P. V., "Thermal Diffusivity and Thermal Conductivity of Vanadium at High Temperatures," Fiz. Tverd. Tela, **11**(10), 3045–8, 1969; English translation: Sov. Phys.-Solid State, **11**(10), 2475–7, 1970.

[1623] Zinov'ev, V. E., Krentsis, R. P., Petrova, L. N., and Gel'd, P. V., "Thermal Conductivity of Cobalt at High Temperatures," Fiz. Metal. i Metalloved, **26**(11), 60–5, 1968; English translation: Phys. Metals Metallog., **26** (1), 57–63, 1968.

[1624] Zolotukhin, G. E., "Investigation of the Heat Conductivity of Metals and Alloys at Thermal Equilibrium by Using an Arc-Type Discharge as Heat Source," Fiz. Metal. i Metalloved, **3**, 508–12, 1956.

[1625] Zwikker, C., "Physical Properties of Tungsten at High Temperatures," Arch. Neerl. Sci., **9**, 207–339, 1925.

[1626] Zwikker, C., "Physical Properties of Molybdenum at High Temperatures," Physica, **7**, 71–4, 1927.

☆U.S. GOVERNMENT PRINTING OFFICE: 1974 O—528-613

(Continuation of cumulative listing of reprints)

Reprints

13. The Surface Tension of Pure Liquid Compounds, *Joseph J. Jasper,* Vol. 1, No. 4, pp. 841-1009 (1972) $8.50
14. Microwave Spectra of Molecules of Astrophysical Interest, 1. Formaldehyde, Formanide, and Thioformaldehyde, *Donald R. Johnson, Frank J. Lovas, and William H. Kirchhoff,* Vol. 1, No. 4, pp. 1-10 (1972) $4.50
15. Osmotic Coefficients and Mean Activity Coefficients of Uni-univalent Electrolytes in Water at 25°C, *Walter J. Hamer and Yung Chi Wu, Vol. 1,* No. 4, pp. 1047-1099 (1972) $5.00
16. The Viscosity and Thermal Conductivity Coefficients of Gaseous and Liquid Fluorine, *H.J.M. Hanley and R. Prydz,* Vol. 1, No. 4, pp. 1101-1113 (1972). $3.00
17. Microwave Spectra of Molecules of Astrophysical Interest. II. Methylenimine, *William H. Kirchhoff, Donald R. Johnson, and Frank J. Lovas,* Vol. 2, No. 1, pp. 3-12 (1973) $3.00
18. Analysis of Specific Heat Data in the Critical Region of Magnetic Solids, *F.J. Cook,* Vol. 2, No. 1, pp. 11-24 (1973) $3.00
19. Evaluated Chemical Kinetic Rate Constants for Various Gas Phase Reactions, *Keith Schofield,* Vol. 2, No. 1, pp. 25-84 (1973) $5.00
20. Atomic Transition Probabilities for Forbidden Lines of the Iron Group Elements. (A Critical Data Compilation for Selected Lines), *M.W. Smith and W.L. Wiese,* Vol. 2, No. 1, pp. 85-120 (1973) $4.50
21. Tables of Molecular Vibrational Frequencies, Part 6, *T. Shimanouchi,* Vol. 2, No. 1, pp. 121-162 (1973) $4.50
22. Compilation of Energy Band Gaps in Elemental and Binary Compound Semiconductors and Insulators, *W.H. Strehlow and E.L. Cook,* Vol. 2, No. 1, pp. 163-200 (1973) $4.50
23. Microwave Spectra of Molecules of Astrophysical Interest. III. Methanol, *R.M. Lees, F.J. Lovas, W.H. Kirchhoff, and D.R. Johnson,* Vol. 2, No. 2, pp. 205-214 (1973) $3.00
24. Microwave Spectra of Molecules of Astrophysical Interest. IV. Hydrogen, Sulfide, *Paul Helminger, Frank C. De Lucia, and William H. Kirchhoff,* Vol. 2, No. 2, pp. 215-224 (1973) $3.00
25. Tables of Molecular Vibrational Frequencies. Part 7, *T. Shimanouchi,* Vol. 2, No. 2, pp. 225-256 (1973) $4.00
26. Energy Levels of Neutral Helium (^{4}He I), *W.C. Martin,* Vol. 2, No. 2, pp. 257-266 (1973) $3.00
27. Survey of Photochemical and Rate Data for Twenty-eight Reactions of Interest in Atmospheric Chemistry, *R.F. Hampson, Editor, W. Braun, R.L. Brown, D. Garvin, J.T. Herron, R.E. Huie, M.J. Kurylo, A.H. Laufer, J.D. McKinley, H. Okabe, M.D. Sheer, W. Tsang, and D.H. Stedman,* Vol. 2, No. 2, pp. 267-312 (1973) $4.50
28. Compilation of the Static Dielectric Constant of Inorganic Solids, *K.F. Young and H.P.R. Frederikse,* Vol. 2, No. 2, pp. 313-410 (1973) $6.50
29. Soft X-Ray Emission Spectra of Metallic Solids: Critical Review of Selected Systems, *A.J. McAlister, R.C. Dobbyn, J.R. Cuthill, and M.L. Williams,* Vol. 2, No. 2, pp. 411-426 (1973) $3.00
30. Ideal Gas Thermodynamic Properties of Ethane and Propane, *J. Chao, R.C. Wilhoit, and B.J. Zwolinski,* Vol. 2, No. 2, pp. 427-438 (1973) $3.00
31. An Analysis of Coexistence Curve Data for Several Binary Liquid Mixtures Near Their Critical Points, *A. Stein and G.F. Allen,* Vol. 2, No. 3, pp. 443-466 (1973). $4.00
32. Rate Constants for the Reactions of Atomic Oxygen (O^3P) with Organic Compounds in the Gas Phase, *John T. Herron and Robert E. Huie,* Vol. 2, No. 3, pp. 467-518 (1973) $5.00
33. First Spectra of Neon, Argon, and Xenon 136 in the 1.2-4.0 μm Region, *Curtis J. Humphreys,* Vol. 2, No. 3, pp. 519-530 (1973) $3.00
34. Elastic Properties of Metals and Alloys, I. Iron, Nickel, and Iron-Nickel Alloys, *H.M. Ledbetter and R.P. Reed,* Vol. 2, No. 3, pp. 531-618 (1973) $6.00
35. The Viscosity and Thermal Conductivity Coefficients of Dilute Argon, Krypton, and Xenon, *H.J.M. Hanley,* Vol. 2, No. 3, pp. 619-642 (1973). $4.00
36. Diffusion in Copper and Copper Alloys. Part I. Volume and Surface Self-Diffusion in Copper, *Daniel B. Butrymowicz, John R. Manning, and Michael E. Read,* Vol. 2, No. 3, pp. 643-656 (1973) $3.00
37. The 1973 Least-Squares Adjustment of the Fundamental Constants, *E. Richard Cohen and B.N. Taylor,* Vol. 2, No. 4, pp. 663-734 (1973) $5.50
38. The Viscosity and Thermal Conductivity Coefficients of Dilute Nitrogen and Oxygen, *H.J.M. Hanley and James F. Ely,* Vol. 2, No. 4, pp. 735-756 (1973). $4.00
39. Thermodynamic Properties of Nitrogen Including Liquid and Vapor Phases from 63K to 2000K with Pressures to 10,000 Bar, *Richard T. Jacobsen and Richard B. Stewart,* Vol. 2, No. 4, pp. 757-922 (1973) $8.50

(Continuation of cumulative listing of reprints)

Reprints

40. Thermodynamic Properties of Helium 4 from 2 to 1500 K at Pressures to 10^8 Pa, *Robert D. McCarty,* Vol. 2, No. 4, pp. 923–1042 (1973) $7.00

41. Molten Salts: Volume 4, Part 1, Fluorides and Mixtures Electrical Conductance, Density, Viscosity, and Surface Tension Data, *G.J. Janz, G.L. Gardner, Ursula Krebs, and R.P.T. Tomkins,* Vol. 3, No. 1, pp. 1-115 (1974) $7.00

42. Ideal Gas Thermodynamic Properties of Eight Chloro- and Fluoromethanes, *A.S. Rodgers, J. Chao, R.C. Wilhoit, and B.J. Zwolinski,* Vol. 3, No. 1, pp. 117-140 (1974) $4.00

43. Ideal Gas Thermodynamic Properties of Six Chloroethanes, *J. Chao, A.S. Rodgers, R.C. Wilhoit, and B.J. Zwolinski,* Vol. 3, No. 1, pp. 141-162 (1974) $4.00

44. Critical Analysis of Heat-Capacity Data and Evaluation of Thermodynamic Properties of Ruthenium, Rhodium, Palladium, Iridium, and Platinum from 0 to 300 K. A Survey of the Literature Data on Osmium, *George T. Furukawa, Martin L. Reilly, and John S. Gallagher,* Vol. 3, No. 1, pp. 163-209 (1974) $4.50

45. Microwave Spectra of Molecules of Astrophysical Interest V. Water Vapor, *Frank C. De Lucia, Paul Helminger, and William H. Kirchhoff,* Vol. 3, No. 1, pp. 211-219 (1974) $3.00

46. Microwave Spectra of Molecules of Astrophysical Interest VI. Carbonyl Sulfide and Hydrogen Cyanide, *Arthur G. Maki,* Vol. 3, No. 1, pp. 221-244 (1974) $4.00

47. Microwave Spectra of Molecules of Astrophysical Interest VII. Carbon Monoxide, Carbon Monosulfide, and Silicon Monoxide, *Frank J. Lovas and Paul H. Krupenie,* Vol. 3, No. 1, pp. 245-257 (1974) $3.00

48. Microwave Spectra of Molecules of Astrophysical Interest VIII. Sulfur Monoxide, *Eberhard Tiemann,* Vol. 3, No. 1, pp. 259-268 (1974) $3.00

49. Tables of Molecular Vibrational Frequencies. Part 8, *T. Shimanouchi,* Vol. 3, No. 1, pp. 269-308 (1974) $4.50

50. JANAF Thermochemical Tables, 1974 Supplement, *M.W. Chase, J.L. Curnutt, A.T. Hu, H. Prophet, and L.C. Walker,* Vol. 3, No. 2, pp. 311–480 (1974) $8.50

51. High Temperature Properties and Decomposition of Inorganic Salts, Part 4. Oxy-Salts of the Halogens, *Kurt H. Stern,* Vol. 3, No. 2, pp.481–526 . . . . $4.50

52. Diffusion in Copper and Copper Alloys, Part II. Copper–Silver and Copper–Gold Systems, *Daniel B. Butrymowicz, John R. Manning, and Michael E. Read,* Vol. 3, No. 2, pp. 527–602 (1974) $5.50

53. Microwave Spectral Tables
I. Diatomic Molecules,
Frank J. Lovas and Eberhard Tiemann, Vol. 3, No. 3, pp. 609–770 (1974) $8.50

54. Ground Levels and Ionization Potentials for Lanthanide and Actinide Atoms and Ions, *W.C. Martin, Lucy Hagan, Joseph Reader, and Jack Sugar,* Vol. 3, No. 3, pp. 771–750 (1974) $3.00

55. Behavior of the Elements at High Pressures, *John Francis Cannon,* Vol. 3, No. 3, pp. 781–824 (1974) $4.50

56. Reference Wavelengths from Atomic Spectra in the Range 15 Å to 25000 Å, *Victor Kaufman and Bengt Edlen,* Vol. 3, No. 4, pp. 825–895 (1974) $5.50

57. Elastic Properties of Metals and Alloys.
II. Copper,
H.M. Ledbetter and E.R. Naimon, Vol. 3, No. 4, pp. 897–935 (1974) $4.50

58. A Critical Review of H-Atom Transfer in the Liquid Phases: Chlorine Atom, Alkyl, Trichloromethyl, Alkoxy, and Alkylperoxy Radicals, *D.G. Hendry, T. Mill, L. Piszkiewicz, J.A. Howard, and H.K. Eigenmann,* Vol. 3, No. 4, pp. 937–978 (1974) . . $4.50

59. The Viscosity and Thermal Conductivity Coefficients for Dense Gaseous and Liquid Argon, Krypton, Xenon, Nitrogen and Oxygen, *H.J.M. Hanley, R.D. McCarty, and W.M. Haynes,* Vol. 3, No. 4, pp. 979–1017 (1974) $4.50

Journal of **Physical and Chemical Reference Data**

Cumulative Listing of Reprints and Supplements

Reprints

1. Gaseous Diffusion Coefficients, *T.R. Marrero and E.A. Mason,* Vol. 1, No. 1, pp. 1–118 (1972) $7.00
2. Selected Values of Critical Supersaturation for Nucleation of Liquids from the Vapor, *G.M. Pound,* Vol. 1, No. 1, pp. 119–134 (1972) $3.00
3. Selected Values of Evaporation and Condensation Coefficients of Simple Substances, *G.M. Pound,* Vol. 1, No. 1, pp. 135–146 (1972) $3.00
4. Atlas of the Observed Absorption Spectrum of Carbon Monoxide between 1060 and 1900 Å, *S.G. Tilford and J.D. Simmons,* Vol. 1, No. 1, pp. 147–188 (1972) $4.50
5. Tables of Molecular Vibrational Frequencies, Part 5, *T. Shimanouchi,* Vol. 1, No. 1, pp. 189–216 (1972). . . $4.00
6. Selected Values of Heats of Combustion and Heats of Formation of Organic Compounds Containing the Elements C,H,N,O,P, and S, *Eugene S. Domalski,* Vol. 1, No. 2, pp. 221–278 (1972) $5.00
7. Thermal Conductivity of the Elements, *C.Y. Ho, R.W. Powell and P.E. Liley,* Vol. 1, No. 2, pp. 279–422 (1972). $7.50
8. The Spectrum of Molecular Oxygen, *Paul H. Krupenie,* Vol. 1, No. 2, pp. 423–534 . . . . $6.50
9. A Critical Review of the Gas-Phase Reaction Kinetics of the Hydroxyl Radical, *W.E. Wilson, Jr.,* Vol. 1, No. 2, pp. 535–574 (1972). $4.50
10. Molten Salts: Volume 3, Nitrates, Nitrites, and Mixtures, Electrical Conductance, Density, Viscosity, and Surface Tension Data, *G.J. Janz, Ursula Krebs, H.F. Siegenthaler, and R.P.T. Tomkins,* Vol. 1, No. 3, pp. 581–746 (1972) $8.50
11. High Temperature Properties and Decomposition of Inorganic Salts—Part 3, Nitrates and Nitrites, *Kurt H. Stern,* Vol. 1, No. 3, pp. 747–772 (1972). $4.00
12. High-Pressure Calibration: A Critical Review, *D.L. Decker, W.A. Bassett, L. Merrill, H.T. Hall, and J.D. Barnett,* Vol. 1, No. 3, pp. 773–836 (1972). $5.00

(Cumulative Listing of Reprints continued on next page)

Supplements

1. Physical and Thermodynamics Properties of Aliphatic Alcohols, *R.C. Wilhoit and B.J. Zwolinski,* Vol. 2, Supplement No. 1 (1973) . . . . Hardcover-$33.00
   Softcover (non-member)- 30.00
   Softcover (member)- 10.00
2. Thermal Conductivity of the Elements: A Comprehensive Review, *C.Y. Ho, R.W. Powell and P.E. Liley,* Vol. 3, Supplement No. 1 (1974) . . . . Hardcover-$60.00
   Soft cover (Non-member) - 60.00
   Soft cover (Member)- 55.00

To: **American Chemical Society**
Subscription Service Department
1155 Sixteenth Street N.W.
Washington, D.C. 20036

Please ship the following reprints and supplements:

Reprint No. ______ , ______ copies, $ ________

Reprint No. ______ , ______ copies, $ ________

Reprint No. ______ , ______ copies, $ ________

Reprint No. ______ , ______ copies, $ ________

Reprint No. ______ , ______ copies, $ ________

Reprint No. ______ , ______ copies, $ ________

Supplement No. ____ to Vol. ______ $ ________

Supplement No. ____ to Vol. ______ $ ________

Other: ____________________

BULK RATES: Subtract 20% from the listed price for orders of 50 or more of any one item.

***ORDERS FOR REPRINTS MUST BE PREPAID**

Please enter my subscription for the calendar year 1975 as follows:

	Non-Member		Member*	
Journal of	Domestic°	Foreign	Domestic°	Foreign
Physical and Chemical Reference Data	☐ $60	☐ $63	☐ $20	☐ $23
Supplements	☐	☐	☐	☐

(Check appropriate box if you wish to enter a standing order for all **1975** Supplements. Prices to be announced.)

*Member of **ACS** or member of **AIP** member or affiliated society
°Domestic rates apply to U.S. and possessions, Canada and Mexico.

Name ____________________

Address ____________________

City __________ State __________ Zip __________

Country ____________________

I am a member of ____________________
ACS or AIP Member or Affiliated Society

☐ Check Enclosed ☐ Please Bill Me ☐ Purchase Order Enclosed
(Make checks payable to the American Chemical Society)

Journal of
Physical and Chemical Reference Data

Volume 3
1974

a new quarterly journal of critically evaluated physical and chemical property data, and critical reviews of measurement techniques

published by the **American Chemical Society** and the **American Institute of Physics** for the **National Bureau of Standards**

please use the attached reply card to enter your subscription and to order reprints of individual articles

FIRST CLASS
Permit No.
1411—R
Washington, D.C.

BUSINESS REPLY MAIL
No Postage Stamp Necessary if Mailed in United States

Postage Will Be Paid By

American Chemical Society
Subscription Service Department
1155 Sixteenth Street, N.W.
Washington, D.C. 20036

FIRST CLASS
Permit No.
1411—R
Washington, D.C.

BUSINESS REPLY MAIL
No Postage Stamp Necessary if Mailed in United States

Postage Will Be Paid By

American Chemical Society
Subscription Service Department
1155 Sixteenth Street, N.W.
Washington, D.C. 20036

Fill out this card to gain access to the most reliable reference data avâilable today. This can mean improved efficiency in research and development and avoidance of a great deal of duplication of effort.

Please enter my subscription for Volume 4, 1975 as follows:

Journal of **Physical and Chemical Reference Data** Supplements	Non-Member Domestic°	Non-Member Foreign	Member* Domestic°	Member* Foreign
	☐ $60	☐ $63	☐ $20	☐ $23
	☐	☐	☐	☐

(Check appropriate box if you wish to enter a standing order for all **1974** Supplements. Prices to be announced.)

☐ Check here if you wish information on back issues.
*Member of **ACS** or member of **AIP** member or affiliated society
°Domestic rates apply to U.S. and possessions, Canada and Mexico

Name ______________________

Address ______________________

City ______________ State ______ Zip ______

Country ______________________

I am a member of ______________________
ACS or AIP Member or Affiliated Society

☐ Check Enclosed ☐ Please Bill Me ☐ Purchase Order Enclosed

(Make checks payable to the American Chemical Society)

To: **American Chemical Society**
Subscription Service Department
1155 Sixteenth Street N.W.
Washington, D.C. 20036

Please ship the following reprints and supplements:

Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______

Supplement No. ____ to Vol. ______ $ ______
Supplement No. ____ to Vol. ______ $ ______

Other: ______________________

BULK RATES: Subtract 20% from the listed price for orders of 50 or more of any one item.

***ORDERS FOR REPRINTS MUST BE PREPAID**

Please enter my subscription for Volume 4, 1975 as follows:

Journal of **Physical and Chemical Reference Data** Supplements	Non-Member Domestic°	Non-Member Foreign	Member* Domestic°	Member* Foreign
	☐ $60	☐ $63	☐ $20	☐ $23
	☐	☐	☐	☐

(Check appropriate box if you wish to enter a standing order for all **1974** Supplements. Prices to be announced.)

☐ Check here if you wish information on back issues.
*Member of **ACS** or member of **AIP** member or affiliated society
°Domestic rates apply to U.S. and possessions, Canada and Mexico

Name ______________________

Address ______________________

City ______________ State ______ Zip ______

Country ______________________

I am a member of ______________________
ACS or AIP Member or Affiliated Society

☐ Check Enclosed ☐ Please Bill Me ☐ Purchase Order Enclosed

(Make checks payable to the American Chemical Society)

To: **American Chemical Society**
Subscription Service Department
1155 Sixteenth Street N.W.
Washington, D.C. 20036

Please ship the following reprints and supplements:

Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______
Reprint No. ______ , ______ copies, $ ______

Supplement No. ____ to Vol. ______ $ ______
Supplement No. ____ to Vol. ______ $ ______

Other: ______________________

BULK RATES: Subtract 20% from the listed price for orders of 50 or more of any one item.

***ORDERS FOR REPRINTS MUST BE PREPAID**

American Institute of Physics

335 East 45 Street
New York, N.Y. 10017

H. Richard Crane	Chairman, Governing Board
H. William Koch	Director
Sidney Millman	Secretary
Gerald F. Gilbert	Treasurer
Lewis Slack	Associate Director, General Activities
Robert H. Marks	Associate Director, Publishing
A. W. Kenneth Metzner	Director of Publications

The American Institute of Physics was founded in 1931 as a federation of leading societies in the field of physics, operating as a single agency capable of serving the interest of physics in those functions that can best be performed by the societies jointly. Its purpose is the advancement and diffusion of the knowledge of physics and its application to human welfare. About 50,000 physicists are members of its seven Member Societies: The American Physical Society, Optical Society of America, Acoustical Society of America, Society of Rheology, American Association of Physics Teachers, American Crystallographic Association, American Astronomical Society. In addition there are 19 Affiliated Societies, over 100 Corporate Associates and a Society of Physics Students.

AIP is the world's leading publisher of physics journals, including translations from Russian originals. In addition, AIP offers Current Physics Information, an integrated package of current awareness journals, microfilm and magnetic tapes.

AIP also makes available to the public reliable communications on physics and its progress; strengthens physics education on all levels; assists in the documentation and study of the history and philosophy of recent physics; cooperates with local, national and international organizations related to physics; and, in general, fosters the relations of the science of physics to other sciences and to the arts and industry.

American Chemical Society

1155 Sixteenth Street, NW
Washington, D.C. 20036

Herman H. Bloch	Chairman of the Board
Alan C. Nixon	President
Robert W. Cairns	Executive Director
Richard L. Kenyon	Director, Public Affairs and Communication Division*
Dale B. Baker	Director, Chemical Abstracts Service Division
John K. Crum	Director, Books and Journals Division
Robert E. Henze	Director, Membership Division

*Inquiries regarding ACS participation in JPCRD should be directed to this division.

The American Chemical Society was founded in 1876 as a scientific and educational society, and in 1937 was granted a national charter by an act of Congress. Its objects include the advancement of chemistry, the promotion of research in science and industry, improvement of qualifications and usefulness of chemists, increased diffusion of chemical knowledge, and the promotion of scientific interest and inquiry.

ACS publishes 22 magazines, journals, and other scientific periodicals in addition to its participation in publication of the *Journal of Physical and Chemical Reference Data.* It also publishes books and other non-periodical reports and operates the Chemical Abstracts Service, the key to the world's chemical literature. It pursues its objectives through its services to chemists and chemical engineers and to education, industry, and government.

National Bureau of Standards

U.S. Department of Commerce
Washington, D.C. 20234

Richard W. Roberts	Director

The National Bureau of Standards was established by an Act of Congress March 3, 1901. The overall goal of NBS is to strengthen and advance the Nation's science and technology and to facilitate their effective application for public benefit. The Bureau consists of the following operational units:

The Institute for Basic Standards provides the central basis within the United States of a complete and consistent system of physical measurement and coordinates that system with measurement systems of other Nations.

The Institute for Materials Research conducts research leading to improved methods of measurement, standards, and data, on the properties of materials needed by industry, commerce, educational institutions, and Government.

The Institute for Applied Technology provides technical services to promote the use of available technology and to facilitate technological innovation in industry and Government.

The Center for Computer Sciences and Technology conducts research and provides technical services designed to aid Government agencies in the selection, acquisition, and effective utilization of automatic data processing equipment.

The Office for Information Programs promotes optimum dissemination and accessibility of scientific information generated within NBS, including the output of the National Standard Reference Data System, and provides appropriate scientific information services to the NBS staff.

Journal of
Physical and Chemical Reference Data
Volume 3, 1974
Supplement No. 1

Thermal Conductivity of the Elements: A Comprehensive Review

C.Y. Ho, R.W. Powell and P.E. Liley

Contents