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Thermal Conductivity of Selected Materials

part. 1

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i.
National Standard Reference Data Series-
U.S. National Bureau of Standards—8
(Category 5—Thermodynamic and Transport Properties)

Issued November 25, 1966

For sale by the Superintendent of Documents, U.S. Government Printing Office
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Foreword

The National Standard Reference Data System is a government-wide effort to give to the technical community of the United States optimum access to the quantitative data of physical science, critically evaluated and compiled for convenience. This program was established in 1963 by the President's Office of Science and Technology, acting upon the recommendation of the Federal Council for Science and Technology. The National Bureau of Standards has been assigned responsibility for administering the effort. The general objective of the System is to coordinate and integrate existing data evaluation and compilation activities into a systematic, comprehensive program, supplementing and expanding technical coverage when necessary, establishing and maintaining standards for the output of the participating groups, and providing mechanisms for the dissemination of the output as required.

The NSRDS is conducted as a decentralized operation of nation-wide scope with central coordination by NBS. It comprises a complex of data centers and other activities, carried on in government agencies, academic institutions, and nongovernmental laboratories. The independent operational status of existing critical data projects is maintained and encouraged. Data centers that are components of the NSRDS produce compilations of critically evaluated data, critical reviews of the state of quantitative knowledge in specialized areas, and computations of useful functions derived from standard reference data.

For operational purposes, NSRDS compilation activities are organized into seven categories as listed below. The data publications of the NSRDS, which may consist of monographs, loose-leaf sheets, computer tapes, or any other useful product, will be classified as belonging to one or another of these categories. An additional "General" category of NSRDS publications will include reports on detailed classification schemes, lists of compilations considered to be Standard Reference Data, status reports, and similar material. Thus, NSRDS publications will appear in the following eight categories:

Category	*Title*
1	General
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5	Thermodynamic and Transport Properties
6	Chemical Kinetics
7	Colloid and Surface Properties
8	Mechanical Properties of Materials

Within the National Bureau of Standards publication program a new series has been established, called the National Standard Reference Data Series. The present report, which is in Category 5 of the above list, is Number 8 of the new series and is designated NSRDS–NBS 8.

A. V. Astin, *Director.*

PREFACE

The work presented in this report consists of the critical evaluation and analysis of the available thermal conductivity data on eleven metals and nine nonmetals mainly for the solid state, on seven fluids for both the liquid and gaseous states and on two for the liquid state only. The materials studied were selected primarily for their potential applicability as reference standards or because of their technical importance. The temperature range for which values are given often exceeds that for which these values are known with a high degree of certainty. While TPRC assumes full responsibility for the recommendations of these reference data, it also reserves the right to revise these recommendations in the light of better or more complete information that may become available subsequently.

Graphite was amongst the materials originally selected for study but is omitted from this report. While the work on graphite has been completed and the data scrutinized, it has not been possible to arrive at a satisfactory basis on which to recommend "most probable" standard reference values. This effort will continue into the second year and it is hoped that further consideration of the problem will enable the formulation of appropriate recommendations.

The preparation of this report has aroused interest in several other materials for which similarly assessed thermal conductivity values are required. These will receive detailed consideration in subsequent reports of this series.

As a result of this study, it has become possible to assess the state of adequacy of our knowledge on the thermal conductivity of a selected group of materials. Unfortunately, the results are not encouraging in a large number of the cases and serious new measurement effort and the establishment of improved capabilities are indicated. TPRC has taken active measures to contribute to this most urgent measurement program on a selective basis, based on findings as discussed in this report.

The present work was greatly facilitated by the wide scope of knowledge previously collected and organized at TPRC. In fact, without such extensive input, the scope of work generated during the first year could not have been possible. The senior staff affiliated with this program consisted of Dr. R. W. Powell and Dr. C. Y. Ho who collaborated on the sections comprising the metallic and nonmetallic solids and Dr. P. E. Liley who was responsible for the sections on fluids. Dr. Y. S. Touloukian has served as coordinator and adviser to the program. The senior authors are grateful for the cooperation and assistance they have received from Mr. George Wang and his group and the staff of TPRC's Scientific Documentation Division, who have directly contributed to this program.

In order to give a greater degree of confidence to the recommendations set forth in this work, the preliminary report was distributed to some 54 active workers in this field for their comments and criticisms. The authors wish to express their appreciation and sincere gratitude to all who responded so generously. Particular acknowledgment is made for the valuable contributions of the following individuals:
Dr. N. G. Bäcklund, Royal Institute of Technology, Stockholm, Sweden,
Dr. C. F. Bonilla, Columbia University, New York City, New York,
Dr. A. Cezairliyan, National Bureau of Standards, Washington, D. C.,
Mr. G. L. Denman, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio.,
Dr. E. Deviatkova, Institute for Semiconductors, Leningrad, U. S. S. R.,
Mr. D. R. Flynn, National Bureau of Standards, Washington, D. C.,
Dr. P. E. Glaser, Arthur D. Little, Inc., Cambridge, Mass.,
Dr. D. T. Jamieson, National Engineering Laboratory, East Kilbride, Scotland,
Dr. J. Kestin, Brown University, Providence, R. I.,
Dr. P. G. Klemens, Research Center, Westinghouse Electric Corporation, Pittsburgh, Pa.,
Dr. M. J. Laubitz, National Research Council, Ottawa, Canada,
Mr. C. F. Lucks and Mr. H. W. Deem, Battelle Memorial Institute, Columbus, Ohio.

Dr. D. L. McElroy and his colleagues, Oak Ridge National Laboratory, Oak Ridge, Tennessee,
Mr. A. Missenard, Paris, France,
Mr. C. D. Pears, Southern Research Institute, Birmingham, Alabama,
Dr. W. A. Plummer, Corning Glass Works, Corning, N. Y.,
Dr. H. Poltz, Physikalisch-Technische Bundesanstalt, Braunschweig, W. Germany,
Dr. R. L. Powell, National Bureau of Standards, Boulder, Colorado,
Dr. F Richter, Phoenix-Rheinrohr Ag., Dusseldorf, W. Germany,
Dr. K. Schafer, University of Heidelberg, W. Germany,
Dr. G. A. Slack, General Electric Research Laboratory, Schenectady, N. Y.,
Prof. N. B. Vargaftik, Moskovskii Aviatsionnyi Institut, Moscow, U. S. S. R.,
Dr. R. G Vines, C. S. R. I. O., Melbourne, Australia,
Dr. G. K. White, National Standards Laboratory, C. S. I. R. O., Chippendale, N. S. W., Australia

It goes without saying that while the individuals mentioned above have read selected parts of the preliminary report and given helpful comments and criticisms, this in no way commits them to the views expressed in this report for which the authors assume complete responsibility.

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PART I

THERMAL CONDUCTIVITY OF METALS

A. Introduction

The metals studied in this report consist of aluminum (solid and liquid state),*copper, gold, iron (Armco and pure), manganin, mercury (liquid state), platinum, platinum alloyed with 40% rhodium, silver, and tungsten.

In order to provide as complete a background of available knowledge as possible, the TPRC data sheets for each of the above materials have been thoroughly updated. In doing this, the original papers have been critically reexamined and more complete specification tables have been prepared.

Earlier analytical work [1, 2, 3]‡ at the TPRC, had dealt in the main with the thermal conductivities of metals at low temperatures. This work showed that the available data for 22 metals, some 1,000 points for 83 different samples, could be reduced to a single curve by plotting the reduced thermal conductivity against the reduced temperature. At low temperatures the thermal conductivity of a metal has a maximum value, k_m, at a corresponding temperature, T_m. The reduced thermal conductivity, k^*, has been defined as k/k_m, and the reduced temperature, T^*, as T/T_m.

The standard deviation of the experimental points from the curve

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

is calculated to be 0.0320.

It was further shown that in the low temperature region, $0<T<1.5\,T_m$, the thermal conductivity could be calculated by the equation

$$k = \left[\alpha' T^n + \beta/T\right]^{-1} \tag{2}$$

where

$$\alpha' = \alpha''\left(\frac{\beta}{n\alpha''}\right)^{\frac{a}{m+1}} \tag{3}$$

In this equation α'', a, m, and n are constants for a metal whereas β and α' are dependent on the purity and perfection. Theoretically,

$$\beta = \rho_0/L_0 \tag{4}$$

where ρ_0 is the residual electrical resistivity and L_0 is the theoretical value of the Lorenz function and equal to 2.443×10^{-8} volt^2 K^{-2}. The parameter β is also obtainable by fitting observed values of the thermal conductivity at temperatures below T_m to Equation (2), and, for sufficiently low values of T, $\beta = T/k$ is a good approximation. Hence, β can be calculated from either the residual electrical resistivity or the thermal conductivity at very low temperatures. This quantity is a function of the net chemical purity and physical imperfection of the sample, becoming less than 0.02 for highly pure metals. This form of equation indicates the very marked dependence of the thermal conductivity in the region of T_m on the value of β, that is, on the degree of purity and perfection of the sample.

In the present report the foregoing equations have been used to derive thermal conductivity values up to temperatures of about $1.5\,T_m$. The values of the constants α'', a, m and n for each metal are given in Table 1 together with the three parameters α', β, and the electrical resistivity ratio $\rho_{273K}/\rho_{4.2K}$ which are functions of the degree of purity and perfection of the metal and hence differ from one specimen to another.

The values of β, included in Table 1, column 9, are the lowest that have been obtained for each metal from thermal conductivity measurements, and, in some instances, these values can be compared with those derived for the same sample from electrical resistivity measurements, column 8. Where the β values derived in these

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‡ References appear under the heading REFERENCES for each of the parts.

two ways agree reasonably well, that obtained from the thermal conductivity measurements, has been the value chosen for subsequent calculations. However, for iron and tungsten, where the agreement is poor, the β value derived from the electrical resistivity data has been used.

The values of $\rho_{273K}/\rho_{4.2K}$ of column 6, relate to the purest samples for which low-temperature thermal conductivity measurements have been reported, whereas the values of this ratio given in the last column of the table are the highest that have been reported, so far. Comparison of the values in these two columns reveals very large differences for all metals. This indicates that the much purer samples now becoming available will possess correspondingly lower β values according to Equation (4) and higher thermal conductivities, according to Equation (2).

At the present time, the choice exists of reporting for a pure metal in this low temperature range, either the highest thermal conductivity values based on actual measurement of the property, or, the much higher thermal conductivity values that would result when these much lower β values are inserted in Equation (2).

The low temperature thermal conductivities given in Table 2a and shown graphically in Figure 1 have been obtained by the first of these two methods. The corresponding values of ρ_0 and the chemical purity for each pure metal are included in Table 2a. These quantities specify each pure metal for which thermal conductivity values are tabulated to about $1.5\,T_m$ and, in the temperature interval from this limit to about 100 K, smoothly falling curves have been drawn to link on with the most probable curves proposed for the higher temperature range.

Because of the very strong dependence of the low-temperature thermal conductivity of a pure metal on the physical perfection and on the degree of purity, it follows that a pure metal is not likely to be an ideal material for use as a thermal conductivity standard at low temperatures. In the high thermal conductivity region there will probably be no alternative, but, when otherwise acceptable, a binary alloy is to be preferred. This should be composed of reasonably pure constituents, be metallurgically stable and insensitive to small compositional changes. When a pure metal is used, a recommended procedure for a particular sample would be to measure ρ at room and liquid helium temperatures, then to evaluate β from Equation (4) and derive k from Equation (2). This should be done after the sample is mounted in the thermal conductivity apparatus and when it is unlikely to be subjected to further strain.

In order to assist in determining the most probable thermal conductivity - temperature curve for each metal in the higher temperature range, the available experimental data have been plotted with linear coordinates in Figures 3 to 13.

Following the figure for each metal is a specification table which provides the chemical composition and other details for each specimen. In the tables, the code designations used for the experimental methods are as follows:

C	Comparative method
E	Electrical 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 curves listed in the specification table but not shown in the figure, particularly in the low temperature region, one is referred to the TPRC Data Book, Volume 1, Chapter 1 [4], in which complete numerical data tables are also given.

Each figure includes a heavy broken line which is considered to represent the most probable curve of thermal conductivity versus temperature for a high purity sample of the metal. This curve has at times been based on rather scanty information, and should therefore be accepted as an attempt to make the most of existing knowledge and subject to modification in the light of further work. Guidance has at times been sought from electrical resistivity data, but these are often missing. Furthermore, the extent to which the Wiedemann-Franz-Lorenz law can be used to evaluate thermal conductivities over a wide temperature range is a matter that still has to be more fully investigated. Only as more thermal conductivity workers collaborate by including electrical resistivity measurements whenever possible, will sufficient knowledge become available to determine just how the Lorenz function varies with temperature for the different metals. At sufficiently high temperatures the Lorenz function often tends to approximate to the theoretical value, but it seems that transition metals may present an exception. At low temperatures, $T<\theta$, where θ is the Debye temperature, two opposing effects become important and the Lorenz function may either increase or decrease with decreasing temperature before finally returning to about the theoretical value at near absolute zero.

Some pertinent comments regarding the thermal conductivity of each metal for temperatures above 100 K are given in the following section, and the recommended values are reported collectively in Table 2b and plotted in Figure 2. In the Tables 2a and 2b, the third significant figure is given only for the purpose of comparison and for smoothness and is not indicative of the degree of accuracy.

B. Thermal Conductivity of a Group of Selected Metals

Aluminum

For aluminum additional measurements would be of interest at temperatures immediately above and below room temperature for a range of compositions including a sample of really high purity. Interest in this temperature region has been revived since Powell et al. [5] reported a minimum at about 220 K in the thermal conductivity-temperature curve for a sample of high purity aluminum (99.993%). For another sample, Flynn [6] has since reported a minimum at about 240 K and, amongst older results, minima have been found at about 160 K and 145 K by Lees [7] and Powers, Ziegler and Johnston [8] for samples of much lower purity (99% and 98.17%). These four results indicate the temperature of the minimum to increase with increase in thermal conductivity and presumably with purity, and it is of interest to note that the measurements of Powers, Schwartz and Johnston [9] for a highly pure (99.99^{+}%) sample had decreased to a constant value at 237.6 K, the upper limit of their experiment. At temperatures above normal there are strong indications that the thermal conductivity increases to a gentle maximum and then decreases to the melting point, but so far, only one set of measurements, those reported by Flynn, have covered a sufficient range to include both the minimum and the maximum. This explains the need for further investigations to be made on a range of samples of aluminum.

The recommended curve follows the data of Powers, Schwartz and Johnston at 100 K, falls to a minimum lying between their data and Flynn's, rises to a maximum following the data of Powell et al., then continues close to the data of these latter workers.

Electrical resistivity values have been reported by Powell et al. [5] and by Mikryukov [10]. The values derived for the Lorenz function by these workers agree to within 1 or 2 percent for all but the lowest temperatures, but the electrical resistivities of the Russian work are up to 5 percent greater. These results support the conclusion of Powell et al. that the Lorenz function of aluminum is only weakly dependent on purity at temperatures above normal and can serve as an aid in determining the thermal conductivity of a particular sample from a measurement of its electrical resistivity. The Lorenz function can be assumed to be 2.35×10^{-8}, 2.40×10^{-8}, and 2.42×10^{-8} volt^2 K^{-2} at 473, 673, and 873 K, respectively. The work of Powell et al. [11] would indicate very little change in the Lorenz function to occur on entering the liquid phase.

Figure 3b relates to the thermal conductivity of liquid aluminum and shows very diverse values to have been obtained. Only Powell et al. 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% and 1.5% lower at 973 and 1223 K. Mention of this is made because Grosse [12] has recently assumed the theoretical value of the Lorenz function to hold from the melting point to the critical point when deriving values for the thermal conducitivity of aluminum over the entire liquid range. For the electrical conductivity of molten metals Grosse [13] has proposed an equation of the form

$$(\sigma^* + b)\ (T^+ + b) = a \qquad (5)$$

where $\sigma^* = \sigma_T/\sigma_f$

σ_T is the electrical conductivity of the molten metal at a temperature T between the melting point T_f and the critical point T_c, and σ_f is the corresponding electrical conductivity at the melting point. T^+ is given by $(T - T_f)/(T_c - T_f)$. The quantities a and b are constants. At T_c both σ and k are assumed to be zero. Part of the curve derived in this way for the thermal conductivity of liquid aluminum is shown by the thin dash-dot line of Figure 3b. This curve has a maximum value of 1.17 W cm^{-1} K^{-1} at 2200 K.

The electrical conductivity values assumed by Grosse for liquid aluminum near the melting point were those of Roll and Motz [14]. These values were some 6 percent higher than those of Powell et al. which accounts for much of the difference between their thermal conductivity curves. The two curves are almost parallel, and the present recommended curve is the heavy broken line shown between them, but biased toward the experimentally determined thermal conductivity values. At about 950 K this line passes close to the values due to Konno [15] 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.

The recommended values are thought to be accurate to within ±4 percent below room temperature and ±2 percent to ±3 percent above. For liquid aluminum the values are probably good to within ±5 percent.

More attention should also be directed to the determination of the electrical resistivity of liquid aluminum.

Copper

Well over a hundred separate determinations of the thermal conductivity of copper have appeared in the literature. Despite this large number, there is the usual dearth of information in the immediate sub-normal temperature region and at high temperatures. Indeed, no measurements to high temperatures appear to have been made for high-purity copper. Furthermore, relatively few workers have included measurements of the electrical resistivity of their samples. Of these, the data of Meissner [16], Jaeger and Diesselhorst [17], Schofield [18], Smith and Palmer [19], Mikryukov and Rabotnov [20] and Powell and Tye [21] all yield values of the Lorenz function which are in the range 2.25×10^{-8} to 2.42×10^{-8} $volt^2$ K^{-2}, that is below the theoretical value. Only the work of Mikryukov [10] yields values as high as 2.50×10^{-8}, suggesting that his thermal conductivity measurements for copper may err on the high side. The earlier measurements of Mikryukov and Rabotnov [20] were made on a less pure sample and at their highest temperatures of about 800 to 1000 K their thermal conductivity values agree with those of Fieldhouse et al. [22] for a sample of electrolytic tough pitch copper to within 4 percent. Both of these curves are believed to be below the curve of high purity copper. The broken line proposed for the latter has been derived by assuming the Lorenz function to increase from 2.29×10^{-8} at 273 K to 2.40×10^{-8} at 873 K and above. The electrical resistivity values of Meechan and Eggleston [23] for a 99.999 percent copper have been used.

Values for the thermal conductivity of liquid copper are available, but these have been shown [11, 24] to be from 16 to 60 percent below the straight line

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

which fits the experimental data for several molten metals and alloys. They are also below the curve derived by Grosse [12] from electrical conductivity data [25]. Further measurements are thought to be necessary before any firm recommendations can be made for copper in the liquid phase.

To proceed from 1.5 T_m to room temperature the recommended curve follows the data of White and Tainsh [26] to 55 K and continues through about the mean of results of several workers including Lees [7], Berman and MacDonald [27], White [28], Powell, Rogers and Coffin [29], and Powell, Roder and Hall [30] to link on with the proposed higher temperature curve. The measurements by the last mentioned workers were on one of the purest samples, yet from about 60 K upwards their curve tends to lie below the curves for samples of lower purity, and, at their upper temperature limit of 105 K their value is some 7.5 percent below the present recommendation. Clearly this is unsatisfactory, and further attention should be given to pure copper in the sub-normal temperature region.

Owing to the dearth of data for high-purity copper, the recommended curve has a probable uncertainty of ± 3 percent near room temperature increasing to ± 5 percent at low and high temperatures.

Gold

Much more experimental work is required on gold before any firm recommendations can be made. Only Mikryukov [10] has made determinations of the thermal conductivity of gold at temperatures above 373 K, and the usual dearth of information in the immediate sub-normal temperature region also exists. The measurements of White [31] had extended from liquid helium temperatures to about 150 K and at the upper limit the curves for four specimens had each passed through a minimum and had commenced to increase. Much of this effect was, however, attributed by White to no correction being made for heat transfer by radiation and no definite claim had been made that a true minimum had been obtained. Indeed, White [32] has suggested that the appropriate corrections for specimen Au4 would amount to approximately -0.15 ± 0.03 W cm^{-1} K^{-1} at 150 K, about -0.08 at 125 K, and -0.02 at 100 K. It will be seen that these corrections suffice to remove the minimum for this sample. The most probable curve has been drawn to closely satisfy these corrected values, but the values in this region should be regarded as very tentative and subject to modification.

At higher temperatures the measurements of Mikryukov over the range 330 to 963 K yield Lorenz functions that are in good agreement with the theoretical value, but his electrical resistivity values appear to be high. At his highest temperature Mikryukov's electrical resistivity is 11 percent greater than that of Meechan and Eggleston [23]. But this is not the only uncertainty. The resistivity at 273 K derived from Meechan and Eggleston's value of 2.35×10^{-6} ohm cm at 293 K is about 2.19×10^{-6}. The Jaeger and Diesselhorst [17] value of 2.42×10^{-6} at 291 K converts to 2.27×10^{-6} at 273 K whilst other reported values at 273 K are: Kannuluik [33] 2.13×10^{-6}, Meissner [16] 2.065×10^{-6}, Grüneisen and Goens [34] 2.04×10^{-6} and Damon and Klemens [35] 2.032×10^{-6}. Thus the extreme difference in the values reported for the electrical resistivity of gold at 273 K amounts nearly to 12 percent. Unpublished measurements by R. W. Powell tend to confirm the lowest values. Therefore, in deriving the thermal conductivity values shown by the broken line use has been made of Powell's resistivity values of 2.2, 3.71, 5.52, 7.47, 9.65, and 12.64 μohm cm at 293, 473, 673, 873, 1073, and 1273 K, respectively, and of assumed values for the Lorenz function which increase from 2.37×10^{-8} $volt^2$ K^{-2} at 293 K to 2.45×10^{-8} at 573 K and thereafter remain constant. It is clear that the values at present proposed have but little experimental support. Yet gold might well prove to be an acceptable material for a reference standard. Gold is also a metal of 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 8θ. The lack of information on gold is surprising and further investigations are highly desirable so that the uncertainties of from ± 3 percent in the present most probable values at normal temperature, rising to about ± 6 percent at higher and lower temperatures can be reduced.

Iron

A commercial grade of iron known as Armco iron[*] has been used extensively as a reference standard of thermal conductivity. Hence, recommended values for Armco iron are given separately from those for high-purity iron.

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[*] Typical weight percent composition of Armco iron: 0.015 C, 0.09 O; 0.08 Cu, Ni each; <0.05 Al, Cr, Mn, Mo each; 0.015 Ti, S, Si, V each; 0.005 N, P each; 0.0001 H.

Armco Iron

In 1962, Powell [36], 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 two laboratories for the thermal conductivity of this sample have been published [37, 38] and those of three others have been available privately.

On comparing these five sets of values as given at 100 C intervals, with the suggested 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 proposed values. After taking the averages of the round-robin value at each temperature, differences from the earlier proposal [36] were noted to be + 1. 7% at 1273 K, + 1. 1% at 1173 K, and -1. 1% 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 [39]. 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 unpublished measurements of the National Physical Laboratory. At 1059 K, about 16 K above the Curie temperature, the thermal conductivity ceases to fall and remains almost constant up to the alpha-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.

Below room temperature the National Bureau of Standards and the National Physical Laboratory have obtained values that agree closely for this round-robin sample. Also available are results from the National Bureau of Standards and the Battelle Memorial Institute 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 sub-normal temperatures.

These recommendations are thought to have an accuracy of ± 3 percent below room temperature, ± 2 percent to about 1000 K, the uncertainty probably increasing to about ± 8 percent at 1600 K.

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 [40]. 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.

High Purity Iron

The thermal conductivity of high purity iron has been plotted separately in Figure 7. Except at low temperatures any real differences in the two grades of iron are so small that they tend to be masked by the experimental inaccuracies. Fortunately, the Oak Ridge National Laboratory workers, Fulkerson, Moore and McElroy [41] have used the same radial heat flow method for measurements on both Armco iron and an 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 unpublished results obtained at the NPL 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. The reliability of these recommendations is thought to be similar to those for Armco iron.

In view of the scientific and technical importance of iron it is considered appropriate to include a brief discussion of the present state of knowledge regarding the thermal conductivity of liquid iron. This seems to be particularly desirable since 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 [42] reported an increase in the resistivity of about 9 percent for the liquid state, and Mokrovskii and Regel [25] 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 ± 0.05 W cm^{-1} K^{-1}. Grosse [12], by using only the electrical resistivity data of Mokrovskii and Regel, predicted a value of 0.39 W cm^{-1} K^{-1} at the melting point followed by a smooth curve rising to a maximum value of 0.47 W cm^{-1} K^{-1} at 3000 K and falling to 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 values at present available which serves to limit the reliability of any derived thermal conductivity data for molten iron.

For the thermal conductivity of high purity iron at temperatures below 1.5 T_m, values were calculated as already explained in terms of a value of $\rho_0 \approx 3.27 \times 10^{-8}$ ohm cm due to Arajs, Oliver and Dunmyre [43] who appear to have worked with the purest iron so far studied. These workers also measured the thermal conductivity of this iron, and the results are given in Figure 7 and Table 7 by curves 34 and 35. These experimental curves have not been used since the value of T_m appears to be displaced on the high side by several degrees, and, as is evident from Table 1, the β value derived from the thermal conductivity data is much smaller than that derived from ρ_0. Above 1.5 T_m, the recommended curve continues smoothly, following the general trend, to join the higher temperature curve at about 250 K.

Manganin (copper 84%, manganese 12%, nickel 4% by weight)

Relatively few determinations have been made on manganin and those of Lees [7] and of Jaeger and Diesselhorst [17] are old measurements. In spite of this, their values are thought to be acceptable, since these were workers of high repute and it is only because of the low purity of the metals then available that some of their thermal conductivity values for metals have been replaced by later values. With a complex alloy such as manganin, impurities in the constituent elements will be likely to have a reduced effect.

The determinations to low temperatures were made by Zavaritskii and Zeldovich [44] to a reported accuracy of 5 percent on an alloy of slightly different composition (3% instead of 4% nickel). The effect of this is uncertain but should be small.

The three available sets of data are in good agreement and serve to give values for the thermal conductivity of manganin for the range 3 to 373 K. Further information is required to provide values to higher temperatures.

Mikryukov and Chou [45] however have studied from about 350 to 970 K a series of copper alloys, each containing 0.9 percent of beryllium and with manganese contents of 3.65, 5.47, 7.30, and 9.12 percent, respectively. Extrapolation of these values to a manganese content of 12 percent leads to a value at 373 K which is some 26 percent lower than the recommended curve. This indicates that the inclusion of a smaller weight percent of beryllium than nickel causes a greater decrease in thermal conductivity. Similar treatment of the Russian data for higher temperatures leads to a curve which from 373 to 600 K is parallel to that of Jaeger and Diesselhorst and then turns up. This provides some justification for the extrapolated values that have been suggested for use at higher temperatures pending the availability of further experimental data for manganin. The values near room temperature should be accurate to about ± 3 percent, the uncertainty increasing to nearly ± 10 percent at higher temperatures.

Mercury

Until recently the thermal conductivity of liquid mercury, even at room temperature, was very uncertain. Recent work has, however, led to the availability of three sets of data [46, 47, 48] carried out in Great Britain, the USSR and the USA, which agree to within about 10 percent at 350 K and more closely at higher temperatures.

In the case of liquid mercury it is again possible to refer to the predicted values of Grosse [12]. For this metal the electrical conductivity has been determined by Birch [49] and decreases with increase of temperature along a smooth curve to a value of about 10 $\text{ohm}^{-1}\ \text{cm}^{-1}$ at the critical point of 1733 K indicated by this experiment.

In this instance, Grosse used a value of the Lorenz function of $2.60 \times 10^{-8}\ V^2\ K^{-2}$ 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 given in Figure 9. A maximum value is indicated at about 760 K, followed by a fall at an increasing rate to meet the estimated saturated vapor value of about 0.001 $\text{W cm}^{-1}\ \text{K}^{-1}$ at about 1720 K.

The difference between Grosse's predicted curve and the measured values at the highest 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. The probable uncertainty is ± 5 percent.

In the solid phase, mercury has a rhombohedral crystal structure and its thermal conductivity will be dependent on the crystal orientation. This phase is not included in the present treatment.

Platinum

Platinum has been suggested by Powell and Tye [50] and Slack [51] as a promising material for consideration as a thermal conductivity reference standard, yet the determination of a curve that represents the true variation with temperature of the thermal conductivity of this metal is proving unusually difficult.

Most earlier determinations have followed that of Holm and Stormer [52] with a linear increase of nearly 30 percent from room temperature to 1000 C. Then came the measurements by Powell and Tye [50] on two high-purity (99.999^{+}%) samples of 1/4 inch and 1/2 inch diameter that indicated the thermal conductivity to be almost constant over this range of temperature. Their values could however be fitted by a very shallow concave curve and later measurements by Powell, Tye and Woodman [53] on the smaller rod have given a definite negative temperature coefficient from about 80 to 300 K, linking on well with the earlier measurements at the upper temperature limit.

Thus a very gradual minimum occurs in the thermal conductivity of this sample at a temperature well above room temperature, say at about 520 K.

Very recent preliminary measurements by Flynn [54] at the National Bureau of Standards on another bar of platinum of lower purity (99.98%) have given quite different results. The shallow minimum occurs at 223 K where the NBS value is lower than that of the NPL by some 9 percent; at about 500 K the curves cross and at 1000 K the NBS value exceeds that of the NPL by about 10 percent.

For a high purity (99.999$^+$%) rod of platinum, Laubitz [55] has reported for the range 300 to 1000 K values that agree with those derived for high purity (99.999%) platinum by Martin and Sidles [56] from thermal diffusivity measurements. At that time Martin and Sidles made what seemed to be a surprising claim that the thermal conductivity of another sample of platinum of lower purity (99.9%) was higher at high temperatures. Laubitz's measurements were for one of the purest samples so far tested, yet at just above 300 K his experimental points are lower than those of Powell, Tye and Woodman by from 5 to 7.5 percent and lower than Flynn's by 0.5 to 3 percent; at about 1000 K his points are lower than Flynn's by 3 to 5.5 percent but higher than Powell and Tye's by 5 to 7.5 percent.

Of the indirect determinations that have been restricted to temperatures above 1200 K those of Hopkins and Griffith [57] tend to support the measurements of Holm and Stormer whilst those of Wheeler [58] tend to support Powell and Tye, but these two series of indirect determinations differ by nearly 20 percent.

The present situation is difficult to understand, particularly as the thermal conductivity differences do not seem to be reflected in similar electrical conductivity determinations that have been made. Either some, as yet undetermined, variable is affecting the thermal conductivity of platinum or certain experimental uncertainties must greatly exceed their estimated values. That these uncertainties persist near room temperature is most surprising.

Much more experimental work is clearly essential over the full temperature range and this should include the interchange of specimens between different workers in the hope that this might help to determine whether the differences are purely experimental or are related to particular specimens.

On the assumption that the differences are mainly experimental, a very tentative most probable curve has been indicated by the broken line in Figure 10. This has a minimum value at about 520 K.

By way of an independent indication of the need for clarification of this matter, the recent measurements of Kobushko, Merisov and Khotkevich [59] might be mentioned. This group of Russian workers have proposed a variant of the electrically heated wire method for determining the thermal conductivity of metals to high temperatures, and have selected platinum as the metal with which to check this method. The values which they obtained were regarded as satisfactory since they agreed well with data reported for platinum by Vargaftig [60]. These would no doubt be the original data of Holm and Stormer, and until the present uncertainties in the thermal conductivity of platinum have been resolved, platinum is hardly suitable for this type of test.

Platinum 60%-Rhodium 40% Alloy

Two sets of experimental data are available for this alloy at high temperatures and the agreement between them is very poor.

The National Bureau of Standards is responsible for one of these sets of measurements [61] in which electrical resistivity determinations were also included. Since these data have enabled values of the Lorenz function to be calculated and good agreement with the theoretical value is indicated, these thermal conductivity values have been given preference. As reported, the Lorenz function follows a slightly wavy course with a minimum at 773 K and a maximum at 1173 K. Hence, in deciding on the recommended values a slight adjustment has been made to give a Lorenz function which decreases smoothly with increase in temperature. Some extrapolation has been included at both ends of the reported temperature range. The values for the experimentally measured range should be accurate to about ± 3 percent.

Silver

The situation in the case of silver is similar to that of gold in that surprisingly few determinations have been made of its thermal conductivity at temperatures above 373 K.

Bailey [62] extended the measurements on Lees' specimen to higher temperatures, but this sample was clearly not of the highest purity. The minimum value obtained at 660 K is very questionable. The other two workers, Evans [63] and Mikryukov [10] 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 [7] and Jaeger and Diesselhorst [17] have obtained for silver Lorenz functions in the range 2.31×10^{-8} to 2.39×10^{-8} whereas Mikryukov's value at 338 K is 2.45×10^{-8} volt^2 K^{-2}. This is why the recommended curve has been drawn below that of Mikryukov in this region. The recommended curve also agrees reasonably well with the data of the other named workers after allowance has been made for the electrical conductivities of their samples being less than that of pure silver. Here the uncertainty is about ± 2 percent increasing to about ± 5 percent at extreme temperatures.

Further measurements are considered desirable for pure silver.

Tungsten

The TPRC has located 103 sets of data for the thermal conductivity of tungsten, yet, ignoring the very low values reported for some samples of low density, only three sets of measurements have been in the temperature range 700 to 1100 K.

The values now recommended for the thermal conductivity of tungsten differ condsiderably, particularly at high temperatures, from the earlier TPRC recommended values. Measured values for tungsten in the region 80 to 110 K by deHaas and deNobel [64] and White and Woods [65] agree well and appear to relate to samples of high purity. At the low temperature end the curve now recommended starts in the region of these values, agrees closely with the values of Tye [66], Powell and Tye [21], and Moore, Graves, Fulkerson and McElroy [67] and has been smoothly continued from 1273 to 3500 K. Over this later range it lies within ± 5 percent of measurements by Wheeler [58], Osborn [68], Gumenyuk and Lebedev [69], Timrot and Poletskii [70], and the measurements of Platunov and Federov [71] 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 assumed 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 dealt with in the foregoing paragraphs the Lorenz function is considered to tend toward the theoretical value of 2.443×10^{-8} volt^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. For a lattice component of thermal conductivity of this magnitude to persist to high temperatures is unusual, thus, whilst these present recommended values are thought to be within ± 3 to ± 5 percent of the true values, further confirmatory work on tungsten still seems to be required.

TABLE 1. DERIVED VALUES OF β AND ASSOCIATED CONSTANTS FOR HIGH-PURITY METALS

Metal	Curve* No.	Author(s)	Year	Purity (%)	$\frac{\rho_{273K}}{\rho_{4.2K}}$	ρ_0** (ohm cm)	β (calculated from ρ_0) (cm K^2 watt^{-1})	β (derived from k data) (cm K^2 watt^{-1})	a	m	n	α'' (cm K^{1-m} watt^{-1})	α' (cm K^{1-n} watt^{-1})	1965 "highest" $\rho_{300K}/\rho_{4.2K}$
Aluminum	18	Andrews, F. A., Webber, R. T., and Spohr, D. A.	1951	99.996^+	840	3.04×10^{-9}	0.124	0.129	0.31	2.61	2.30	0.50×10^{-5}		35,500 [72]
Copper	120	White, G. K. and Tainsh, R. J.	1960	99.999^+	$1938\ (=\frac{\rho_{294K}}{\rho_{4.2K}})$	0.865×10^{-9}	0.0354	0.0348	0.19	2.59	2.40	0.416×10^{-5}		29,000 [73]
Gold	7	White, G. K.	1953	99.999^+				0.225	0.46	2.46	2.00	4.60×10^{-5}		6,040 [74]
Iron	34	Arajs, S., Oliver, B. F., and Dunmyre, G. R.	1965	99.998^+	$302\ (=\frac{\rho_{297K}}{\rho_{4.2K}})$	32.7×10^{-9}	1.34	0.714	0.37	2.47	2.10	2.05×10^{-5}		1,963‡‡[75]
Platinum	4	Mendelssohn, K. and Rosenberg, H. M.	1952	99.999	$202\ (=\frac{\rho_{293K}}{\rho_{20K}})$			0.433	‡	‡	2.10	‡	30.1×10^{-5}	7,000 [76]
Silver	14	White, G. K.	1953	99.999^+				0.0254	0.55	2.75	2.20	0.73×10^{-5}		1200-1900 [77]
Tungsten	17	de Haas, W. J. and de Nobel, J.	1938		2778	1.7×10^{-9}	0.0696	0.015	‡	‡	2.40	‡	2.06×10^{-5}	147,000 [78]

*These are the curve numbers in the respective figures and tables of the metals.

**The value of ρ at 4.2K is used approximately as ρ_0.

‡The low-temperature thermal conductivity data available for platinum and tungsten are not sufficient for determining these constants, and hence an average value of α' is given.

‡‡This value is for an iron whisker of 40 μ diameter and with axis along <100> direction.

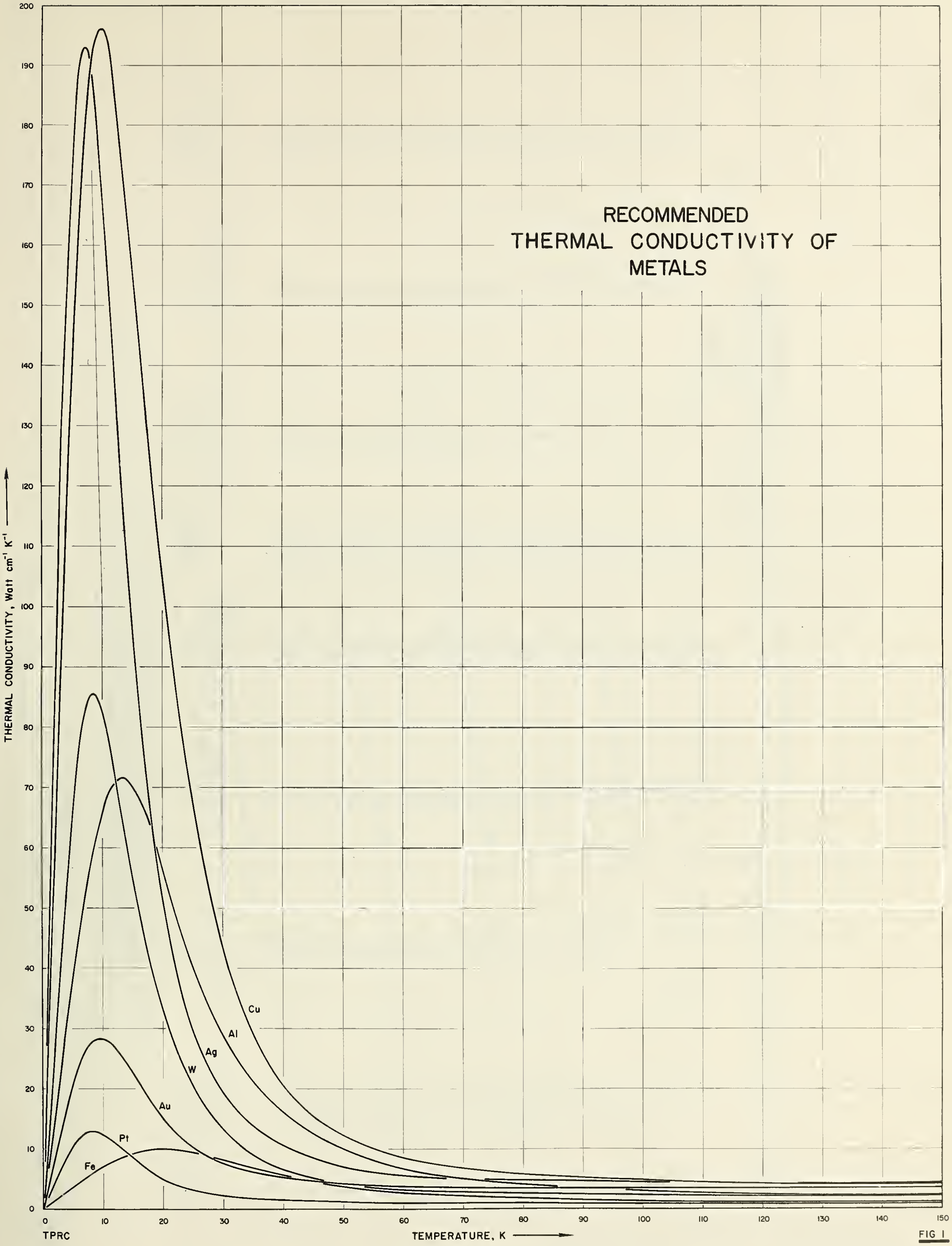
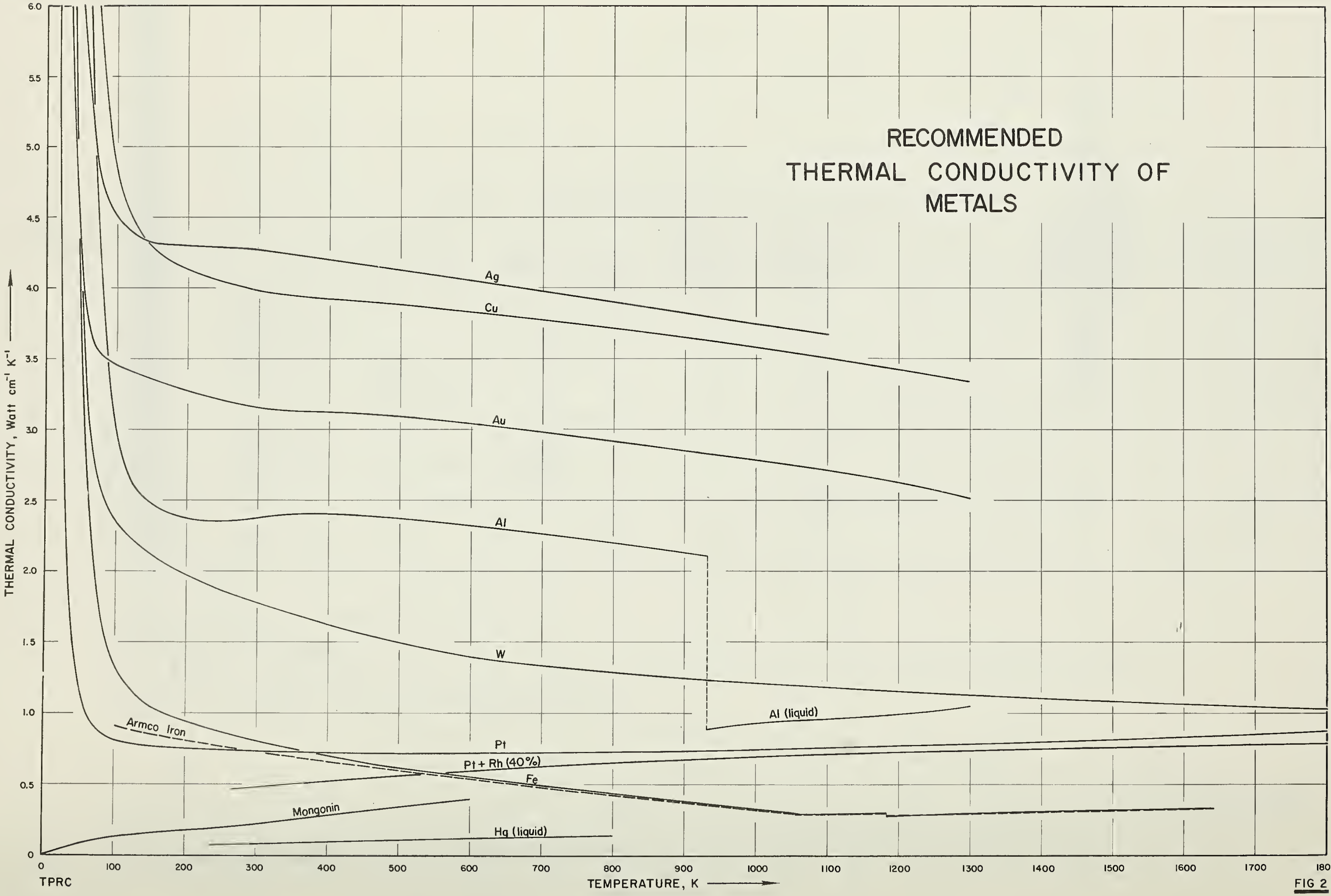

RECOMMENDED
THERMAL CONDUCTIVITY OF
METALS
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
Cu
Al
Ag
W
Au
Pt
Fe
TPRC

FIG 1



RECOMMENDED THERMAL CONDUCTIVITY OF METALS

FIG 2

TABLE 2a. RECOMMENDED THERMAL CONDUCTIVITY OF METALS AT LOW TEMPERATURES*

Thermal Conductivity, k, Watt cm^{-1} K^{-1}

T, K	Aluminum	Copper	Gold	Iron	Manganin**	Platinum	Silver	Tungsten	T, K
	99.996$^+$% pure $\rho_0 = 0.00315$ μohm cm	99.999$^+$% pure $\rho_0 = 0.000851$ μohm cm	99.999$^+$% pure $\rho_0 = 0.0055$ μohm cm	99.998$^+$% pure $\rho_0 = 0.0327$ μohm cm		99.999% pure $\rho_0 = 0.0106$ μohm cm	99.999$^+$% pure $\rho_0 = 0.00062$ μohm cm	99.99$^+$% pure $\rho_0 = 0.0017$ μohm cm	
0	0	0	0	0	0	0	0	0	0
1	7.8	28.7	4.4	0.75	0.0007	2.31	39.4	14.4	1
2	15.5	57.3	8.9	1.49	0.0018	4.60	78.3	28.7	2
3	23.2	85.5	13.1	2.24	0.0031	6.79	115	42.6	3
4	30.8	113	17.1	2.97	0.0046	8.8	147	55.6	4
5	38.1	138	20.7	3.71	0.0062	10.5	172	67.1	5
6	45.1	159	23.7	4.42	0.0078	11.8	187	76.2	6
7	51.5	177	26.0	5.13	0.0095	12.6	193	82.4	7
8	57.3	189	27.5	5.80	0.0111	12.9	190	85.3	8
9	62.2	195	28.2	6.45	0.0128	12.8	181	85.1	9
10	66.1	196	28.2	7.05	0.0145	12.3	168	82.4	10
11	69.0	193	27.7	7.62	0.0162	11.7	154	77.9	11
12	70.8	185	26.7	8.13	0.0180	10.9	139	72.4	12
13	71.5	176	25.5	8.58	0.0197	10.1	124	66.4	13
14	71.3	166	24.1	8.97	0.0215	9.3	109	60.4	14
15	70.2	156	22.6	9.30	0.0232	8.4	96	54.8	15
16	68.4	145	20.9	9.56	0.0250	7.6	85	49.3	16
18	63.5	124	17.7	9.88	0.0285	6.1	66	40.0	18
20	56.5	105	15.0	9.97	0.0322	4.9	51	32.6	20
25	40.0	68	10.2	9.36	0.0410	3.15	29.5	20.4	25
30	28.5	43	7.6	8.14	0.0497	2.28	19.3	13.1	30
35	21.0	29	6.1	6.81	0.0583	1.80	13.7	8.9	35
40	16.0	20.5	5.2	5.55	0.067	1.51	10.5	6.5	40
45	12.5	15.3	4.6	4.50	0.075	1.32	8.4	5.07	45
50	10.0	12.2	4.2	3.72	0.082	1.18	7.0	4.17	50
60	6.7	8.5	3.8	2.65	0.097	1.01	5.5	3.18	60
70	5.0	6.7	3.58	2.04	0.110	0.90	4.97	2.76	70
80	4.0	5.7	3.52	1.68	0.120	0.84	4.71	2.56	80
90	3.4	5.14	3.48	1.46	0.127	0.81	4.60	2.44	90
100	3.0	4.83	3.45	1.32	0.133	0.79	4.50	2.35	100

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* In the table the third significant figure is given only for the purpose of comparison and for smoothness and is not indicative of the degree of accuracy.

**Values for manganin are taken from the measurements of Zavaritskii and Zeldovich [44], since Equations (1) to (4) do not apply to an alloy.

TABLE 2b. RECOMMENDED THERMAL CONDUCTIVITY OF METALS AT MODERATE AND HIGH TEMPERATURES*

Thermal Conductivity, k, Watt cm^{-1} K^{-1}

T, K	Aluminum	Copper	Gold	Iron (Armco)	Iron	Manganin	Mercury	Platinum	Pt + Rh (40%)	Silver	Tungsten	T, K
100	3.0	4.83	3.45	0.913	1.32	0.133		0.79		4.50	2.35	100
150	2.47	4.28	3.35	0.854	1.04	0.156		0.762		4.32	2.10	150
200	2.37	4.13	3.27	0.804	0.94	0.172		0.748		4.30	1.97	200
250	2.35	4.04	3.20	0.764	0.865	0.193	[0.073]	0.737		4.28	1.86	250
273	2.36	4.01	3.18	0.747	0.835	0.206	[0.078]	0.734	(0.464)	4.28	1.82	273
300	2.37	3.98	3.15	0.727	0.803	0.222	[0.084]	0.730	(0.476)	4.27	1.78	300
350	2.40	3.94	3.13	0.691	0.744	0.250	[0.092]	0.726	(0.497)	4.24	1.70	350
400	2.40	3.92	3.12	0.657	0.694	(0.279)	[0.098]	0.722	(0.516)	4.20	1.62	400
500	2.37	3.88	3.09	0.593	0.613	(0.338)	[0.109]	0.719	0.555	4.13	1.49	500
600	2.32	3.83	3.04	0.531	0.547	(0.397)	[0.120]	0.720	0.589	4.05	1.39	600
700	2.26	3.77	2.98	0.473	0.487		[0.127]	0.723	0.623	3.97	1.33	700
800	2.20	3.71	2.92	0.422	0.433		[0.130]	0.729	0.650	3.89	1.28	800
900	2.13	3.64	2.85	0.372	0.380			0.737	0.672	3.82	1.24	900
1000	[0.93]**	3.57	(2.78)	0.323	0.326			0.748	0.692	(3.74)	1.21	1000
1100	[0.96]	3.50	(2.71)	0.294	0.297			0.760	0.711	(3.66)	1.18	1100
1200	[0.99]	3.42	(2.62)	0.287	0.282			0.775	0.727	(3.58)	1.15	1200
1300	[1.02]	(3.34)†	(2.51)	0.296	0.299			0.791	0.738		1.13	1300
1400				0.305	0.309			0.807	0.748		1.11	1400
1500				0.314	0.318			0.824	(0.758)		1.09	1500
1600				(0.322)	(0.327)			0.842	(0.768)		1.07	1600
1700								0.860	(0.778)		1.05	1700
1800								0.877	(0.787)		1.03	1800
1900								(0.895)			1.02	1900
2000								(0.913)			1.00	2000
2200											0.98	2200
2400											0.96	2400
2600											0.94	2600
2800											0.925	2800
3000											0.915	3000
3200											0.905	3200
3400											0.900	3400
3600											(0.895)	3600
930	2.11 (Solid-liquid phase transformation)											
940	[0.91]											
1059				0.293	0.296 (Sharp change in slope)							
1180				0.296	0.299 (α-γ structural transformation)							
1190				0.286	0.280							
1820					[0.35]‡							

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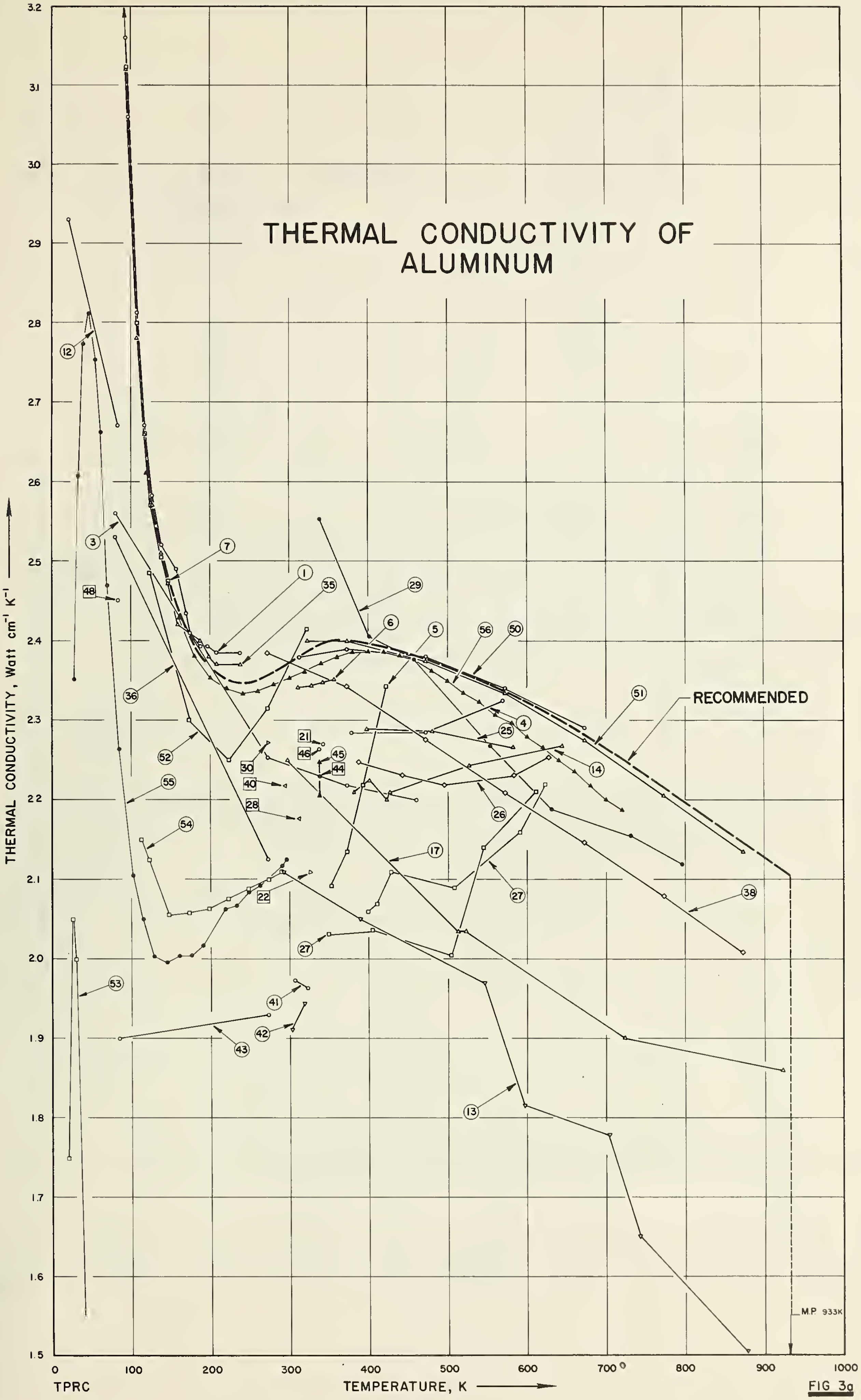
[*] In the table the third significant figure is given only for the purpose of comparison and for smoothness and is not indicative of the degree of accuracy.

[**] Values in square brackets are for liquid state.

[†] Values in parentheses are extrapolated.

[‡] Estimated.


THERMAL CONDUCTIVITY OF ALUMINUM
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
3.2
3.1
3.0
2.9
2.8
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
0
100
200
300
400
500
600
700
800
900
1000
RECOMMENDED
M.P. 933K
1
3
4
5
6
7
12
13
14
17
21
22
25
26
27
27
28
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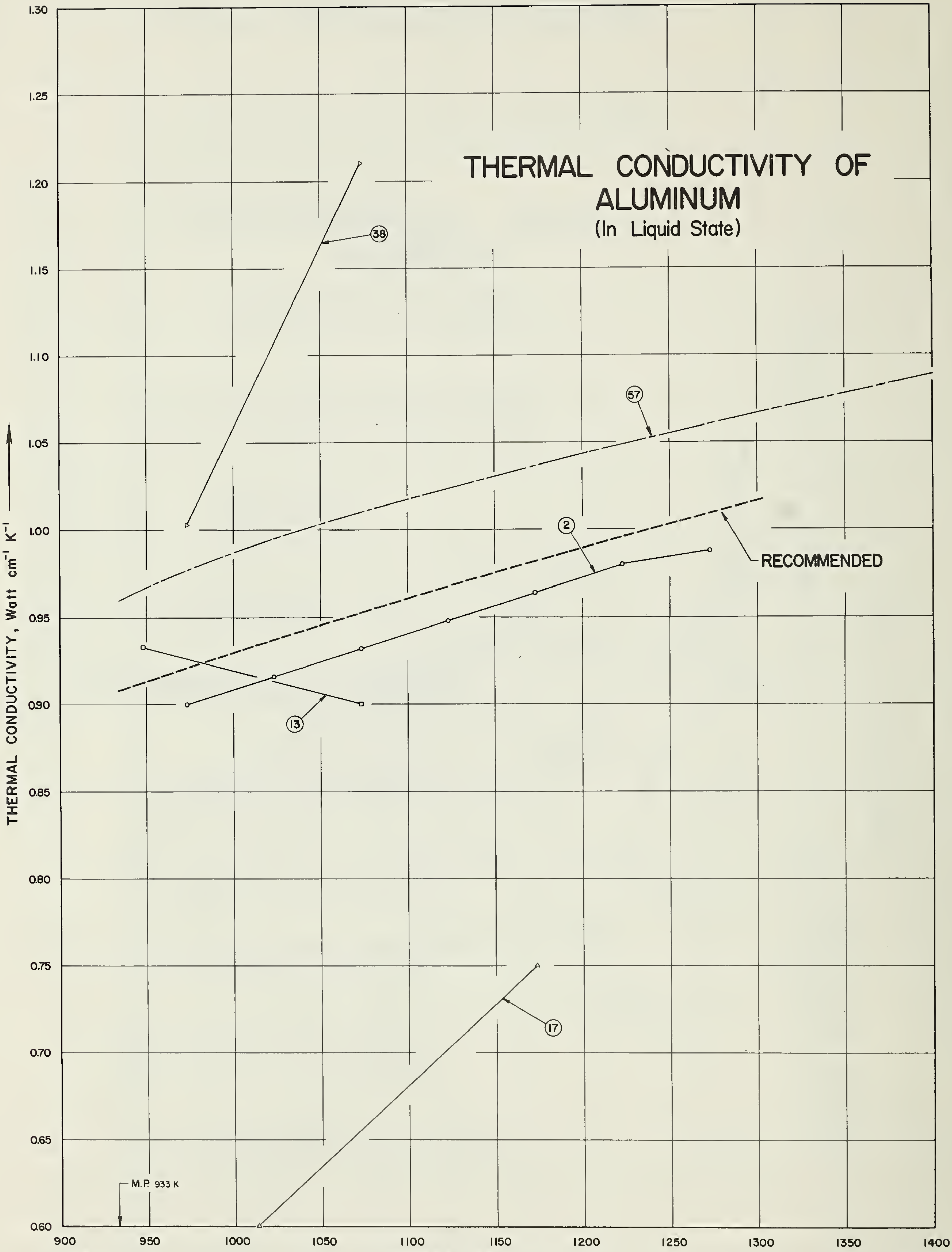
TPRC

FIG 3a


THERMAL CONDUCTIVITY OF ALUMINUM
(In Liquid State)
THERMAL CONDUCTIVITY, Watt 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
38
57
2
RECOMMENDED
13
17
M.P. 933 K

TPRC

FIG 3b

TABLE 3. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	114	Powers, R.W., Schwartz, D., and Johnston, H. L.	1951	L	25-238		99. 99$^+$ pure; cold-drawn by 55% reduction.
2	658	Powell, R.W., Tye, R. P., and Metcalf, S.C.	1965	C	973-1273	S. P.	S. P. (super pure) aluminum from British Aluminum Co.; in molten state; electrical resistivity 26. 3 x 10^{-6} ohm cm at 700 C and 30. 9 x 10^{-6} ohm cm at 1000 C; Morgan Crucible Co. grade EY 9 graphite used as comparative standard.
3	93	Mannchen, W.	1931	L	80-460		Extremely pure.
4	20	Bungardt, W. and Kallenbach, R.	1951	L	379-570		99. 92 pure; 0. 04 Si, 0. 03 Fe, 0. 006 Cu, 0. 005 Ti; annealed at 450 C.
5	53	Grand, C. and Villey, J.	1927	E	353-423		High purity.
6	17	Bode, K.-H. and Fritz, W.	1958	L	311-357		99. 986 pure; 0. 003 Cu, 0. 0045 Fe, 0. 0062 Si, 0. 0001 Mg.
7	491	Johnston, H. L.	1948	C	94-147		99. 99$^+$ pure.
8	104	de Nobel, J.	1951	L	16-87		High purity; as rolled.
9	36	Eucken, A. and Warrentrup, H.	1935	L	81, 273		99. 7 pure; annealed bar.
10	66	Hall, W.J., Powell, R. L., and Roder, H.M.	1957	L	4. 0-127	S. C.	99. 995 pure; single crystal.
11	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Al-1	Very pure; annealed in vacuo at 300 C.
12	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Al-100	Commercially pure; annealed in vacuo at 250 C.
13	85	Konno, S.	1919	L	389-1073		Pure.
14	127	Schofield, F.H.	1925	L	382-645		99. 7 pure; annealed at 450 C.
15	97	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2. 5-46		99. 994 pure; annealed polycrystal.
16	122	Rosenberg, H. M.	1955	L	2. 6-42		99. 994 pure; annealed polycrystal.
17	15	Bidwell, C.C. and Hogan, C. L.	1947	F	298-1173	Al-1	99. 95 pure.
18	3	Andrews, F.A., Webber, R. T., and Spohr, D.A.	1951	L	2. 6-17	Al-1	99. 996$^+$ pure; 0. 001 Mg, 0. 001 Si, 0. 0006 Fe, 0. 0004 Cu, 0. 0004 Na; single crystal; residual electrical resistivity R_0 = 3. 04 x 10^{-9}; $R_{273\,K}$ = 2. 55 x 10^{-6} ohm cm; R_{273}/R_0 = 840.
19	3	Andrews, F.A., Webber, R. T., and Spohr, D.A.	1951	L	2. 1-22	Al-2	Same composition as above but R_0 = 3. 85 x 10^{-9}; R_{273K} = 2. 50 x 10^{-6} ohm cm; R_{273}/R_0 = 676.
20	3	Andrews, F.A., Webber, R. T., and Spohr, D.A.	1951	L	2. 4-27	Al-3	99. 995$^+$ pure; 0. 002 Mg, 0. 001 Si, traces of Fe, Cu and Na; annealed polycrystal; residual electrical resistivity R_0 = 5. 51 x 10^{-9}; R_{273K} = 2. 57 x 10^{-6} ohm cm; R_{273}/R_0 = 467.
21	276	Weeks, J. L. and Seifert, R. L.	1953	C	343. 2	2S-Al	2S Aluminum with density equal to 2. 7 g cm^{-3}.
22	230	Smith, A.W.	1925	L	326		99. 97$^+$ pure.
23	400	Mendelssohn, K. and Renton, C. A.	1953	L	0. 36-0. 81	Al-2	Polycrystalline; in superconducting state.
24	404	Andrews, F.A., Webber, R. T., and Spohr, D.A.	1951	L	2. 6-16		99. 996$^+$ pure; single crystal; machined and then etched; crystal slightly damaged by machining.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 3. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM (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	405	Hase, R., Heierberg, R., and Walkenhorst, W.	1940	E	398-583		99.992 Al, 0.0030 Fe, 0.0024 Cu, 0.0027 Si; cast at 700 C in a mold having a temperature of 200 C, and drawn to 6.5 mm diameter.
26	405	Hase, R., Heierberg, R., and Walkenhorst, W.	1940	E	388-628		99.93 Al, 0.038 Fe, 0.0022 Cu, 0.03 Si; cast at 700 C in a mold having a temperature of 200 C, and drawn to 6.5 mm diameter.
27	405	Hase, R., Heierberg, R., and Walkenhorst, W.	1940	E	399-623		99.5 Al; cast at 700 C in a mold having a temperature of 200 C, and drawn to 6.5 mm diameter.
28	406	Van Dusen, M. S.	1922	C	313.2		99.7 pure.
29	617	Mikryukov, V. E.	1957		338-797		99.99 pure; polycrystal; at 64.8 C, ρ (electrical resistivity) = 3.15×10^{-6} ohm cm and L (Lorenz number) = 2.34×10^{-8} V^2K^{-2}; at 184 C, $\rho = 4.65 \times 10^{-8}$ and $L = 2.40 \times 10^{-8}$; at 357.8 C, $\rho = 6.82 \times 10^{-6}$ and $L = 2.39 \times 10^{-8}$; at 253.4 C, $\rho = 9.14 \times 10^{-6}$ and $L = 2.41 \times 10^{-8}$.
30	410	Eucken, A. and Warrentrup, H.	1935	E, R	273.2	Al-1	99.7 Al.
31	409	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	409	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	409	Zavaritskii, N. V.	1958	L	0.16-1.2	Al-2	Same specification as the above specimen Al-1; in superconducting state.
34	409	Zavaritskii, N. V.	1958	L	0.21-1.2	Al-2	The above specimen in normal state.
35	495	Powers, R. W. and Schwartz, D.	1949	L	38-238	Alcoa	99.99^{+} pure; cold-drawn.
36	496	Aoyama, S. and Ito, T.	1940	C	80, 273		Pure.
37	497	Johnston, H. L.	1949	L	25-82	Alcoa	99.99^{+} pure; cold-drawn.
38	490	Hogan, C. L.	1950	F	273-1073		99.996 pure.
39	498	Howling, D. H., Mendoza, E., and Zimmerman, J. E.	1955	P	1.8-3.9		99.998 pure; annealed in vacuo for 5 hrs at 500 C; specimen dia. 2.00 mm length 9.88 cm.
40	504	Parker, W. J., Jenkins, R. J., Butler, C. P., and Abbott, G. L.	1960	P	295.2		Pure; density (at 20 C) 2.70 g cm^{-3}.
41	618	Fritz, W. and Bode, K.-H.	1960	C	307-321		Commercially pure; specimen dia. 20 mm length 18 mm; using yellow brass as standard.
42	618	Fritz, W. and Bode, K.-H.	1960	C	303-318		Commercially pure; specimen dia. 20 mm length 18 mm; using aluminum as standard.
43	619	Schott, R.	1916	L	85-273		Commerically pure.
44	591	Jones, T. I., Street, K. N., Scoberg, J. A., and Baird, J.	1963	C	338.2		0.15 U; as cast.
45	591	Jones, T. I., Street, K. N., Scoberg, J. A., and Baird, J.	1963	C	338.2		0.15 U; heat treated at 620 C for 5 days.
46	591	Jones, T. I., Street, K. N., Scoberg, J. A., and Baird, J.	1963	C	338.2		99.99 pure; extruded.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 3. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM (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	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Al-3	From same cast piece as Al-1; drawn and annealed; 2.5% stretched; recrystallized by annealing; grain size 5 cm to 15 cm long.
48	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Al-101	Same material as Al-100; tempered then 3% stretched; recrystallized by annealing; thermal conductivity measuring length = 2 crystal grains.
49	57	Gruneisen, E and Goens, E.	1927	L	21, 83	Al-21	Moderately pure; single crystal; grown by recrystallization.
50	659	Powell, R.W., Tye, R.P. and Woodman, M.J.	1965	C	313-673	S. P.	S P. (super pure) aluminum rod from British Aluminum Co., 2.53 cm in diameter and 20.4 cm long; electrical resistivity 2.86×10^{-6} ohm cm at 40 C and 7.12×10^{-6} ohm cm at 400 C; Armco iron used as comparative standard; energy also measured by waterflow calorimeter.
51	659	Powell, R.W., Tye, R.P. and Woodman, M.J.	1965	L	323-873	S. P.	S.P. (super pure) aluminum; 99.993 pure; British Aluminum Co.; 2.81 cm in diameter and 28.0 cm long; electrical resistivity 2.98×10^{-6} ohm cm at 50 C and 9.92×10^{-6} ohm cm ohm cm at 50 C; energy measured in terms of electrical input and also by waterflow calorimeter.
52	659	Powell, R.W., Tye, R.P. and Woodman, M.J.	1965	L	123-323	S. P.	S.P. (super pure) aluminum from British Aluminum Co.; with square cross section of 0.44 cm side; 8.0 cm long; electrical resistivity 0.74×10^{-6} ohm cm at -150 C and 3.02×10^{-6} ohm cm at 50 C; energy measured in terms of electrical input.
53	672	Gladun, C. and Holzhauser, W.	1964	L	4-50		99.99 pure.
54	88	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 ohm cm^{-3} at 0 C.
55	226	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.
56	‡	Flynn, D.R.	1965		120-720		No details.
57	694	Grosse, A.V.	1964		933.4-8650		Calculated from electrical resistivity according to the Wiedemann-Franz-Lorenz law.

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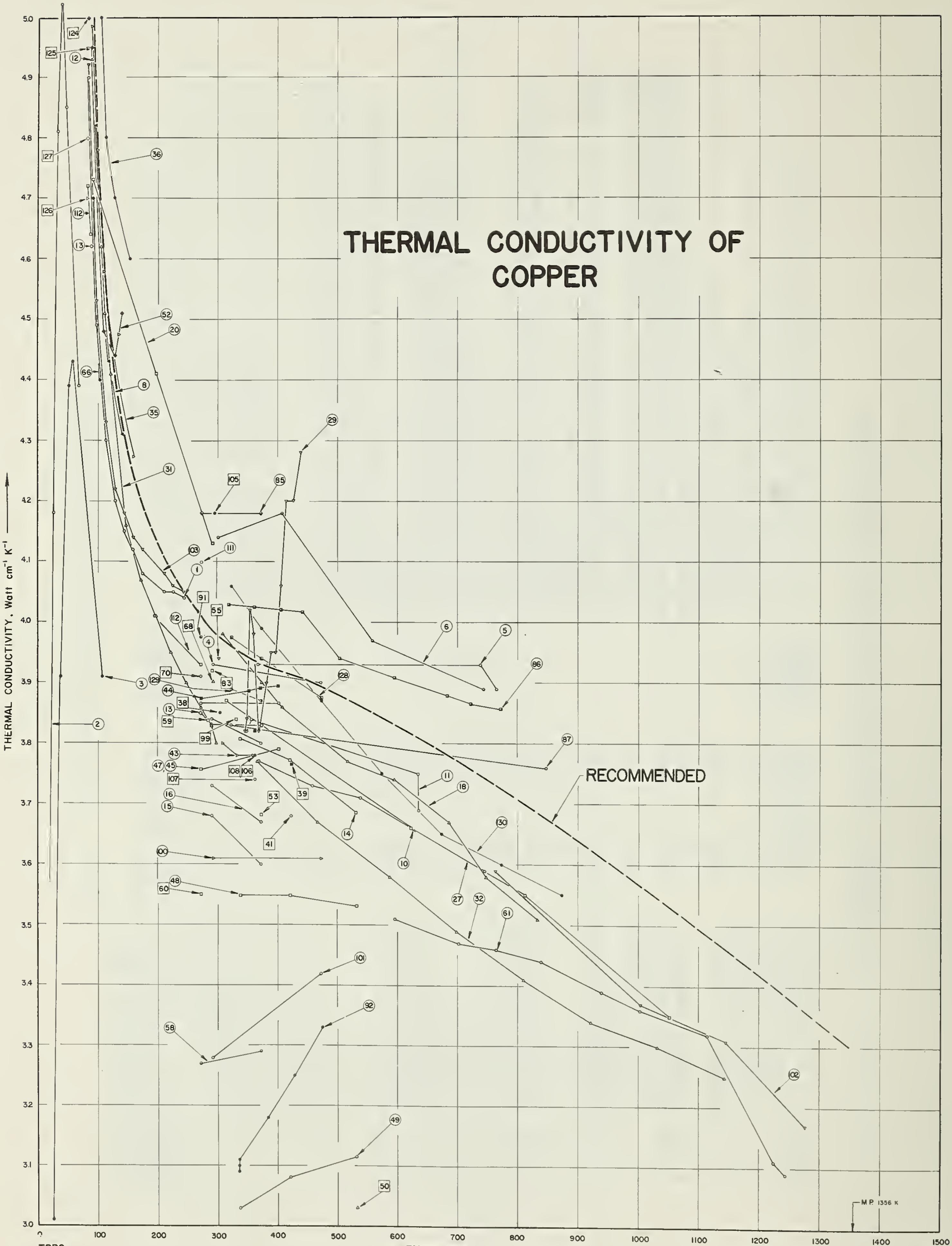
*See TPRC Data Book Vol. 1, Chapter 1, References

‡Private Communication, March 1965



THERMAL CONDUCTIVITY OF COPPER

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FIG 4

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	114	Powers, R.W., Schwartz, D., and Johnston, H.L.	1950	L	23-245	OFHC Cu	Free from oxygen; high conductivity.
2	154	Zavaritskii, N.V., and Zeldovich, A.G.	1956	L	2.9-70	1	Approx. 0.20 Ni; 0.10 O; approx. 0.05 each of As, Sb, Fe, Pb, and Sn, approx. 0.01 S; annealed.
3	154	Zavaritskii, N.V., and Zeldovich, A.G.	1956	L	2.4-108	2	Same as above, but unannealed.
4	135	Smith, C.S., and Palmer, E.W.	1935	L	293, 473		99.986 pure; 0.022 O, 0.0016 Fe, 0.0015 S; annealed at 550 C.
5	124	Sager, G.F.	1930	P	368-766	1	Electrolytically pure; annealed for about 10 min. at a bright red heat, preliminary run.
6	124	Sager, G.F.	1930	P	302-744	2	Electrolytically pure; annealed for about 10 min. at a bright red heat.
7	90	Lucks, C.F., and Deem, H.W.	1957	L	1456;1550		99.972 pure; 0.02 Ag, 0.002 Al, 0.002 Fe, traces of Ni, Mg, Si, O and Ca; in molten state.
8	109	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, traces of Sn, Te, Ag, and Bi; annealed in helium 4 hrs at 400 C, cooled slowly to 200 C, and then kept in helium at 200 C for 8 hrs.
9	152	Wilkinson, K.R., and Wilks, J.	1949	L	10-20		Electrical copper wire; annealed.
10	108	Pott, F.P.	1958	E	315-1058		Commercial electrolytic copper.
11	84	King, R.W.	1918	P	349-636		Pure; cold-drawn.
12	95	Meissner, W.	1915	E	21-374	Cu I	Electrolytically pure; wire.
13	95	Meissner, W.	1915	E	22-375	Cu II	Electrolytically pure but purity lower than the above specimen.
14	52	Goglia, M.J., Hawkins, G.A., and Deverall, J.E.	1952	L	339-533	A	Less than 0.01 O; oxygen-free high-conductivity copper.
15	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Cu II	Less than 0.05 each Zn and Fe; cast.
16	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Cu II W	Less than 0.05 each Zn and Fe; wire.
17	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Cu III	0.05 Pb, traces of Ni and Fe; drawn.
18	130	Sidles, P.H. and Danielson, G.C.	1951	P	309-834		Pure; about 1/8 in. in diameter and at least 50 cm long.
19	41	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 Trace 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	80	Kannuluik, W.G. and Laby, T.H.	1928	L	95-293		High purity; single crystal.
21	57	Gruneisen, 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 3 hrs at 380 C.
22	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Cu 3	Electrolytically very pure; with fine grains.
23	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Cu 4a	Electrolytically very pure; with fine grains; annealed 4 1/2 hrs at 380 C.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
24	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 6a	Not very pure single crystal; annealed 7.5 hrs at 380 C.
25	18	Bremmer, H. and deHass, W.J.	1936	L	15-20		Very high purity; a thin wire of 0.2 mm in diameter.
26	58	Gruneisen, E. and Reddemann, H.	1934	L	22,79	Cu 2b	Very high purity; somewhat deformed.
27	127	Schofield, F.H.	1925	L	369-898		99.9 pure; annealed.
28	97	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-40		99.999 pure; JM4234 from Johnson, Matthey and Co.; polycrystalline; annealed for several hours at two-thirds of the melting point.
29	23	Child, C.D. and Quick, R.W.	1894	E	347-440		Pure.
30	103	Nicol, J. and Tseng, T.P.	1953	L	0.29-4.2		Commercially pure; polycrystalline; high purity magnetic wire.
31	88	Lees, C.H.	1908	L	107-299		Pure; soft-drawn high-conductivity copper; density 8.84 g cm^{-3} at 23 C.
32	89	Lucks, C.F. and Deem, H.W.	1956	C	367-1144	Electrolytic tough pitch	Electrolytic tough pitch copper; Federal Specification QQC-502 (minimum 99.9 Cu); density 8.92 g cm^{-3} at 24 C.
33	11	Berman, R. and MacDonald, D.K.C.	1952	L	2.6-91		99.999 pure; about 0.0005 Ag, <0.0003 Ni, <0.0004 Pb; JM4234 from Johnson, Matthey and Co.; drawn and annealed in a helium atmosphere at 450 C for 6 hrs.
34	2	Allen, J.F. and Mendoza, E.	1948	L	1.8-4.1		0.003 Ag, 0.003 Ni, 0.003 Pb; approximate composition; free from oxygen; annealed in air.
35	145	White, G.K.	1953	L	2.0-160	Cu 1	99.999 pure; JM4272 from Johnson, Matthey and Co.; about 0.0005 Ag, 0.0004 Pb, and <0.0003 Ni, and barely visible spectral lines of Ga and Fe; 2 mm diameter rod; as drawn.
36	145	White, G.K.	1953	L	2.5-155	Cu 2	The above specimen annealed in vacuo at 550 C for 3 hrs.
37	116	Quick, R.W., Child, C.D., and Lanphear, B.S.	1895	F	219-260		Pure.
38	186	Ellis, W.C., Morgan, F.L., and Sager, G.F.	1928	P	305.2		Electrolytically pure.
39	224	Williams, H.M. and Bihlman, V.W.	1923	L	423.2		99.98 pure; annealed.
40	224	Williams, H.M. and Bihlman, V.W.	1923	L	428.2		99.98 pure; cast.
41	224	Williams, H.M. and Bihlman, V.W.	1923	L	423.2		99.97 pure; hard-drawn.
42	224	Williams, H.M. and Bihlman, V.W.	1923	L	430.2		99.76 pure; cast.
43	270	King, R.W.	1915	P	308,333		Pure; density =8.93 gm cm^{-3} at room temperature.
44	271	Chubb, W.F.	1938	L	273-403		≈0.079 O.
45	271	Chubb, W.F.	1938	L	273-403		≈0.079 O, 0.106 Ni.
46	271	Chubb, W.F.	1938	L	273-403		≈0.022 O.
47	271	Chubb, W.F.	1938	L	273-403		≈0.022 O, 0.106 Ni.

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* See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER (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	52	Goglia, M.J., Hawkins, G.A., and Deverall, J.E.	1952	L	339-533	B	0.015 Fe, 0.011 P; cast.
49	52	Goglia, M.J., Hawkins, G.A., and Deverall, J.E.	1952	L	339-533	C	0.061 Fe, 0.016 P; cast.
50	52	Goglia, M.J., Hawkins, G.A., and Deverall, J.E.	1952	L	339-533	D	0.089 Fe, 0.015 P; cast.
51	341	White, G.K. and Woods, S.B.	1954	L	1.9-130		0.056 Fe; nominal composition; homogenized and annealed; residual electrical resistance (at helium temp) =0.56 x 10^{-6} ohm cm.
52	341	White, G.K. and Woods, S.B.	1954	L	1.9-142		0.0043 Fe; nominal composition; homogenized and annealed; residual electrical resistance (at helium temp) =0.041 x 10^{-6} ohm cm.
53	225	Maybrey, H.J.	1928	L	373.2		Electrolytic.
54	145	White, G.K.	1953	L	5.0-58	Cu 3	99.999 pure; JM4272 from Johnson, Matthey and Co.; about 0.0005 Ag, 0.0004 Pb, and 0.0003 >Ni, and barely visible spectral lines of Ga and Fe; 1 mm diameter rod; as drawn.
55	427	Sutton, W.H.	1960	L	303.2		Electrolytic tough pitch.
56	404	Andrews, F.A., Webber, R.T., and Sphor, D.A.	1951	L	2.5-4.6		99.998^{+} pure; polycrystal.
57	428	McClelland, J.D., Rasor, N.S., Dahleen, P.C., and Zehms, E.H.	1957	R	1673-2500		In liquid state.
58	246	Sedstrom, E.	1919	C	273, 373		Rolled, drawn, and then heated 1/2 hr at temperature close to melting point.
59	429	Gabler, F.	1937	R	285.7		Pure.
60	430	Sedstrom, E.	1924	T	273.2		Pure; rolled and drawn to wire 3 cm long and 1 mm^2 cross section, and heated at temperature close to melting point.
61	431	Mikrykov, V.E. and Rabotnov, S.N.	1944	E	597-1245		Pure; polycrystal.
62	432	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, each of Fe, As, Sb <0.0005; 0.0001 Te; and Bi <0.00005; cold rolled, annealed for 1 hr at 650 C and redrawn and reannealed for 17 min at 760 C, followed by grinding to sample size of 0.144 in. in diameter; small voids present; density 8.899 g cm^{-3}; porosity 0.5%.
63	432	Powell, R.L., Roder, H.M., and Rogers, W.M.	1957	L	4.0-40	Electrolytic tough pitch	0.01 Fe, 0.001 each Ag and Zn, each of Al, Cr, Pb, Mg, Mn, and Sn <0.0001; electrolytic tough pitch; density 8.914 g cm^{-3}; ground.
64	432	Powell, R.L., Roder, H.M., and Rogers, W.M.	1957	L	5.0-100	Phosphorus deoxidized Cu	0.027 P, 0.01 each of Fe, Ag, and Zn, 0.001 each Ni and Si, <0.0001 each of Al, Cr, Pb, Mg, and Mn; density 8.917 g cm^{-3}; ground.

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* See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER (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	433	Aoyama, S. and Ito, T.	1940	L	78.2	Electrolytic Cu	0.015 Sb, 0.010 Fe, 0.007 S, trace Pb.
66	434	Powell, R.L., Roder, H.M., and Hall, W.J.	1959	L	4.0-105		99.999 pure; swaged from about 3/8 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 a vacuum for 2 hrs at 400 C, drawn through tungsten carbide dies to 0.070 in., cleaned with acids, and finally annealed again in a vacuum for 2 hrs at 400 C; slight unavoidable work hardening of the sample during installation in the apparatus.
67	434	Powell, R.L., Roder, H.M., and Hall, W.J.	1959	L	4.0-105		99.999 pure; swaged from about 3/8 in. down to about 0.0816 in., cleaned with acids, annealed in a 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%; not annealed again after drawing.
68	435	Gruneisen, E.	1900	L	291.2		Pure.
69	435	Gruneisen, E.	1900	L	291.2		Trace As.
70	410	Eucken, A. and Warrentrup, H.	1935	R	273.2		Pure.
71	436	Gruneisen, 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) $=0^\circ$ at which the electrical resistivity is nearly minimum and H nearly parallel to [100] direction.
72	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.17	Cu 12	The above specimen measured at H =2280 oersteds and $\Theta=0^\circ$.
73	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.18	Cu 12	The above specimen measured at H =4490 oersteds and $\Theta=0^\circ$.
74	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.21	Cu 12	The above specimen measured at H =8750 oersteds and $\Theta=0^\circ$.
75	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.23	Cu 12	The above specimen measured at H =10880 oersteds and $\Theta=0^\circ$.
76	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.25	Cu 12	The above specimen measured at H =12200 oersteds and $\Theta=0^\circ$.
77	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.17	Cu 12	The above specimen measured at H =0 oersteds and $\Theta=40^\circ$ at which the electrical resistivity is nearly maximum and H nearly parallel to [110] direction.
78	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.18	Cu 12	The above specimen measured at H =2280 oersteds and $\Theta=40^\circ$.
79	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.19	Cu 12	The above specimen measured at H =4490 oersteds and $\Theta=40^\circ$.
80	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.24	Cu 12	The above specimen measured at H =8750 oersteds and $\Theta=40^\circ$.
81	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.24	Cu 12	The above specimen measured at H =10800 oersteds and $\Theta=40^\circ$.
82	436	Gruneisen, E. and Adenstedt, H.	1938	L	21.30	Cu 12	The above specimen measured at H =12200 oersteds and $\Theta=40^\circ$.
83	437	Schaufelberger, W.	1902	E	291.2		Pure.
84	390	Zolotukhin, G.E.	1956	P	354.2		Pure.
85	438	Meissner, W.	1914	E	21-373		Electrolytic copper wire; not annealed and not bent, but heated considerably during soldering.
86	620	Mikryukov, V.E.	1956		320-773		99.99 pure; polycrystalline.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER (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	439	Ranque, G., Henry, P., and Chaussian, M.	1935	L	323-848		99.9 pure.
88	355	White, G.K. and Woods, S.B.	1955	L	1.5-142		99.98 pure; 0.02 Ge.
89	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 9	Not very pure; single crystal solidified from melt; completely undeformed and unworked.
90	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 2a	Very high purity; porous natural crystal; hammered from 3 mm to 1.3 mm diameter.
91	440	Aoyama, S. and Ito, T.	1940	L,R	78,273	Electrolytic Cu	Impurities; 0.015 Sb, 0.010 Fe, 0.007 S, 0.0003 As; annealed in nitrogen stream for 20 hrs at 380 - 400 C.
92	134	Smith, C.S.	1931	L	337-477	93	99.94 pure; 0.042 P, 0.04 Fe; annealed at 650 C.
93	134	Smith, C.S.	1931	L	337-494	82	99.97 pure; 0.075 P, 0.04 Fe; annealed at 650 C.
94	134	Smith, C.S.	1931	L	325-496	95	99.74 pure; 0.18 P; annealed at 650 C.
95	67	Hansen, D. and Rogers, C.E.	1932	L	438		99.917 pure; 0.083 P; annealed.
96	67	Hansen, D. and Rogers, C.E.	1932	L	438		99.865 pure; 0.135 P; annealed.
97	67	Hansen, D. and Rogers, C.E.	1932	L	438		99.93 pure; 0.07 As; annealed.
98	67	Hansen, D. and Rogers, C.E.	1932	L	438		99.856 pure; 0.144 As; annealed.
99	230	Smith, A.W.	1925	L	332.2		Impurity <0.03.
100	135	Smith, C.S. and Palmer, E.W.	1935	L	293,473	Bar 114	0.07 Mn, 0.01 Fe, 0.02 Mg; annealed at 700 C.
101	135	Smith, C.S. and Palmer, E.W.	1935	L	293,473	Bar 115	0.14 Mn, 0.01 Fe, 0.01 Mg; annealed at 700 C.
102	40	Fieldhouse, I.B., Hedge, J.C., Lang, J.I., and Waterman, T.E.	1956	L	764-1287	Electrolytic tough pitch	Electrolytic tough pitch copper meeting Federal Specification QQC 576 (minimum 99.9 Cu); density 8.83 g cm^{-3}.
103	621	Powers, R.W.	1949	L	23-245	OFHC	Pure.
104	496	Aoyama, S. and Ito, T.	1940	C	80,273		Pure.
105	504	Parker, W.J., Jenkins, R.J., Butler, C.P., and Abbott, G.L.	1960	P	295.2	OFHC	Pure; density (at 20 C) 8.96 g cm^{-3}.
106	622	Taga, M.	1960	P	363.2		Commercial grade.
107	622	Taga, M.	1960	P	363.2		Second run of the above specimen.
108	622	Taga, M.	1960	P	363.2		Third run of the above specimen.
109	622	Taga, M.	1960	P	363.2		Fourth run of the above specimen.
110	579	DeHaas, W.J. and Biermasz, Th.	1936	L	15-20		No details given.
111	619	Schott, R.	1916	L	20-273		High purity single crystal natural copper.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 4. SPECIFICATIONS OF THE SPECIMENS OF COPPER (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	619	Schott, R.	1916	L	22-273		Commercially pure; fine crystalline.
113	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 4	Electrolytically very pure; with fine grains.
114	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 4b	The above specimen hammered, then annealed for 4 1/2 hrs at 380 C, and then recrystallized at 950 C for 5 min.
115	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 6	Not very pure; single crystal; sawn from larger block and lathed into rod.
116	57	Gruneisen, 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 diameter and annealed for 3 hrs at 380 C.
117	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 6c	Same as 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	57	Gruneisen, 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	57	Gruneisen, E. and Goens, E.	1927	L	21,83	Cu 7a	Same as the above specimen Cu 7 except annealed for 4 hrs at 380 C.
120	623	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.; less than 0.0001 each of Fe, Sb, Se, and less than 0.0002 each of Te and As; 0.030 inch diameter wire was rolled and drawn from a 3/4 in. diameter rod and then annealed at 530 C in vacuo for some hours; residual electrical resistivity $0.865 \pm 0.01 \times 10^{-9}$ ohm cm.
121	672	Gladun, C. and Holzhauser, W.	1964	L	19-83		Electrolytic copper.
122	672	Gladun, C. and Holzhauser, W.	1964	L	18-83		The above specimen measured after stretching with $\Delta l/l = 7.8\%$.
123	672	Gladun, C. and Holzhauser, W.	1964	L	18-83		The above specimen measured after further stretching with total $\Delta l/l = 14.0\%$.
124	672	Gladun, C. and Holzhauser, W.	1964	L	20-84		The above specimen measured after further warming up to room temperature.
125	672	Gladun, C. and Holzhauser, W.	1964	L	18-84		The above specimen measured after further stretching with total $\Delta l/l = 19.9\%$.
126	672	Gladun, C. and Holzhauser, W.	1964	L	18-84		The above specimen measured after further stretching with total $\Delta l/l = 25.4\%$.
127	672	Gladun, C. and Holzhauser, W.	1964	L	19-84		The above specimen measured after further stretching with total $\Delta l/l = 30.8\%$.
128	‡	Powell, R.W. and Tye, R.P.	1966	C	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; Laboratory No. 4351, stated to be oxygen free and of a high degree of purity; 7 mm in diameter and 15 cm long; heat treated to 1173 K; electrical resistivity at 293, 323, 373, 473, 573, 673, 773, 873, and 1173 K were, respectively, 1.75, 1.93, 2.25, 2.93, 3.60, 4.33, 5.08, 5.88, and 8.30 μohm cm.
129	‡	Powell, R.W. and Tye, R.P.	1966	C	323,373	Q.M.C. Sample; No. 2	"Pure copper"; rod of 1 cm in diameter and 10 cm long; no heat treatment prior to the test; electrical resistivity at 293, 323, and 373 K were, respectively, 1.78, 1.95, and 2.28 μohm cm.
130	‡	Powell, R.W. and Tye, R.P.	1966	C	323-873	M.S. Sample; No. 3	"Pure copper"; rod of 1.27 cm in diameter and 10 cm long; no heat treatment prior to the test; electrical resistivity at 293, 323, 373, 473, 573, 673, 773, and 873 K were, respectively, 1.73, 1.93, 2.27, 2.97, 3.68, 4.43, and 5.17 μohm cm.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

[‡] In course of publication.

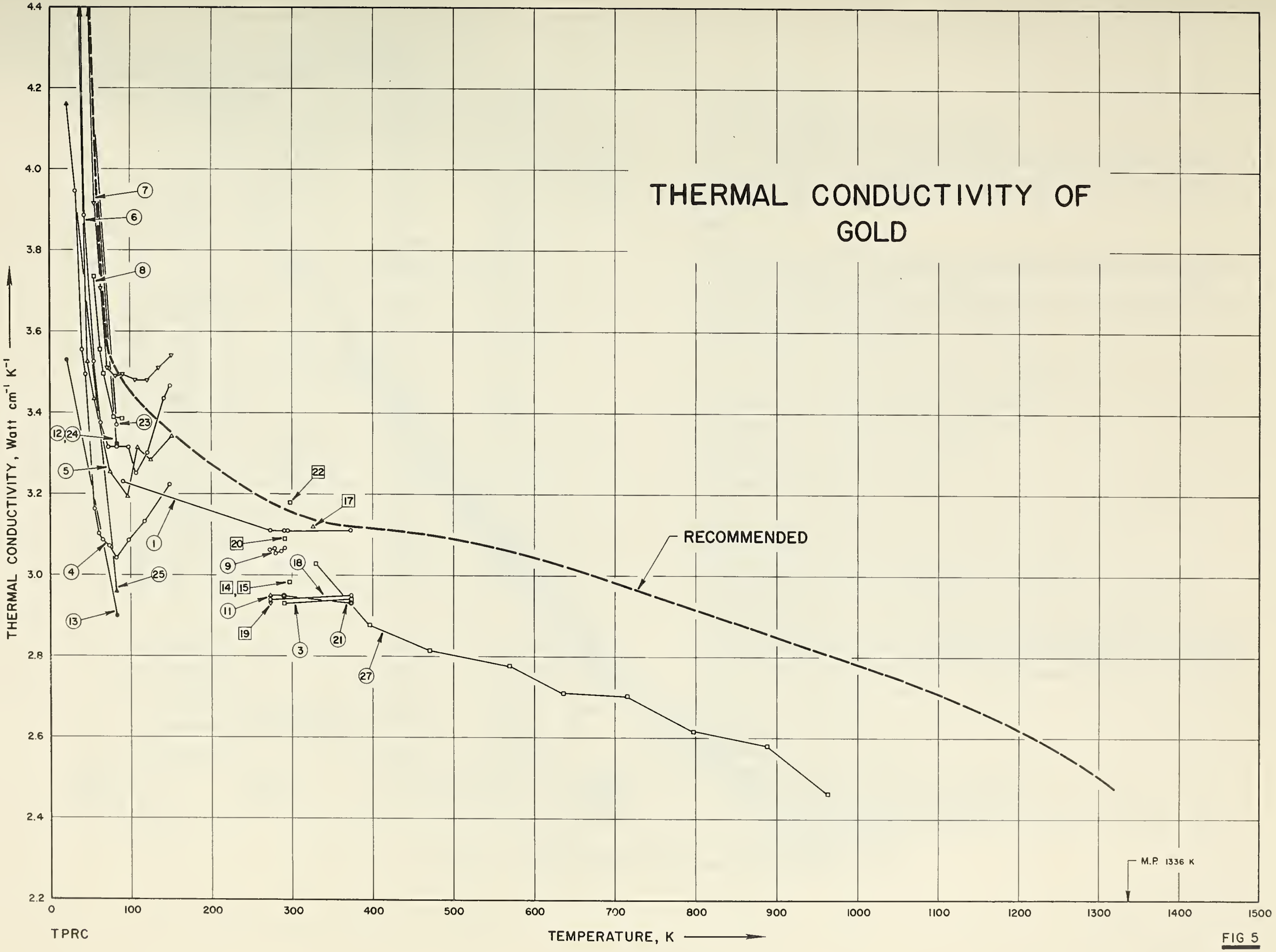
THERMAL CONDUCTIVITY OF GOLD

FIG 5

TABLE 5. SPECIFICATIONS OF THE SPECIMENS OF GOLD

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), and Remarks
1	95	Meissner, W.	1915	E	22-374		99.999 pure.
2	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Au I	99.8 pure; 0.1 Fe, 0.1 Cu.
3	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Au II	High purity.
4	146	White, G. K.	1953	L	2.7-141	Au 1	99.9 pure; major impurity Ag, trace Pt.
5	146	White, G. K.	1953	L	2.3-150	Au 2	99.9 pure; major impurity Ag, trace Pt; annealed at 700 C in vacuo and slowly cooled.
6	146	White, G. K.	1953	L	2.3-148	Au 3	Greater than 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 diameter rod; cold drawn.
7	146	White, G. K.	1953	L	2.1-151	Au 4	The above sample annealed at 700 C in vacuo for about 3 hrs and slowly cooled to 200 C in 6 hrs.
8	146	White, G. K.	1953	L	2.2-90	Au 5	The above annealed specimen cold drawn to 1.3 mm diameter.
9	78	Kannuluik, W. G.	1931	E	273-292		99.99 pure; wire.
10	97	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-21	Au 1	99.999 pure; polycrystalline wire.
11	8	Barratt, T. and Winter, R. M.	1914	L	273-373		Pure; sp. gravity = 19.49.
12	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au 12	High purity; single crystal; unstrained.
13	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au II	Commercially pure; cold-worked and annealed.
14	172	Masumoto, H.	1927	E	297.2	1 a	Pure; forged.
15	172	Masumoto, H.	1927	E	297.2	1 b	Pure; forged and then annealed at 600 C for 1 hour.
16	450	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.
17	487	Gray, J. H.	1894	L	326.2		Pure; specimen 2.0 mm diameter.
18	246	Sedstrom, E.	1919	C	273, 373		Rolled and drawn; heated 1/2 hr close to melting point.
19	430	Sedstrom, E.	1924	T	273.2		Pure; rolled and drawn to wire of 3 cm in length and 1 mm^2 in cross-section, and then heated close to melting point.
20	451	Johansson, C. H. and Linde, J. O.	1930		291.2		Pure; tempered at 800 C and quenched to become ductile, and then rolled and drawn.
21	399	Barratt, T. and Winter, R. M.	1925	L	290, 373		Pure.
22	241	Schulze, F. A.	1911		298.2		Pure.
23	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au 14	High purity; single crystal; unstrained.
24	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au 13	Originally single crystal, hammered to 2 mm diameter; annealed 5 1/2 hrs at 380 C.
25	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au II a	Commercially pure; remelted and hammered to 2 mm diameter; annealed; tempered 3 hrs at 390 C.
26	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	Au I	High purity; cold-worked to thin rod; untempered.
27	617	Mikryukov, V. E.	1957		331-964		99.99 pure; polycrystal.

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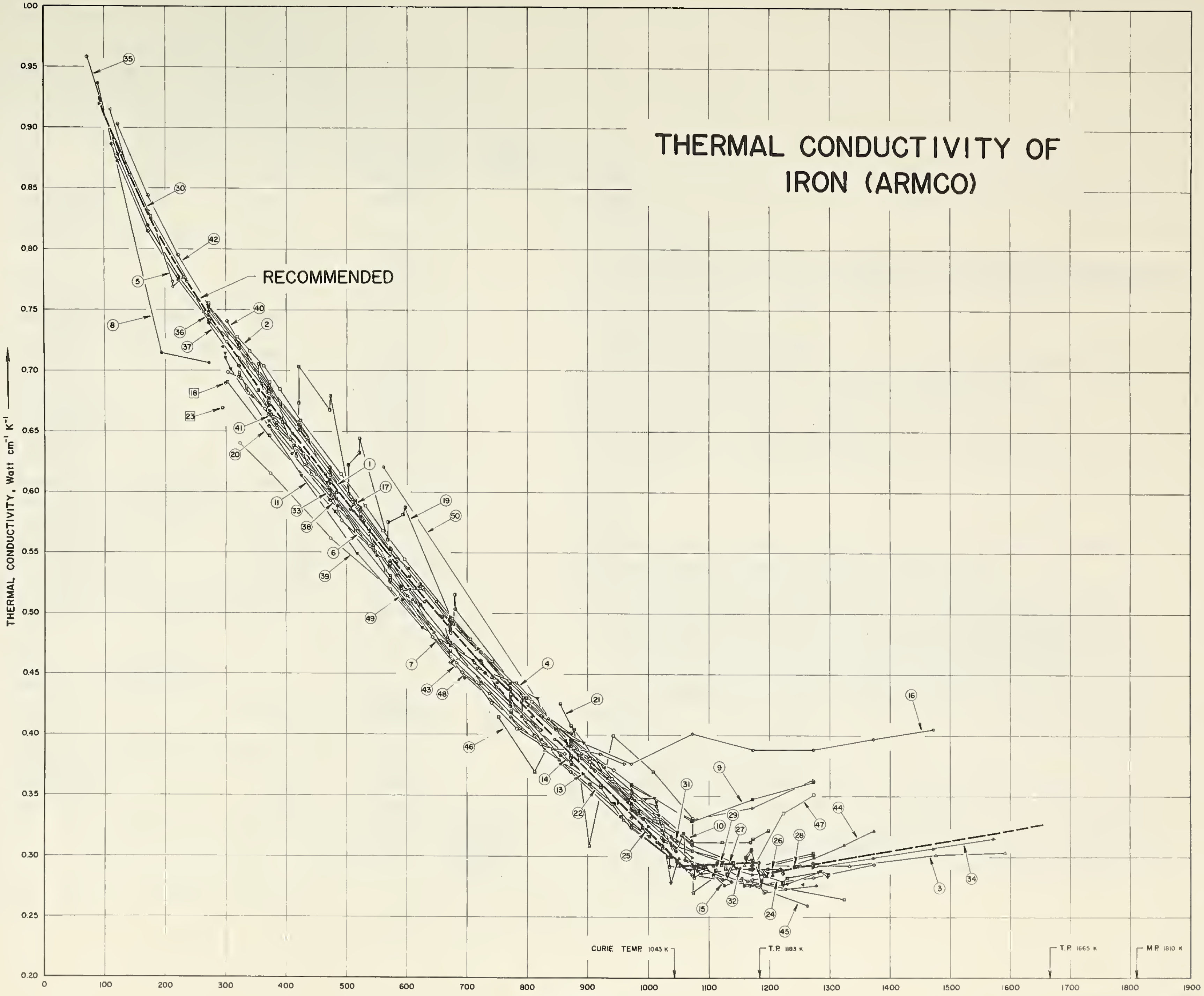
[*] See TPRC Data Book Vol. 1, Chapter 1, References


THERMAL CONDUCTIVITY OF
IRON (ARMCO)
RECOMMENDED
THERMAL CONDUCTIVITY, Watt cm^{-1} K^{-1}
TEMPERATURE, K
CURIE TEMP. 1043 K
T.P. 1183 K
T.P. 1665 K
M.P. 1810 K
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TPRC

FIG 6

TABLE 6. SPECIFICATIONS OF THE SPECIMENS OF ARMCO IRON

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	110	Powell, R. W.	1934	L	303-1073		99.918 pure; 0.023 C, 0.025 Mn, 0.007 Si, 0.02 S, 0.007 P.
2	5	Armstrong, L. D. and Dauphinee, T. M.	1947	L	320-1016		99.80 pure; 0.028 C, 0.035 Mn, 0.039 S, 0.067 Cu, 0.024 Ni; hot-rolled.
3	39	Fieldhouse, I. B., Hedge, J. C. and Lang, J. I.	1958	R	371-1594		No details.
4	21	Burr, A. C.	1951	R	718-1008		No details.
5	91	Lucks, C. F., Thompson, H. B., Smith, A. R., Curry, F. P., Deem, H. W. and Bing, G. F.	1951	C	111-394		0.014 C, 0.015 Mn, 0.004 P, 0.026 S, 0.035 Cu.
6	69	Hattori, D.	1937	L	323-961		0.015 C, 0.01 Si, 0.032 Mn, 0.03 S, 0.013 Cu, 0.003 P; annealed at 950 C.
7	69	Hattori, D.	1937	L	304-943		Same as above specimen.
8	79	Kannuluik, W. G.	1933	E	90-273		0.011 C, 0.017 Mn, 0.006 P, 0.026 S, 0.056 Cu, 0.002 Si.
9	89	Lucks, C. F., and Deem, H. W.	1956	C	273-1273		99.906 pure; 0.014 C, 0.026 S, 0.035 Cu, 0.015 Mn, 0.004 P.
10	110	Powell, R. W.	1934	L	273-1073		99.918 pure; 0.025 Mn, 0.023 C, 0.020 S, 0.007 Si and 0.007 P; plated with nickel.
11	251	Abeles, B., Cody, G. D. and Novak, R.	1959	D	300-1298		No details.
12	251	Abeles, B., Cody, G. D. and Novak, R.	1959	D	295,1256		No details.
13	444	Powell, R. W.	1939	C	512-1046		99.918 pure; 0.023 C, 0.007 Si, 0.025 Mn, 0.007 P, 0.020 S; 1/2 in. rod.
14	444	Powell, R. W.	1939	C	730-1138		99.918 pure; 0.023 C, 0.007 Si, 0.025 Mn, 0.007 P, 0.020 S; 1 in. rod.
15	444	Powell, R. W.	1939	R	369-1278		99.918 pure; 0.023 C, 0.007 Si, 0.025 Mn, 0.007 P, 0.020 S.
16	444	Maurer, E.	1936	L	303-1473		99.869 pure; 0.01 C, trace Si, 0.02 Mn, 0.011 P, 0.040 S, 0.05 Cu.
17	217	Zegler, S. T. and Nevitt, M. V.	1959	C	410-1057		99.745 pure; 0.03 C, 0.01 Mn, 0.01 P, 0.03 S, 0.015 Si, 0.16 Cu; obtained from commercial source in wrought form.
18	203	Von Lohberg, K. and Motz, J.	1957	L	300		Commercial Armco iron.
19	340	Loewen, E. G.	1956	L	355-800		0.012 C, 0.017 Mn, 0.005 P, 0.025 S, trace Si.
20	445	Laubitz, M. J.	1960	L	303-1273		0.083 Cu, 0.023 S, 0.006 P, 0.030 Mn, 0.004 Si, 0.02 C; annealed for 1/2 hr at 850 C; one of BMI round robin Armco iron samples; measured with "unmatched guard method".
21	446	Paine, R. M., Stonehouse, A. J. and Beaver, W. W.	1959	R	855-1198		Commercial Armco iron.
22	625	Oak Ridge Nat'l. Lab.	1960		904-1108		No details.
23	504	Parker, W. J., Jenkins, R. J.	1960	P	295		No details.
24	326	Abeles, B., Beers, D. S., Cody, G. D., Novak, R. and Rosi, F	1960	P	995-1298		No details.

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* See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 6. SPECIFICATIONS OF THE SPECIMENS OF ARMCO IRON (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	627	Godfrey, T.G., Fulkerson, W., Kollie, T.G., Moore, J.P. and McElroy, D.L.	1964	R	385-1092		<0.05 Al, <0.05 Cr, 0.1 Cu, 0.05 Mn, <0.05 Mo; 0.1 Ni, <0.02 Si, <0.01 Ti; <0.02 V, 0.013 C, 0.006 P, 0.023 S, <0.0001 H, 0.086 O, and 0.0050 N; run no. 1.
26	627	Godfrey, T.G., Fulkerson, W., Kollie, T.G., Moore, J.P. and McElroy, D.L.	1964	R	484-1198		The above specimen; run no. 2A.
27	627	Godfrey, T.G., Fulkerson, W., Kollie, T.G., Moore, J.P. and McElroy, D.L.	1964	R	993-1206		The above specimen run no. 2 B.
28	627	Godfrey, T.G., Fulkerson, W., Kollie, T.G., Moore, J.P. and McElroy, D.L.	1964	R	1206-1273		The above specimen run no. 2 C.
29	627	Godfrey, T.G., Fulkerson, W., Kollie, T.G., Moore, J.P. and McElroy, D.L.	1964	R	1025-1198		The above specimen run no. 2 D.
30	628	Lucks, C.F. and Deem, H.W.	1958	C	93-1273		99.906 pure, 0.035 Cu, 0.026 S, 0.015 Mn, 0.014 C, and 0.004 P; BMI average values.
31	629	Hedge, J.C. and Fieldhouse, I.B.	1956	R	803-1048		
32	43	Fieldhouse, I.B., Hedge, J.C. Lang, J.I. and Waterman, T.E.	1958	L	808-1153		
33	217	Robinson, H.E.	1959	L, C	373-773		
34	630	Powell, R.W.	1962		273-1573		Recommended most probable values.
35	631	Powell, R.W., Hickman, M.J., Tye, R.P. and Woodman, M.J.	1962		73-1273		Armco iron from American Rolling Mill Co. through the Steels Sales Co.; ladle analysis given by Steels Sales Co: 0.083 Cu, 0.030 Mn, 0.023 S, 0.02 C, 0.004 Si, 0.006 P, 99.834 (by difference) Fe; chemical and spectrographic analysis at NPL showed 0.083 Ni, in addition; rod of 1 in. diameter received at the BMI in the hot-rolled condition and then annealed for 30 min. at 871 C in air followed by furnace cooling; ends stamped No. 2 and No. 3. The No. 2 end immediately adjacent to a length retained at BMI, No. 3 end adjacent to a length sent to NBS; ρ(600C)= 68.8, ρ(900 C)= 112.4 μohm cm.
36	632	Flynn, D.R.	1963	L	113-913		Armco iron cut from the same rod as the above specimen; supplied to NBS by BMI; the ends of this sample stamped No. 3 and No. 4; the No. 3 end immediately adjacent to the sample sent to NPL and the No. 4 end adjacent to the sample sent to NRC; ρ(0C)= 9.88 μohm cm.
37	†	Lucks, C.F.	1964		273-873		Armco iron cut from the same rod as the above specimen; the ends of this sample stamped No. 1 and No. 2; the No. 2 end immediately adjacent to a length sent to NPL.
38	633	Laubitz, M.J.	1963	L	373-1273		Armco iron cut from the same rod as the above specimen; the ends of this sample stamped No. 4 and No. 5; the No. 4 end immediately adjacent to a length sent to NBS; this set of data are the corrected values for the uncorrected data (curve 20) of Laubitz, 1960; ρ(0C)= 10.4, ρ(600 C)= 70.3, ρ(900 C) = 112.0 μohm cm; measured with "unmatched guard method".

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

[†] Private communication

TABLE 6. SPECIFICATIONS OF THE SPECIMENS OF ARMCO IRON (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	624	Mikryukov, V. E.	1959		323-673		Polycrystalline.
40	†	Delle, W.	1964		303-1273		No details.
41	†	Moore, J. P., Fulkerson, W., McElroy, D. L. and Kollie, T. G.	1964	R	323-1273		Armco iron, 99.41$^+$ Fe, <0.0507 Al, <0.05 Cr, 0.0102 Cu, 0.050 Mn, <0.05 Mo, 0.10 Ni, <0.02 Si, <0.01 Ti, <0.02 V, 0.013 C, 0.006 P, 0.023 S, <0.0001 H, 0.087 O, 0.005 N; total equivalent carbon: 0.1432 minimum including oxygen, 0.2002 maximum including oxygen; microstructure showing oxygen present as a second phase, amounting to about 1 vol %; electrical resistivity 10.0 μohm cm at 0 C, 70.66 μohm cm at 600 C, 114.69 μohm cm at 900 C, and 117.95 μohm cm at 1000 C.
42	†	Flynn, D R., Robinson, H. E., and Watson, T. W.	1964		123-473		Armco iron submitted by Redstone Arsenal; 99.80 ± 0.084 Fe, <0.1 Mn, <0.015 Si, 0.03 Cu, 0.04 Ni, 0.01 Cr, <0.01 V, 0.01 Mo, <0.02 W, <0.01 Co, 0.006 Ti, 0.02 Sr, <0.01 Nb, <0.003 Zr; photomicrograph indicated an oriented microstructure typical of a cold-worked material; electrical resistivity 9.36 μohm cm at 0 C.
43	†	Dunworth, R. J.	1963		673-1373		Armco iron.
44	660	Klein, A H., Shanks, H. R., and Danielson, G. C.	1963		273-1373		Armco iron distributed to Iowa State University by Battelle Memorial Institute; thermal conductivity values were calculated from thermal diffusivity data using density d = 7.874 g cm^{-3} as given by Cleaves and Thompson (The Metal-Iron, McGraw-Hill, 1935, p. 271).
45	634	Taylor, R E	1962	R	648-1263		Specimen size 2 in. OD by 3 in. long with a 0.5 in. center hole.
46	634	Taylor, R. E.	1962	R	753-1323		The above specimen measured by using different heat sink.
47	‡	Klein, A. H., Shanks, H. R., and Danielson, G. C.	1965	P	273-1273		Thermal conductivity calculated from the average thermal diffusivity measured by three methods: finite rod method, radial method, and modified Angstrom method using the measured specific heat and assumed constant density 7.874 g cm^{-3}.
48	695, 696	Banaw, A. M. and Chekhovskoi, V. Ya.	1965	R	425-773		99.865 Fe (by difference); 0.07 Mn, 0.04 Si, 0.015 C, and 0.01 Cu.
49	†	Pears, C. D.	1965	C	550-811		Armco iron from BMI round robin stock; specimen of 1 in. in diameter and 1 in. long; measured with a comparative rod apparatus using stainless steel 316 as reference standard.
50	603	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, trace Si; specimen of 3/4 in. in diameter and 3/4 in. long, cold drawn from melt, supplied by Lapham-Hickey Steel Corp.; density 7.53 g cm^{-3}.

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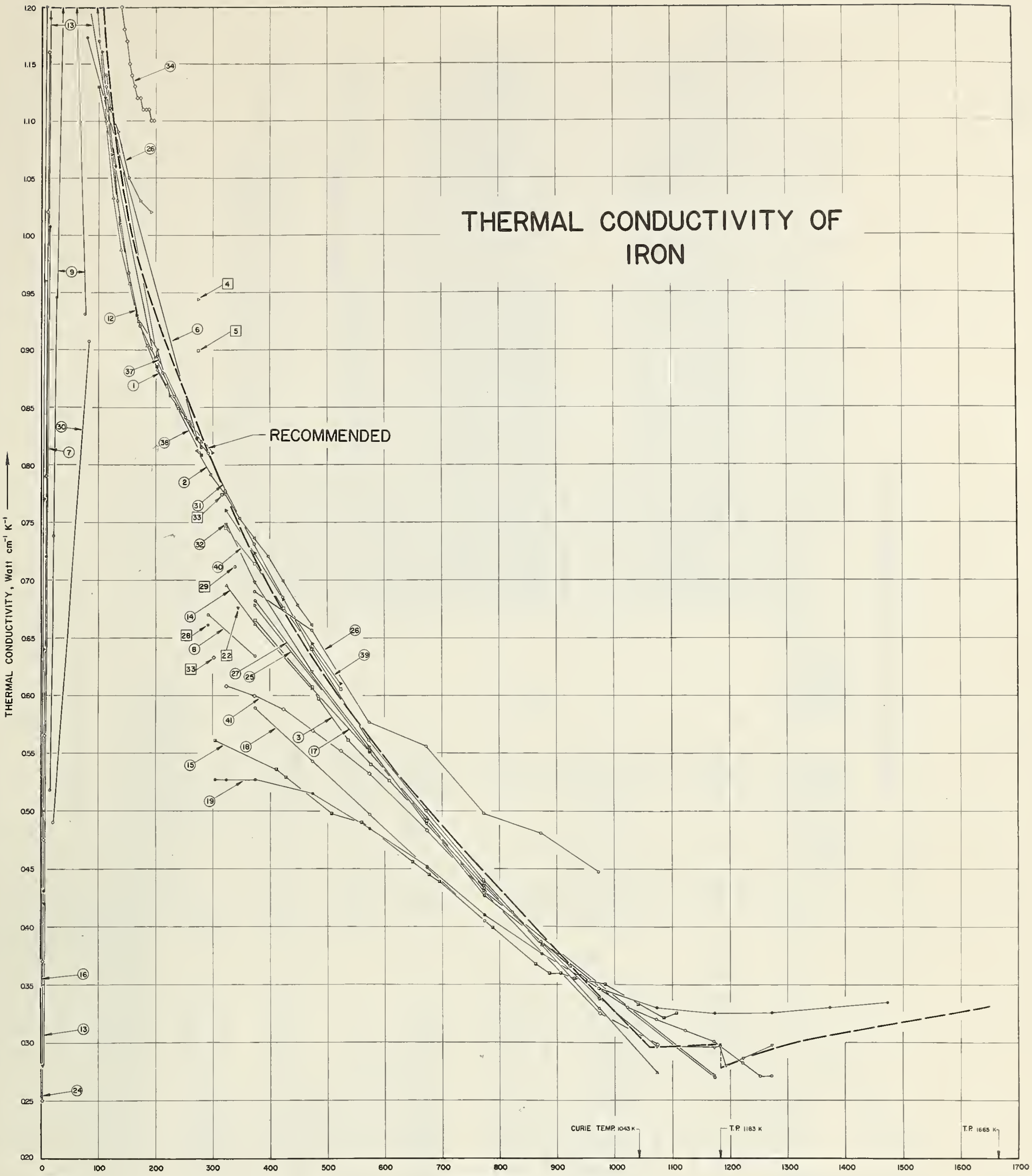
[*] See TPRC Data Book Vol. 1, Chapter 1, References

[†] Private communication

[‡] Unpublished data


THERMAL CONDUCTIVITY OF IRON
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
RECOMMENDED
CURIE TEMP. 1043 K
T.P. 1183 K
T.P. 1665 K
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
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
13
34
26
9
4
12
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TPRC

FIG 7

TABLE 7. SPECIFICATIONS OF THE SPECIMENS OF IRON

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	115	Powers, R W., Ziegler, J. B., and Johnston, H. L.	1951	L	26-292		99.99 pure.
2	1	Adcock, F. and Bristow, C. A.	1935	L	273-473		0.0045 C, 0.002 Mn, 0.0015 S, 0.001 P; measurements by R. W. Powell.
3	129	Shelton, S. M and Swanger, W. H.	1933	C	373-772		0.02 C, 0.03 Mn, 0.042 P, 0.005 S; hot-rolled.
4	34	Eucken, A. and Dittrich, K.	1927	L	80, 273		Electrolytically pure; coarse grained; ρ (electrical resistivity) = 10.4×10^{-6} ohm cm at 273 C.
5	34	Eucken, A. and Dittrich, K.	1927	L	80, 273		Same as the above specimen except $\rho = 9.7 \times 10^{-6}$ ohm cm at 273 C.
6	34	Eucken, A. and Dittrich, K.	1927	L	80, 273		Electrolytically pure; fine grained; $\rho = 9.4 \times 10^{-6}$ ohm cm at 273 C.
7	81	Karweil, J. and Schaefer, K	1939	L	4.9-23		Electrolytically pure.
8	77	Jaeger, W. and Diesselhorst, H.	1900	C	291, 373		0.1 C.
9	104	DeNobel, J.	1951	L	16-93		99.93 pure; forged.
10	57	Grüneisen, E. and Goens, E.	1927	L	21, 83	Fe 1	Electrolytically refined; cold-worked and annealed.
11	57	Grüneisen, E. and Goens, E.	1927	L	21, 83	Fe 2	Commercially pure; polycrystalline; unannealed.
12	699	Kohlhaas, R. and Kierspe, W.	1965	L	88-300		0.064 O, 0.0027 C, 0.002 S, 0.001 Mn, 0.001 N, 0.001 Si, and trace Cr; electrical resistivities at 83, 203, 223, 248, 273, 293, 313, 333, and 353 K were, respectively, 1.22, 5.60, 6.50, 7.65, 8.96, 10.00, 11.30, 12.50, and 13.60 μohm cm.
13	83	Kemp, W. R. G., Klemens, P. G.,	1956	L	1.5-128		99.99 pure; 0.005 Ni, 0.0002 Cu, 0.0001 Ag, traces of Mn and Mg; annealed at 750 C.
14	131	Silverman, L.	1953	C	323-1073		0.02 Mn, 0.026 C, 0.028 Si, 0.021 P, 0.011 S; annealed in vacuum at 900 C.
15	71	Honda, K. and Simidu, T.	1917	L	303-1107		Pure Swedish iron.
16	122	Rosenberg, H. M.	1955	L	2.0-93		99.99 pure; annealed polycrystal.
17	161	Shelton, S. M.	1934	C	373-773		0.02 C, 0.03 Mn, 0.042 P, 0.005 S; hot-rolled.
18	161	Shelton, S. M.	1934	C	373-773		0.04 C, 0.046 Mn, 0.136 P, 0.025 S, 0.265 Si; Grade A wrought iron; A. S. T. M. specification A 84-21.
19	163	Maurer, E.	1936	L	303-1473		99.852 pure; 0.02 C, 0.01 Si, 0.08 Mn, 0.016 P, 0.022 S; unannealed.
20	253	Kemp, W. R. G., Klemens, P. G., and Tainsh, R. J.	1959	L	6.5-90		Doubly refined electrolytic iron; annealed at 950 C and reannealed in vacuo at 950 C in 1927 (specimen from same iron as the specimen Fe 1 of Gruneisen and Goens measured in 1927); rectangular cross-section 2.5-2.5 mm approx.
21	253	Kemp, W. R. G., Klemens, P. G., and Tainsh, R. J.	1959	L	7.9-90		Similar to the above specimen except 2.4 x 1.7 mm cross-section.
22	276	Weeks, J. L. and Seifert, R. L.	1953	C	343		Pure; density (25 C) = 7.8 g cm^{-3}.
23	64	Hall, E. H	1900	L	301, 331		99.93 pure; 0.059 C.
24	98	Mendelssohn, K. and Rosenberg, H. M.	1952	L	2.3-32		99.99 pure; annealed.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 7. SPECIFICATIONS OF THE SPECIMENS OF IRON (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	356	Kuprovskii, B. B. and Gel'd, P. V.	1956	R	372-1172		Pure.
26	439	Ranque, G., Henry, P. and Chaussain, M.	1935	L	373-973		Pure.
27	635	Gel'd, P. V.	1957	R	373-1173		Pure.
28	550	Orrall, F. Q. and Zirker, J. B.	1932	E	289.6		Electrolytic iron.
29	591	Jones, T. I., Street, K. N., Scoberg, J. A. and Baird, J.	1963	C	338.2		99.82 pure; hot-rolled.
30	57	Grüneisen, E. and Goens, E.	1927	L	21, 83		Specimen made by electrolytic method; hammered repeatedly; tempered for 1 hr at 500 C.
31	661	Richter, F. and Kohlhaas, R	1964	R	93-1273		99.96 pure iron, 0.012 O, 0.008 P, 0.007 C, 0.007 Al, 0.004 S, 0.002 N; test disks annealed for several hrs at 900 C; electrical resistivity 1.1×10^{-6} ohm cm at -180 C, 8.8×10^{-6} ohm cm at 0 C, and 113.1×10^{-6} ohm cm at 1000 C.
32	†	Moore, J. P., Fulkerson, W., McElroy, D. L., and Kollie, T. G.	1964	R	323-1273		High-purity iron; 99.97^+ Fe, 0.0001-0.001 Al, 0.0001-0.001 Ca, 0.0001-0.001 Cu, 0.001-0.01 Ni, 0.001-0.01 Si, 0.003 C, 0.0011 P, 0.003 S, <0.0001 H, 0.0025 O, 0.0005 N; total equivalent carbon: 0.00875 minimum including oxygen, 0.01527 maximum including oxygen; specimens obtained by first arc melting Armco iron stock in a pure inert atmosphere to produce pancake shaped billets, which were then rolled into sheets and cut to make feed stock for electron-beam melting, the casting of the melt was a 4 in. diameter by 6 in. long billet, from the center portion of which two radial heat-flow disks were machined; one disk 1.130 in. thick and the other 1.450 in. thick; contained several small voids; microstructure showing no second phase; grain size of the order of 1/8 in. diameter; $\rho(-200 C) = 1.04$, $\rho(0 C) = 9.04$, $\rho(600 C) = 68.89$, $\rho(900 C) = 112.56$, $\rho(1000 C) = 115.49$ $\mu\Omega$ cm.
33	636	Bednar, J., Broz, J., Smirous, K. and Trousil, Z.	1954		316.2		99.99 pure; 0.01 Si, traces of Ni, Cu, Al, Mn, Mo, and Ti (in order of decreasing amounts).
34	670	Arajs, S., Oliver, B. F., and Dunmyre, G. R.	1965	L	6.5-198	A-I	99.998^+ pure; polycrystalline; <0.0020 O, <0.0006 N, 0.0004 C, 0.00015 Co, 0.00011 Cu, 0.000065 Cr, 0.00002 Ti, 0.000019 Ge, and 0.000018 V; specimen of 0.305 cm diameter was made from commercial electrolytic iron which was first chlorinated to produce ferric chloride; the chloride was distilled once and reduced with hydrogen to metal; the metal was electron-beam drip melted into ingots and three of these ingots were zone melted into a bar which was then purified by simultaneous use of heterogeneous reactions and zone melting to the final purity with electrical resitivity ratio, $\rho(297K)/\rho(4.2K)$, equal to 302; the specimen was fabricated by swaging the 1.73 cm diameter bar to 0.483 cm diameter with intermediate annealing at 650 C for half an hour a 0.305 cm diameter gauge section was chemically polished into the specimen; final equiaxed grain size about 0.1 mm.
35	670	Arajs, S., Oliver, B. F., and Dunmyre, G. R.	1965	L	6.5-36	A-II	The second run of the above specimen after the completion of the first run during which the specimen warmed from liquid-helium temperature to room temperature.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

[†] Private communication

TABLE 7. SPECIFICATIONS OF THE SPECIMENS OF IRON (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	670	Arajs, S., Oliver, B. F., and Dunmyre, G.R.	1965	L	6. 0-193	B	99. 925 pure; polycrystalline; 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; no analysis for N; specimen made by vacuum melting commercial electrolytic iron in the conventional fashion; annealed; electrical resistivity ratio, $\rho(297K)/\rho(4.2K)$, equal to 27. 1.
37	671	Bäcklund, N. G.	1961	L	100-280		"Very pure"; manufactured by Philips Research Labs., Eindhoven, Holland; wire of 2. 5 mm diameter; annealed at about 500 C for 10 hrs; electrical resistivity 9. 8 μohm cm at 20 C.
38	†	Bäcklund, N. G.	1965	L	100-280		Spectroscopically standardized iron from Johnson, Matthey and Co.; rod of 5. 0 mm diameter; annealed at about 500 C for 10 hrs; electrical resistivity 9. 9 μohm cm at 20 C.
39	‡	Powell, R. W. and Tye, R. P.	1966	C	323-523	No. 1	0. 0250 Ni, <0. 0100 Mo, <0. 0100 Cu, 0. 0070 Cr, 0. 0050 C, 0. 0040 S, 0. 0040 V, 0. 0040 O, 0. 0030 P, 0. 0010 Mn, <0. 0010 Si, 0. 0006 N, and 0. 000048 H; rod of 1. 27 cm in diameter and 15 cm long; submitted for test by Tube Investments, Ltd., and supplied by Metals Research; electrical resistivity at 323, 373, 423, 473, and 523 K were, respectively, 11. 7, 14. 7, 17. 9, 21. 6, and 25. 6 μohm cm.
40	‡	Powell, R. W. and Tye, R. P.	1966	C	323-523	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 Mn, <0. 0010 Cr, 0. 0008 O, 0. 0007 N, and 0. 000016 H; rod of 1. 27 cm in diameter and shorter than the above sample No. 1; machined from one of several discs specially prepared by Metallurgy Division of NPL; electrical resistivity at 323, 373, 423, 473, and 523 K were, respectively, 11. 9, 14. 9, 18. 2, 21. 8, and 25. 8 μohm cm.
41	‡	Powell, R. W. and Tye, R. P.	1966	C	323-1073	Purefree iron; No. 6	0. 0800 Si, 0. 0300 C, 0. 0150 P, 0. 0100 S, and 0. 0100 Mn; supplied by Low Moor Best Yorkshire Iron, Ltd.; rod of 2. 54 cm in diameter and approximately 20 cm long; electrical resistivity at 323, 373, 423, 473, 523, 573, 673, 773, 873, 973, and 1073 K were, respectively, 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; this sample was of lower purity than Armco iron.

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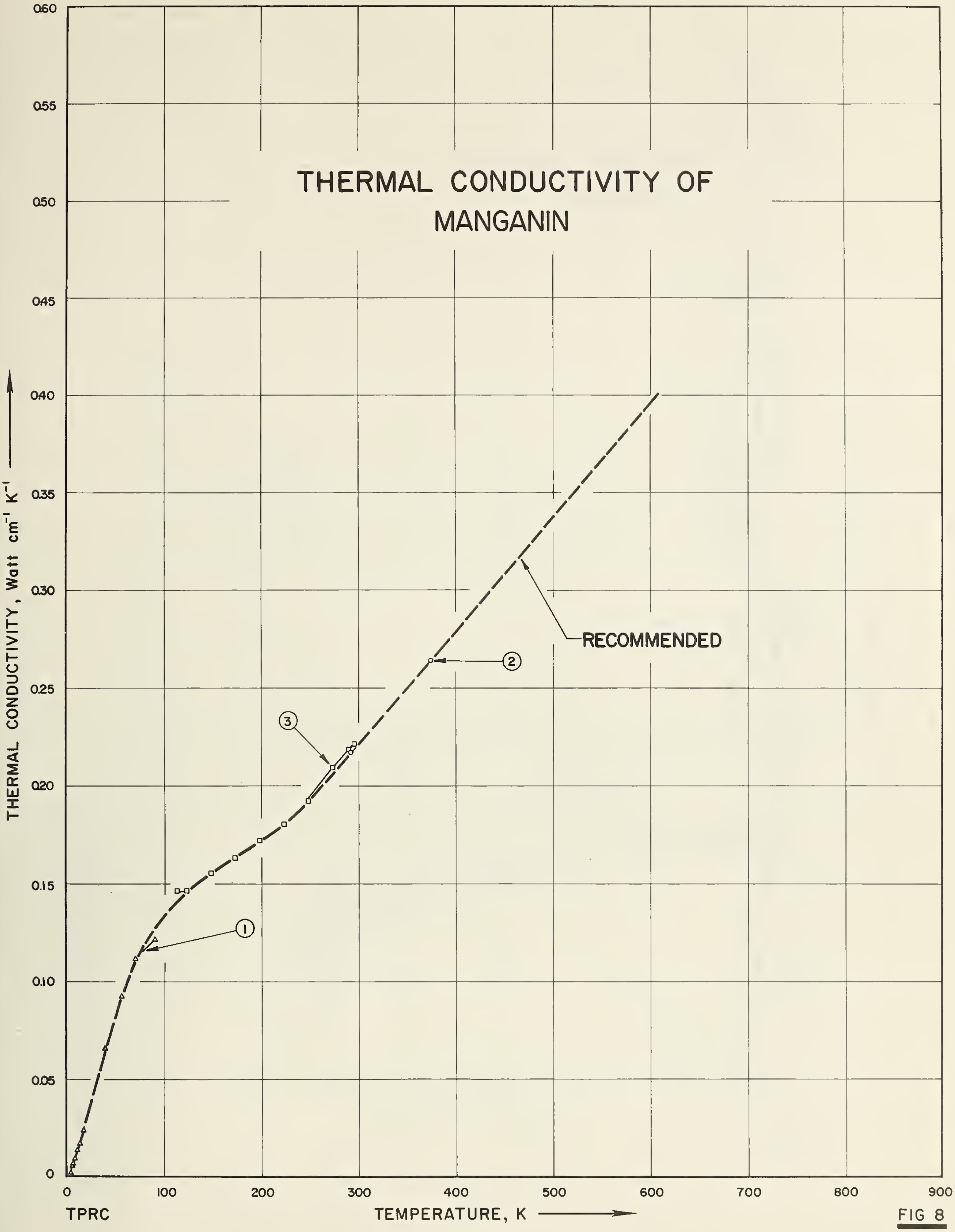
*See TPRC Data Book Vol. 1, Chapter 1, References

†Private communication

‡In course of publication



THERMAL CONDUCTIVITY OF MANGANIN

FIG 8

TABLE 8. SPECIFICATIONS OF THE SPECIMENS OF MANGANIN

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	154	Zavaritskii, N.V. and Zeldovich, A.G.	1956	L	3.0–90	Manganin	85 Cu, 12 Mn, 3 Ni; NMMts Manganin; specimen 3 mm in diameter; unannealed.
2	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Manganin	84 Cu, 12 Mn, 4 Ni; Specimen 1.806 cm in diameter and 27.0 cm in length; density 8.44 g cm^{-3}; drawn.
3	88	Lees, C.H.	1908	L	113–295	Manganin	84 Cu, 12 Mn, 4 Ni; turned from a bar; density 8.42 g cm^{-3} at 22 C.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

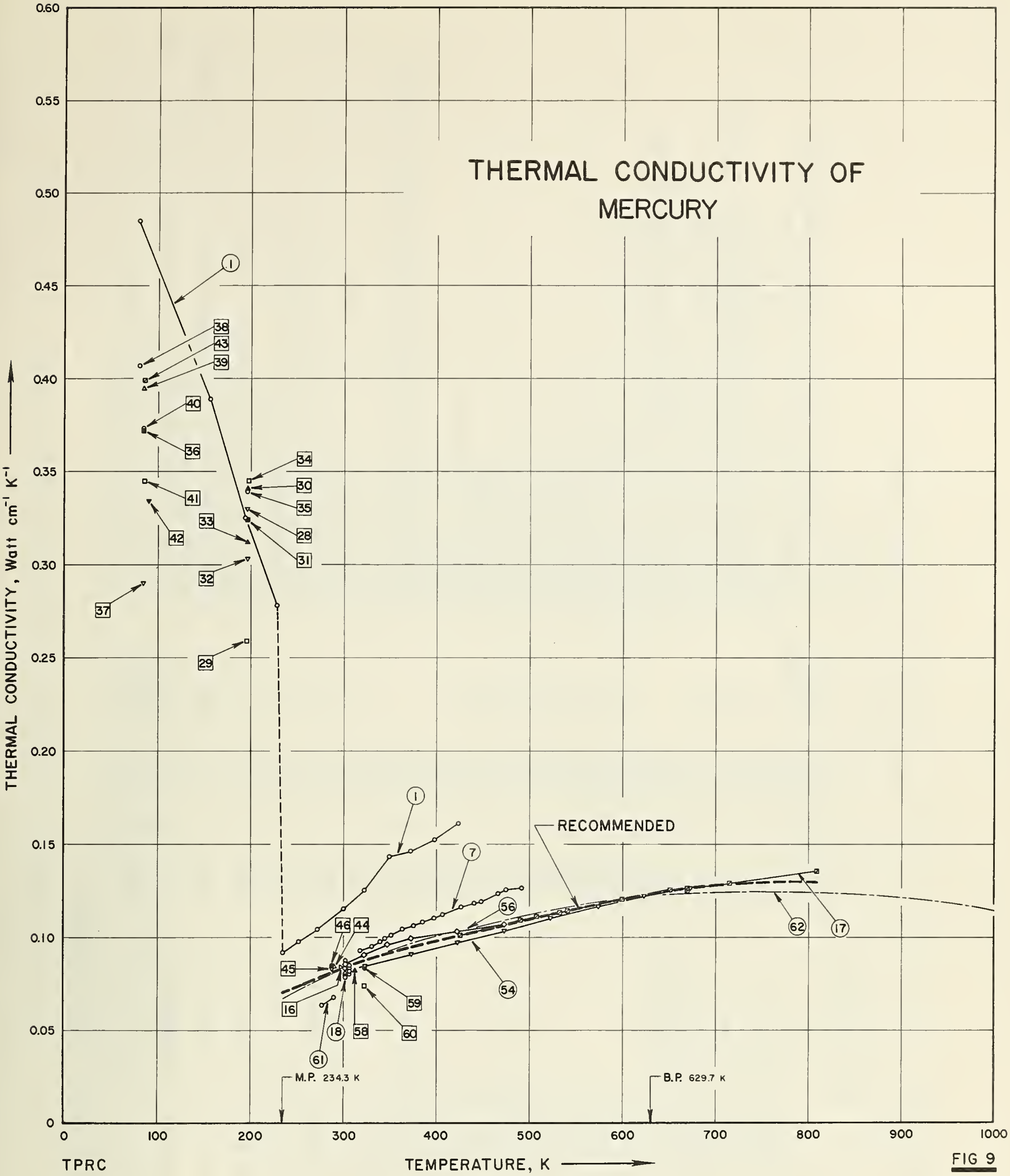
THERMAL CONDUCTIVITY OF MERCURY
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
0
100
200
300
400
500
600
700
800
900
1000
M.P. 234.3 K
B.P. 629.7 K
RECOMMENDED
1
38
43
39
40
36
41
42
33
32
37
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FIG 9

TABLE 9. SPECIFICATIONS OF THE SPECIMENS OF MERCURY

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	50	Gehlhoff, G. and Neumeier, F.	1919	L	80-423		Pure.
2	143	Webber, T. T. and Spohr, D. A.	1957	L	1.5-4.1	Hg 3	99.9 pure; 0.05 Ag, 0.05 Cu; in superconducting state.
3	143	Webber, T. T. and Spohr, D. A.	1957	L	1.4-3.5	Hg 3	The above specimen measured in a magnetic field of 859 gauss; in normal state.
4	143	Webber, T. T. and Spohr, D. A.	1957	L	1.4-4.4	Hg 3	The above specimen measured in a field of 491 gauss; in normal state.
5	59	de Haas, W. J. and Bremmer, H.	1936	L	2.5-4.1		High purity; in superconducting state.
6	59	de Haas, W. J. and Bremmer, H.	1936	L	2.5-4.1		High purity; measured in a magnetic field of 436 gauss; in normal state.
7	65	Hall, W. C.	1938	L	318-492		Pure.
8	74	Hulm, J. K.	1950	L	2.3-4.4	Hg 1	99.99$^+$ pure; in normal state.
9	74	Hulm, J. K.	1950	L	2.3-4.2	Hg 1	99.99$^+$ pure; in superconducting state.
10	74	Hulm, J. K.	1950	L	1.6-2.1	Hg 2	0.002 Cd; in normal state.
11	74	Hulm, J. K.	1950	L	1.6-2.2	Hg 2	0.002 Cd; in superconducting state.
12	74	Hulm, J. K.	1950	L	1.8-4.2	Hg 3	0.007 Cd; in normal state.
13	74	Hulm, J. K.	1950	L	1.8-4.0	Hg 3	0.007 Cd; in superconducting state.
14	74	Hulm, J. K.	1950	L	1.6-4.3	Hg 6	0.10 In; in normal state.
15	74	Hulm, J. K.	1950	L	1.6-4.1	Hg 6	0.10 In; in superconducting state.
16	657	Istrati, M. I.	1926	P	298		In liquid state.
17	265	Ewing, C. T., Seebold, R. E., Grand, J. A., and Miller, R. R.	1955	L	426-810		Purity $\geq$ 99.999; spectrochemical analysis before experiment showed 0.0001-0.001 Mg; chemical analysis after experiment showed 0.0004 Fe, 0.0002 Cr and 0.0001 Ni.
18	258	Weber, R.	1903	L	303-308		Pure.
19	143	Webber, T. T. and Spohr, D. A.	1957	L	1.4-4.2	Hg 3	99.9 pure; 0.05 Ag, 0.05 Cu; trace other elements; measured in a magnetic field of 737 gauss; in normal state.
20	143	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	99.99$^+$ pure; 0.005 Ag, trace Cu; measured in a transverse magnetic field with strength H ranging from 8.4 to 190 gauss; in superconducting state.
21	143	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in a transverse magnetic field with strength H ranging from 247 to 974 gauss; in normal state.
22	143	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in a longitudinal magnetic field with strength H ranging from 139 to 198 gauss; in superconducting state.
23	143	Webber, T. T. and Spohr, D. A.	1957	L	3.1	Hg 1	The above specimen measured in a longitudinal magnetic field with strength H ranging from 284 to 727 gauss; in normal state.
24	143	Webber, T. T. and Spohr, D. A.	1957	L	1.4	Hg 2	99.995$^+$ pure; trace Ag; measured in a transverse magnetic field with strength H ranging from 455 to 965 gauss; in normal state.
25	143	Webber, T. T. and Spohr, D. A.	1957	L	1.8	Hg 2	The above specimen measured in a transverse magnetic field with strength H ranging from 460 to 1,000 gauss; in normal state.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 9. SPECIFICATIONS OF THE SPECIMENS OF MERCURY (continued)

Cur. No.	Ref.[*] No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
26	143	Webber, T. T. and Spohr, D. A.	1957	L	1.67	Hg 2	The above specimen measured in a longitudinal magnetic field with strength H ranging from 455 to 965 gauss; in normal state.
27	143	Webber, T. T. and Spohr, D. A.	1957	L	1.98	Hg 2	The above specimen measured in a longitudinal magnetic field with strength H ranging from 440 to 943 gauss; in normal state.
28	254	Reddemann, H.	1932	L	196.2		Single crystal; the angle between crystal axis and rod axis $\Theta = 21^\circ$.
29	254	Reddemann, H.	1932	L	196.4		Single crystal; $\Theta = 90^\circ$.
30	254	Reddemann, H.	1932	L	196.8		Single crystal; $\Theta = 0^\circ$.
31	254	Reddemann, H.	1932	L	197.5		Single crystal; $\Theta = 28^\circ$.
32	254	Reddemann, H.	1932	L	197.6		Single crystal; $\Theta = 46^\circ$.
33	254	Reddemann, H.	1932	L	197.1		Single crystal; $\Theta = 38^\circ$.
34	254	Reddemann, H.	1932	L	198.4		Single crystal; $\Theta = 0^\circ$.
35	254	Reddemann, H.	1932	L	197.3		Single crystal; $\Theta = 0^\circ$.
36	254	Reddemann, H.	1932	L	85.2		Single crystal; $\Theta = 25^\circ$.
37	254	Reddemann, H.	1932	L	85.4		Single crystal; $\Theta = 90^\circ$.
38	254	Reddemann, H.	1932	L	80.2		Single crystal; $\Theta = 0^\circ$.
39	254	Reddemann, H.	1932	L	85.5		Single crystal; $\Theta = 8^\circ$.
40	254	Reddemann, H.	1932	L	85.5		Single crystal; $\Theta = 28^\circ$.
41	254	Reddemann, H.	1932	L	86.6		Single crystal; $\Theta = 46^\circ$.
42	254	Reddemann, H.	1932	L	90.6		Single crystal; $\Theta = 46^\circ$.
43	254	Reddemann, H.	1932	L	86.2		Single crystal; $\Theta = 0^\circ$.
44	598	Nettleton, H. R.	1913	L[†]	290.5		In liquid state; measured at a flow rate of 871 g per 15 min.
45	598	Nettleton, H. R.	1913	L[†]	288.2		In liquid state; measured at a flow rate of 1003 g per 15 min.
46	598	Nettleton, H. R.	1913	L[†]	289.2		In liquid state; measured at a flow rate of 1079 g per 15 min.
47	598	Nettleton, H. R.	1913	L[†]	290.7		In liquid state; measured at a flow rate of 1099 g per 15 min.
48	598	Nettleton, H. R.	1913	L[†]	288.2		In liquid state; measured at a flow rate of 1159 g per 15 min.
49	598	Nettleton, H. R.	1913	L[†]	288.2		In liquid state; measured at a flow rate of 1199 g per 15 min.
50	598	Nettleton, H. R.	1913	L[†]	287.2		In liquid state; measured at a flow rate of 1296 g per 15 min.
51	598	Nettleton, H. R.	1913	L[†]	288.7		In liquid state; measured at a flow rate of 1301 g per 15 min.
52	598	Nettleton, H. R.	1913	L[†]	288.7		In liquid state; measured at a flow rate of 1361 g per 15 min.
53	598	Nettleton, H. R.	1913	L[†]	288.7		In liquid state; measured at a flow rate of 1422 g per 15 min.
54	637	Vel'tischeva, V. A., Kalakutskaya, N. A., and Nikol'skii, N. A.	1958	L	273-773		In liquid state.
	592	Nikol'skii, N. A., Kolakutskaya, N. A., Pchelkin, I. M., Klassen, T. V., and Vel'tischeva, V. A.	1959	L	273-773		In liquid state.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

[†] But with flowing sample.

TABLE 9. SPECIFICATIONS OF THE SPECIMENS OF MERCURY (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
55	638	Zaitseva, L. S.	1959	R	567-717		Chemically pure mercury vapor.
56	639	Powell, R.W. and Tye, R. P.	1961	C	303-473		Triply distilled liquid mercury; electrical resistivity 96.7 μohm cm at 30 C and 115.0 μohm cm at 200 C.
57	640	Schleiermacher, A.	1889		476.2		Mercury vapor.
58	641	Nettleton, H.R.	1915	L	313		Liquid mercury.
59	642	Berget, A.	1887		323		Liquid mercury.
60	643	Angstrom, A. G.	1864	P	323		Liquid mercury.
61	644	Weber, H. F.	1880		278, 290		Liquid mercury.
62	694	Grosse, A. V.	1964		234-1733		Calculated from electrical conductivity according to the Wiedemann-Franz-Lorenz law.

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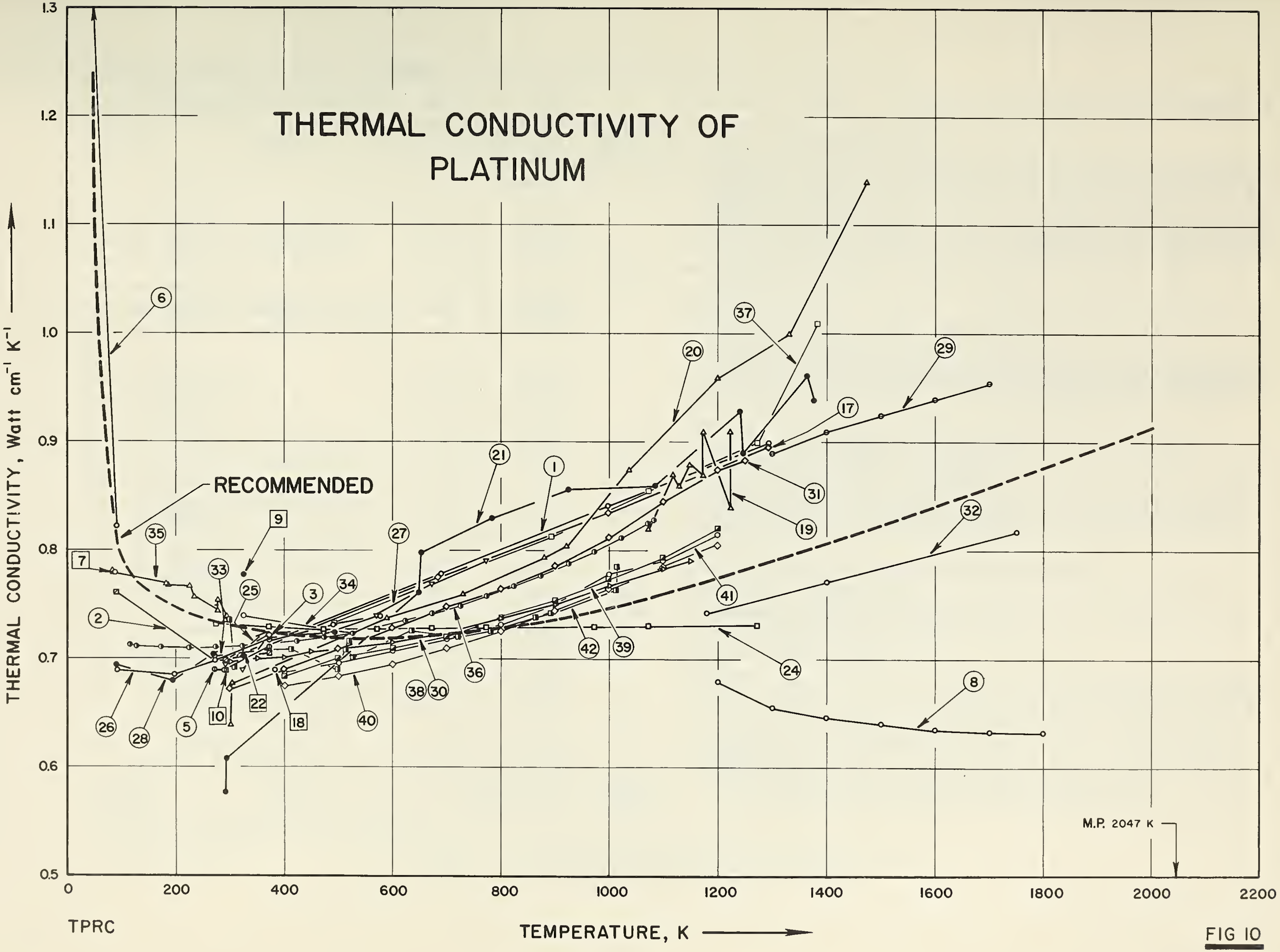
[*] See TPRC Data Book Vol. 1, Chapter 1, References


THERMAL CONDUCTIVITY OF PLATINUM
THERMAL CONDUCTIVITY, Watt cm^{-1} K^{-1}
TEMPERATURE, K
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
RECOMMENDED
M.P. 2047 K
1
2
3
5
6
7
8
9
10
17
18
19
20
21
22
24
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27
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TPRC

FIG 10

TABLE 10. SPECIFICATIONS OF THE SPECIMENS OF PLATINUM

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	70	Holm, R. and Störmer, R.	1930	E	293-1293		99.95 pure.
2	95	Meissner, W.	1915	E	21-374		Very high purity; drawn and electrically annealed.
3	77	Jaeger, W. and Diesselhorst, H.	1900	E	291, 373	Pt II	Pure.
4	98	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.4-32		99.999 pure; annealed wire.
5	8	Barratt, T.	1913	L	273-373		Pure wire.
6	149	White, G.K. and Woods, S.B.	1957	L	2.3-91		99.99$^+$ pure; annealed at 1050 C.
7	57	Grüneisen, E. and Goens, E.	1927	L	21, 83	Pt III	Very pure; drawn and electrically annealed.
8	273	Krishnan, K.S. and Jain, S.C.	1954	E	1200-1800		Spectroscopically pure wire.
9	487	Gray, J.H.	1894	L	326.2		Pure; specimen 2.0 mm in diameter.
10	451	Johansson, C.H. and Linde, J.O.	1930		291.2		Pure; tempered at 800 C and quenched; and then rolled and drawn.
11	399	Barratt, T. and Winter, R.M.	1925	L	290, 373		Pure.
12	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.17	Pt IV 33	Quasi-isotropic; measured without magnetic field.
13	436	Grüneisen, E. and Adenstedt, H.	1938	L	22.01	Pt IV 33	The above specimen measured in a transverse magnetic field with strength H = 2280 oersteds.
14	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.21	Pt IV 33	The above specimen measured at H = 4490 oersteds.
15	436	Grüneisen, E. and Adenstedt, H.	1938	L	22.10	Pt IV 33	The above specimen measured at H = 8750 oersteds.
16	436	Grüneisen, E. and Adenstedt, H.	1938	L	22.15	Pt IV 33	The above specimen measured at H = 10880 oersteds.
17	488	Holm, R.	1929	E	293-1293		Pure.
18	390	Zolotukhin, G.E.	1956	P	384.2		Pure.
19	503	Bode, K.-H.	1961	E	1073-1223		99.9 chemically pure; specimen in the form of a 1 mm diameter wire stretched between two heaters; wire surface polished with Vienese chalk or Paris red (=crocus, polishing powder); annealed at about 1000 C for 12 hrs.
20	599	Cutler, M., Snodgrass, H.R., et al.	1961	E	301-1473		99.9 pure; electrical resistivity 10.6 x 10^{-6} ohm cm at 23 C.
21	599	Cutler, M., Snodgrass, H.R., et al.	1961	E	292-1376		Same as above specimen.
22	241	Schulze, F.A.	1925	L	298		<0.03 impurity.
23	57	Grüneisen, E. and Goens, E.	1927	L	21.2	Pt IV	Pure; polycrystal; annealed.
24	645	Powell, R.W. and Tye, R.P	1963	C	273-1273		99.999$^+$ pure; mean values of thermal conductivity determinations on two specimens; one was the same specimen used to produce curve No. 34, and the other was of 1.269 cm in dia and 10.16 cm in length, with impurities: 0.0001 Fe, 0.0001 Si, <0.0001 Ag, Ca, Cu, Mg, Pd each; density 21.5 g ml^{-1}; annealed at about 1000 C; electrical resistivity at 0, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 C were, respectively, 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; Lorenz function at these temperatures was derived to be, respectively, 2.66, 2.70, 2.68, 2.67, 2.65, 2.64, 2.60, 2.57, 2.54, 2.51, and 2.47 x 10^{-8} V^2 K^{-2}.
25	646	Carter, F.E.	1928		291, 373		No details.
26	647	Kannuluik, W.G. and Carman, E.H.	1952	E	91-578		A wire 11.6 cm long and 1.5 mm in diameter in a hot-wire type gas thermal conductivity cell.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 10. SPECIFICATIONS OF THE SPECIMENS OF PLATINUM (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	624	Mikryukov, V. E.	1959		323-773		99. 99 pure; polycrystal.
28	663	Kannuluik, W. G. and Carman, E. H.	1951	E	90-495		Same as for curve No. 26.
29	**	Hopkins, M. R. and Griffith, R. L.	1958	E	1300-1700		Lorenz function was measured.
30	648	Martin, J. J. and Sidles, P. H.	1964	P	300-1150		99. 999 pure, supplied by J. Bishop and Co., $R_{273K}/R_{4K} = 900$; annealed at 1200 K for at least one hr; thermal conductivity data were 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).
31	648	Martin, J. J. and Sidles, P. H.	1964	P	300-1250		99. 9 pure, supplied by J. Bishop and Co., $R_{273K}/R_{4K} = 12$; annealed at 1200 K for at least one hr; thermal conductivity data were 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).
32	654	Wheeler, M. J.	1965	P	1180-1750		99. 95 pure platinum sheet of 1 mm thick from Johnson, Matthey and Co.; average grain size (after testing) 1000μ; density 21. 5 g cm^{-3}; data calculated from thermal diffusivity measurements using the specific heat data of Kubaschewski, O. and Evans, L. L. (Metallurgical Thermochemistry, Pergamon Press, Ltd., 1956).
33	662	Bode, K. -H.	1964	E	273-373		99. 98 pure; 0. 0007 - 0. 0009 Ag, 0. 0015 - 0. 0017 Al, 0. 0011 Au, 0. 0021 - 0. 0023 Ca, 0. 0004 - 0. 0006 Cu, 0. 0004 - 0. 0005 Fe, about 0. 003 Ir, 0. 0007 - 0. 0009 Mg, 0. 0015 - 0. 0017 Pd, 0. 0021 - 0. 0023 Rh; cylinder of 5. 000 cm diameter and 7. 000 cm length; loaned by Degussa, Hanau; density 21. 32 g ml^{-1} at 20 C; held at 600 C for 2 hrs.
34	665	Powell, R. W., Tye, R. P., and Woodman, M. J.	1962	C	323, 473		99. 999^{+} Pt, 0. 0001 Cu, 0. 0001 Fe, <0. 0001 Pd; rod, 0. 635 cm in diameter and 6. 1 cm long, supplied by Johnson, Matthey and Co., density 21. 51 g ml^{-1}; annealed at about 1273 K; electrical resistivity $\rho(273K) = 9.85$ μohm cm, $\rho(4.2K) = 0.013$ μohm cm; $\rho(273K)/\rho(4.2K) = 758$.
35	†	Powell, R. W., Tye, R. P., and Woodman, M. J.	1966	C	80-294		The above specimen measured again after four years.
36	‡	Flynn, D. R.	1966	L	113-1083	Engelhard E-2 Grade	About 99. 98 pure; Engelhard E-2 Grade; annealed for 1/2 hr at 870 C; bar of 2 cm in diameter; density 21. 38 g cm^{-3} at 21 C; electrical resistivity 9. 847 μohm cm at 0 C, electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 393$.
37	689, 690	Kobushko, V. S., Merisov, B. A., and Khotkevich, V. I.	1965	E	273-1383		Platinum wire of 0. 3 mm in diameter.
38	700	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1100	A	99. 999 Pt (nominal); rod, 3/16 in. in diameter and 10 - 12 in. long, supplied by J. Bishop and Co.; annealed at 1200 K for at least one hr; electrical resistivity at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K were, respectively, 10. 90, 14. 72, 18. 41, 22. 00, 25. 50, 28. 88, 23. 11, 35. 25, and 38. 25 μohm cm, and electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 900$ determined upon completion of the thermal diffusivity measurements; thermal conductivity values were calculated from thermal diffusivity data measured partly in a helium atmosphere and partly in vacuum at the higher temperatures and using a constant density of 21. 37 g cm^{-3} from Smithsonian Physical Tables (1954) and using specific heat data of Jaeger and Rosenbohm (1939).

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*See TPRC Data Book Vol. 1, Chapter 1, References

**Hopkins, M. R. and Griffith, R. L., Z. Physik, 150, 325-31, 1958; thermal conductivity data derived by Powell and Tye [645].

†In course of publication.

‡Unpublished data.

TABLE 10. SPECIFICATIONS OF THE SPECIMENS OF PLATINUM (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	700	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1200	B	99.999 Pt (nominal); rod, 3/16 in. in diameter and 10 - 12 in. long, supplied by Engelhard Industries; annealed at 1200 K for at least one hr; electrical resistivity at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K were, respectively, 10.95, 14.75, 18.45, 22.10, 25.64, 29.00, 32.20, 35.35, and 38.45 μohm cm, and electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 100$ determined upon completion of the thermal diffusivity measurements; thermal conductivity values were calculated from thermal diffusivity data measured partly in a helium atmosphere and partly in vacuum at the higher temperatures and using a constant density of 21.37 g cm^{-3} from Smithsonian Physical Tables (1954) and using specific heat data of Jaeger and Rosenbohm (1939).
40	700	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1200	C	99.9 Pt (nominal); rod, 3/16 in. in diameter and 10 - 12 in. long, supplied by Engelhard Industries; annealed at 1200 K for at least one hr; electrical resistivity at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K were, respectively, 11.30, 15.13, 18.90, 22.60, 26.14, 29.51, 32.76, 35.85, and 38.89 μohm cm, and electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 34$, determined upon completion of the thermal diffusivity measurements; thermal conductivity values were calculated from thermal diffusivity data measured partly in a helium atmosphere and partly in vacuum at the higher temperatures and using a constant density of 21.37 g cm^{-3} from Smithsonian Physical Tables (1954) and using specific heat data of Jaeger and Rosenbohm (1939).
41	700	Martin, J. J., Sidles, P. H., and Danielson, G. C.	1965	P	400-1200	D	99.999 Pt (nominal); rod, 3/16 in. in diameter and 10 - 12 in. long, supplied by Sigmund Cohn Corp.; annealed at 1200 K for at least one hr; electrical resistivity at 300, 400, 500, 600, 700, 800, 900, 1000, and 1100 K were, respectively, 10.90, 14.68, 18.40, 21.98, 25.45, 28.82, 32.04, 35.10, and 38.13 μohm cm, and electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 5000$ determined upon completion of the thermal diffusivity measurements; thermal conductivity values were calculated from thermal diffusivity data measured partly in a helium atmosphere and partly in vacuum at the higher temperatures and using a constant density of 21.37 g cm^{-3} from Smithsonian Physical Tables (1954) and using specific heat data of Jaeger and Rosenbohm (1939).
42	‡	Laubitz, M. J.	1965	L	300-1015	Engelhard E-4 Grade	99.999^{+} Pt, 0.0004 Rh, 0.0003 Fe, <0.0001 Al, <0.0001 Pd, <0.0001 Si, <0.00005 Au, <0.00003 Cu, <0.00003 Mn, 0.00002 Ag, <0.00001 Ca, and <0.00001 Mg; Engelhard E-4 grade platinum; specimen 1.2 cm in diameter and 10 cm long; annealed for 10 hrs at 800 K; density 21.452 ± 0.010 g cm^{-3} at 293.0 K; electrical measurements, made on a rod 0.178 cm in diameter and approximately 20 cm long drawn from the same bar (Bar No. 174961) of material as was used for the manufacture of the specimen and annealed overnight at 900 K gave the following characteristics: electrical resistivity ratio $\rho(273.2K)/\rho(4.2K) = 1890$; thermal emf 3.3 μV (at 1000 K temperature difference) produced by a thermocouple made of this rod and a bar of Engelhard Reference Grade platinum (Bar No. 46315), the rod being negative; the electrical resistivity from 300 to 800 K was given within ± 0.10% by $\rho = 9.820\,[1 + 3.983 \times 10^{-3}\,T - 0.586 \times 10^{-6}\,T^2]$ with ρ in μohm cm and T in C.

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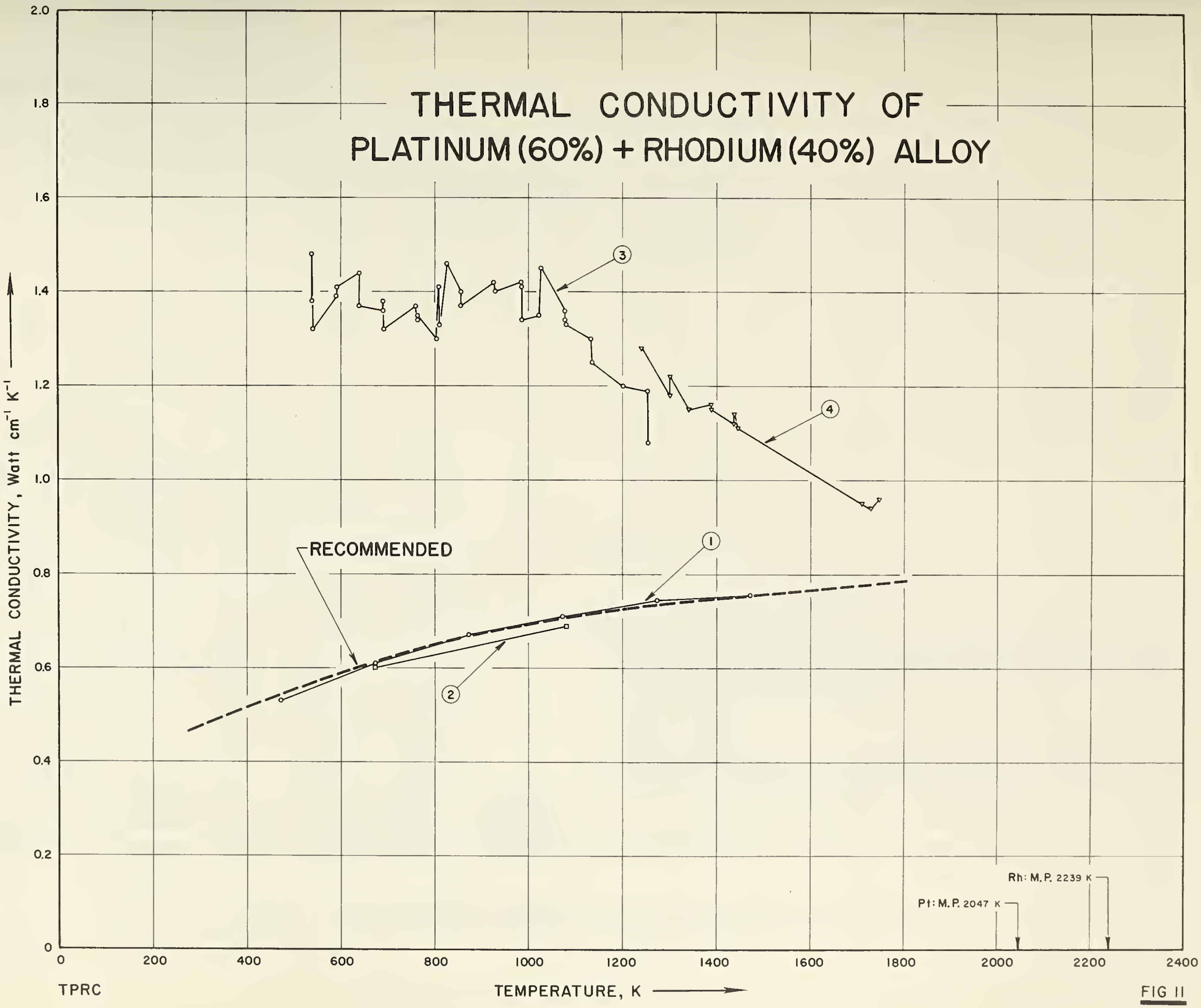
*See TPRC Data Book Vol. 1, Chapter 1, References

‡Unpublished data


THERMAL CONDUCTIVITY OF
PLATINUM (60%) + RHODIUM (40%) ALLOY
THERMAL CONDUCTIVITY, Watt cm^{-1} K^{-1}
TEMPERATURE, K
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
RECOMMENDED
①
②
③
④
Pt: M.P. 2047 K
Rh: M.P. 2239 K

TPRC

FIG 11

TABLE 11. SPECIFICATIONS OF THE SPECIMENS OF PLATINUM (60%) + RHODIUM (40%) ALLOY

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	596	Flynn, D. R.	1962	L	473-1473		0.01 - 0.1 Fe, 0.001 - 0.01 Cu, Ir, Pd, Si, and Zr, and <0.001 B and Ca; machined and then annealed at 1000 C; specimen in the form of right cylinder, 2.539 cm in diameter and 7.5 cm in length, with recesses at either end; the solid portion of the cylinder 6.49 cm in length.
2	596	Flynn, D. R.	1962	L	673, 1073		0.01 - 0.1 Fe, 0.001 - 0.01 Cu, Ir, Pd, Si, and Zr, <0.001 B and Ca; the above specimen measured as the temperature decreases.
3	589	Engelke, W. T. and Pears, C. D.	1962	R	548-1254		1 in. outside dia and 0.25 in. inside dia discs punched from 0.040 in. thick sheet and stacked to 1 in. high; annealed at 1800 F for 30 min; grain size exhibited an increase of 2 to 3 times larger than before the measurement; chemical analysis was not made and composition could not be confirmed.
4	589	Engelke, W. T. and Pears, C. D.	1962	R	1240-1747		The second run of the above specimen.

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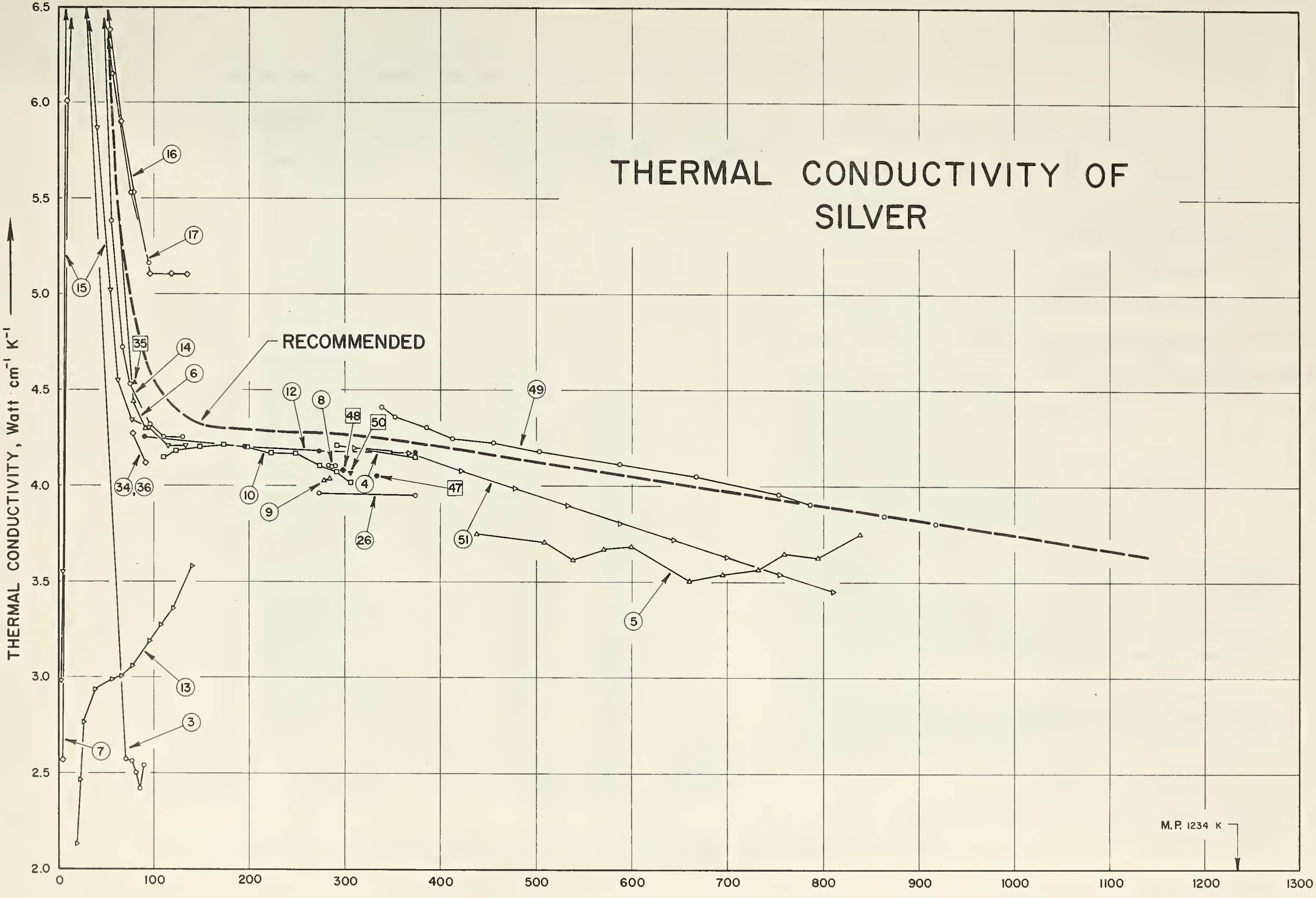
*See TPRC Data Book Vol. 1, Chapter 1, References


THERMAL CONDUCTIVITY OF
SILVER
RECOMMENDED
16
17
15
35
14
6
34, 36
12
8
48
50
4
47
10
9
26
49
51
5
13
3
7
M.P. 1234 K
THERMAL CONDUCTIVITY, Watt cm^{-1} K^{-1}
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
TEMPERATURE, K

TPRC

FIG 12

TABLE 12. SPECIFICATIONS OF THE SPECIMENS OF SILVER

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	51	Gerritsen, A.N. and Linde, J.O.	1956	L	14-21	Ag 2	Commercially pure; cold-worked; $\rho_{273K}/\rho_0 = 384$.
2	51	Gerritsen, A.N. and Linde, J.O.	1956	L	15-21	Ag 2 t	The above specimen annealed at 740 K; $\rho_{273K} = 1.47$ μohm cm; $\rho_{273K}/\rho_0 = 417$.
3	51	Gerritsen, A.N. and Linde, J.O.	1956	L	16-90	Ag 4 t	A similar specimen; annealed at 750 K; $\rho_{273K} = 1.47$ μohm cm; $\rho_{273K}/\rho_0 = 417$.
4	77	Jaeger, W. and Diesselhorst	1900	E	291,373		99.98 pure.
5	6	Bailey, L.C.	1931	L	437-838		99.9 pure; density 10.47 g cm^{-3}; specimen previously studied by Lees.
6	58	Grüneisen, E. and Reddemann, H.	1934	L	21-91	Ag I	Pure; cold-worked and annealed at 350 C.
7	97	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.3-38		99.99 pure; polycrystalline wire.
8	78	Kannuluik, W.G.	1931	E	283-291	Ag I	Electrolytic wire.
9	78	Kannuluik, W.G.	1931	E	278-284	Ag II	Spectroscopically pure wire.
10	88	Lees, C.H.	1908	L	110-306		99.9 pure.
11	122	Rosenberg, H.M.	1955	L	1.5-44	Ag 2	99.99^+ pure; polycrystalline; annealed.
12	79	Kannuluik, W.G.	1933	E	90-373		Traces of Cu, Pb, Bi, Mg, Cd, Na and Si; annealed at 500 C.
13	147	White, G.K.	1953	L	2.0-140	Ag 1	99.999^+ pure; polycrystalline bar.
14	147	White, G.K.	1953	L	3.3-131	Ag 2	The above specimen, Ag 1, after being annealed at 650 C.
15	147	White, G.K.	1953	L	1.7-134	Ag 3	The above specimen, Ag 2, drawn.
16	147	White, G.K.	1953	L	3.0-135	Ag 4	The above specimen, Ag 3, after being annealed at 650 C.
17	147	White, G.K.	1953	L	2.4-95	Ag 5	The above specimen, Ag 4, after being removed and replaced in cryostat.
18	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.3	Ag 1	99.99 pure; polycrystal; annealed; measured in a transverse field of 4.2 kilooersteds.
19	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.2	Ag 2	99.999 pure; polycrystal; annealed; measured in a transverse field of 1.09 kilooersteds.
20	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.2	Ag 2	The above specimen measured in a transverse field of 1.75 kilooersteds.
21	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	3.2	Ag 2	The above specimen measured in a transverse field of 1.97 kilooersteds.
22	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.2	Ag 2	The above specimen measured in a transverse field of 2.7 kilooersteds.
23	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	3.2	Ag 2	The above specimen measured in a transverse field of 3.6 kilooersteds.
24	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.2	Ag 2	The above specimen measured in a longitudinal field of 3.6 kilooersteds.
25	342	Mendelssohn, K. and Rosenberg, H.M.	1953	C	2.2	Ag 2	The above specimen measured in a transverse field of 3.7 kilooersteds.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 12. SPECIFICATIONS OF THE SPECIMENS OF SILVER (continued)

Cur. No.	Ref.* No.	Author (s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
26	246	Sedstrom, E.	1919	C	273, 373		Rolled and drawn; heated 1/2 hr at temperature close to melting point.
27	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Ag 37	Single crystal; measured without magnetic field.
28	436	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) = $+1^{\circ}$ at which the dependence of k on H is maximum.
29	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.26	Ag 37	The preceding specimen measured at H = 10850 oersteds and at $\Theta = +1^{\circ}$.
30	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.18	Ag 37	The above specimen measured without magnetic field.
31	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.20	Ag 37	The above specimen measured at H = 4580 oersteds and at $\Theta = +45^{\circ}$ at which the dependence of k on H is minimum.
32	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.26	Ag 37	The above specimen measured at H = 8810 oersteds and at $\Theta = +45^{\circ}$.
33	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.27	Ag 37	The above specimen measured at H = 10850 oersteds and at $\Theta = +45^{\circ}$.
34	58	Grüneisen, E. and Reddemann, H.	1934	L	79, 91	Ag e_4	Pure; single crystal; deformed.
35	58	Grüneisen, E. and Reddemann, H.	1934	L	80	Ag e_4	The above specimen annealed for 2 hrs at 350 C.
36	58	Grüneisen, E. and Reddemann, H.	1934	L	80, 91	Ag e_5	Pure; single crystal.
37	504	Parker, W.J., Jenkins, R.J., Butler, C.P., and Abbott, G.L.	1961	P	295.2		Pure; density (at 20 C) 10.49 g cm^{-3}.
38	51	Gerritsen, A.N. and Linde, J.O.	1956	L	14-94		99.929 Ag and 0.071 Mn; polycrystalline; annealed at 720 K.
39	51	Gerritsen, A.N. and Linde, J.O.	1956	L	15-94		99.837 Ag and 0.163 Mn; polycrystalline; annealed at 720 K.
40	22	Chari, M.S.R., and DeNobel, J.	1959	L	1.6-74		99.929 Ag, 0.071 Mn and <0.00005 impurities; polycrystal.
41	22	Chari, M.S.R., and DeNobel, J.	1959	L	1.5-76		99.837 Ag, 0.163 Mn and <0.00005 impurities; polycrystal.
42	649	DeNobel, J.	1956	L	1.5-4.1		99.929 Ag and 0.071 Mn; measured in a magnetic field of 25.5 kilooersteds.
43	649	DeNobel, J.	1956	L	1.9-4.1		99.929 Ag and 0.071 Mn; measured in a magnetic feild of 19 kilooersteds.
44	649	DeNobel, J.	1956	L	1.4-4.0		99.929 Ag and 0.071 Mn; measured in a magnetic field of 12 kilooersteds.
45	649	DeNobel, J.	1956	L	3.0-4.0		99.837 Ag and 0.163 Mn; measured in a magnetic field of 19 kilooersteds.
46	649	DeNobel, J.	1956	L	1.5-4.0		99.837 Ag and 0.163 Mn; measured in a magnetic field of 25.5 kilooersteds.
47	230	Smith, A.W.	1925	L	333		Impurities <0.03.
48	241	Schulze, F.A.	1911		298		Impurities <0.03.
49	617	Mikryukov, V.E.	1957		338-917		99.99 pure; polycrystal; at 338.2 K, $\rho = 1.89 \times 10^{-8}$ ohm cm, $L = 2.45 \times 10^{-8}$ $volt^2 K^{-2}$; at 385.2 K, $\rho = 2.21 \times 10^{-6}$ $L = 2.46 \times 10^{-8}$; at 503.2 K, $\rho = 2.97 \times 10^{-6}$ $L = 2.45 \times 10^{-8}$; at 753.2 K, $\rho = 4.62 \times 10^{-6}$, $L = 2.42 \times 10^{-8}$; at 917.2 K, $\rho = 5.91 \times 10^{-6}$, $L = 2.44 \times 10^{-8}$.
50	650	Kudryavtsev, Ye, V. and Chakalev, K. N.	1960		306		99.99 pure.
51	37	Evans, J.E., Jr.	1951	C	310-810		99.4 pure; National Bureau of Standards melting-point standard lead used as reference standard.

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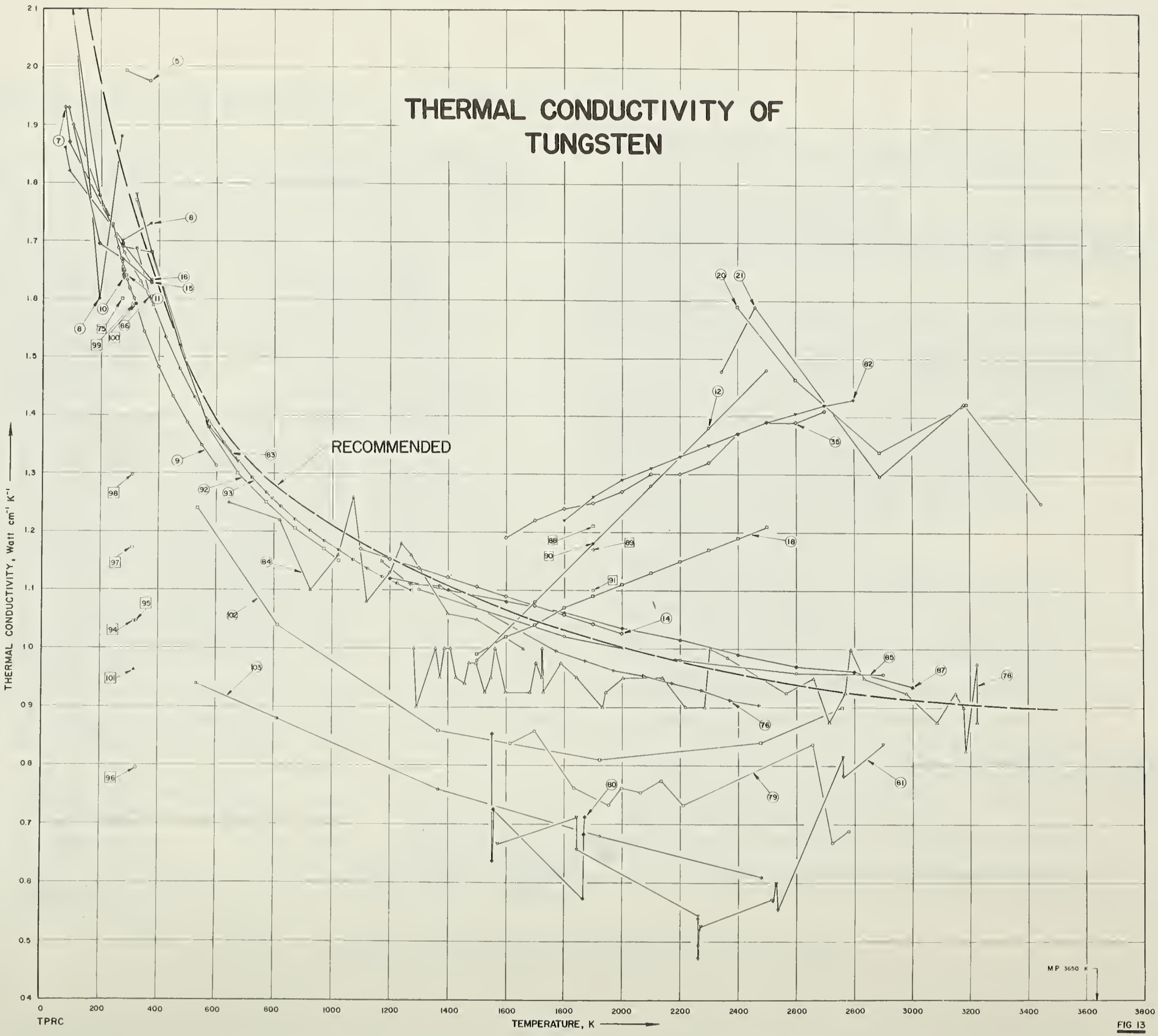
*See TPRC Data Book Vol. 1, Chapter 1, References



THERMAL CONDUCTIVITY OF TUNGSTEN

FIG 13

TABLE 13. SPECIFICATIONS OF THE SPECIMENS OF TUNGSTEN

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	150	White, G.K. and Woods, S.B.	1957	L	1.8-119	W 1b	0.01 Mo, traces of Fe, Si and Cu; annealed in vacuum at 1350 C.
2	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	W 1	High purity; single crystal.
3	57	Gruneisen, E. and Goens, E.	1927	L	21, 83	W 2	Less pure than the above specimen; single crystal.
4	18	Bremmer, H. and deHaas, W.J.	1936	L	16-22		Very pure.
5	8	Barratt, T. and Winter, R.M.	1914	L	290, 373		Pure.
6	24	Cox, M.	1943	E	77-373	2	High purity; wire; aged at 2600 C.
7	24	Cox, M.	1943	E	77-373	8	High purity; wire; aged at 2300 C.
8	99	Michels, W.C. and Cox, M.	1936	E	78-273		Commercially pure; wire.
9	87	Langmuir, I and Taylor, J.B.	1936	E	240-600		Pure; annealed at 2400 K.
10	78	Kannuluik, W.G.	1931	E	276-280	W 1	Commercially pure; wire; annealed at 220 C.†
11	78	Kannuluik, W.G.	1931	E	276-286	W 1'	Commercially pure; wire; annealed at 1300 C.†
12	153	Worthing, A.G.	1914	E	1500-2500		Pure; filament.
13	98	Mendelssohn, K. and Rosenberg, H.M.	1952	L	2.8-43	W 1	99.99 pure; annealed polycrystal.
14	106	Osborn, R.H.	1941	E	1100-2000		Pure; spectro-analysis shows traces of metallic impurities; annealed at 2700 K.
15	79	Kannuluik, W.G.	1933	E	90-373	W 1	99.96$^+$ pure; traces of Si, Ta and V; single crystal; heat flow parallel to crystal axis.
16	79	Kannuluik, W.G.	1933	E	90-373	W 2	Similar to the above specimen but heat flow at 45 degrees to the crystal axis.
17	62	deHaas, W.J. and deNobel, J.	1938	L	15-88		High purity; single crystal; heat flow at 45 degrees to the crystal axis.
18	44	Forsythe, W.E. and Worthing, A.G.	1925	E	1500-2500		Pure; filament.
19	272	deNobel, J.	1957	L	3.4-76	I-38	Pure single crystal; heat flow parallel ± 5° to the crystal axis.
20	255	Allen, R.D., Glasier, L.F., Jr., and Jordan, P.L.	1960	E	2400-3194	1	Commercially pure; 0.004 Fe, 0.005 Ti, 0.005 Ni, 0.006 O, 0.04 Mo, and 0.027 others; pressed and singered metal powder; hot-worked.
21	255	Allen, R.D., Glasier, L.F., Jr., and Jordan, P.L.	1960	E	2344-3451	2	99.95 pure; 0.002 Cu, 0.04 Mo, and 0.008 others; pressed and sintered metal powder; hot-worked.
22	447	Guareschi, P.	1940	L	15-20		High purity; single crystal; heat flow at 45 degrees to the crystal axis; measured in a field of 10.3 kilooersteds perpendicular to specimen axis.
23	447	Guareschi, P.	1940	L	15-20		As above, but measured in a field of 26.39 kilooersteds.
24	447	Guareschi, P.	1940	L	15-20		As above, but measured in a field of 32.65 kilooersteds.
25	447	Guareschi, P.	1940	L	15-20		As above, but measured in a field of 36.27 kilooersteds.
26	62	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 field of 25.85 kilogauss perpendicular to specimen axis.

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* See TPRC Data Book Vol. 1, Chapter 1, References

† Langmuir and Taylor [87] considered these temperatures too low for complete annealing.

TABLE 13. SPECIFICATIONS OF THE SPECIMENS OF TUNGSTEN (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	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 21.83 kilogauss.
28	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 18.96 kilogauss.
29	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 16.69 kilogauss.
30	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 13.82 kilogauss.
31	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 11.44 kilogauss.
32	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 8.18 kilogauss.
33	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 5.22 kilogauss.
34	62	deHaas, W.J. and deNobel, J.	1938	L	15-20		The above specimen measured in a field of 2.61 kilogauss.
35	259	Jenkins, R.J., Parker, W.J. and Butler, C.P.	1959	E	1600-2700		Spectrographically pure tungsten wire of 0.010 inch diameter.
36	448	Grüneisen, E. and Adenstedt, H.	1937	L	22-91	W 1	Without magnetic field.
37	448	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	448	Grüneisen, E. and Adenstedt, H.	1937	L	27.82	W 1	The above specimen measured at H = 6730 oersteds and $\Theta = -90^\circ$.
39	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.79	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -90^\circ$.
40	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.74	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -60^\circ$.
41	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.72	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -50^\circ$.
42	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.74	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -40^\circ$.
43	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.76	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -20^\circ$.
44	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.80	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = 0^\circ$ at which H perpendicular to [111] direction.
45	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.75	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +20^\circ$.
46	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.75	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +40^\circ$.
47	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.78	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +60^\circ$.
48	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.79	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +70^\circ$.
49	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.76	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +80^\circ$.
50	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.75	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +90^\circ$.
51	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.71	W 1	The above specimen measured at H = 4850 oersteds and $\Theta = +70^\circ$.
52	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.55	W 1	The above specimen measured at H = 2520 oersteds and $\Theta = +70^\circ$.
53	448	Grüneisen, E. and Adenstedt, H.	1937	L	21.5	W 1	Without magnetic field.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 13. SPECIFICATIONS OF THE SPECIMENS OF TUNGSTEN (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	436	Grüneisen, E. and Adenstedt, H.	1938	L	22.2	W 1	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	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.72	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = -56^{\circ}$.
56	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.5	W 1	The above specimen measured at H = 12200 oersteds and $\Theta = -56^{\circ}$.
57	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.5	W 1	The above specimen measured at H = 0 oersteds and $\Theta = +70^{\circ}$ at which H perpendicular to [111] direction.
58	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.5	W 1	The above specimen measured at H = 2520 oersteds and $\Theta = +70^{\circ}$.
59	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.7	W 1	The above specimen measured at H = 4850 oersteds and $\Theta = +70^{\circ}$.
60	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.7	W 1	The above specimen measured at H = 6100 oersteds and $\Theta = +70^{\circ}$.
61	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.7	W 1	The above specimen measured at H = 12200 oersteds and $\Theta = +70^{\circ}$.
62	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	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	436	Grüneisen, E. and Adenstedt, H.	1938	L	20.8	W 13a	The above specimen measured at H = 2280 oersteds and $\Theta = -5^{\circ}$.
64	436	Grüneisen, E. and Adenstedt, H.	1938	L	20.9	W 13a	The above specimen measured at H = 4490 oersteds and $\Theta = -5^{\circ}$.
65	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.3	W 13a	The above specimen measured at H = 8750 oersteds and $\Theta = -5^{\circ}$.
66	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 10880 oersteds and $\Theta = -5^{\circ}$.
67	436	Grüneisen, E. and Adenstedt, H.	1938	L	20.9	W 13a	The above specimen measured at H = 11080 oersteds and $\Theta = -5^{\circ}$.
68	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 12200 oersteds and $\Theta = -5^{\circ}$.
69	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 0 oersteds and $\Theta = -50^{\circ}$ at which H parallel to [110] direction.
70	436	Grüneisen, E. and Adenstedt, H.	1938	L	20.8	W 13a	The above specimen measured at H = 2280 oersteds and $\Theta = -50^{\circ}$.
71	436	Grüneisen, E. and Adenstedt, H.	1938	L	20.9	W 13a	The above specimen measured at H = 4490 oersteds and $\Theta = -50^{\circ}$.
72	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.1	W 13a	The above specimen measured at H = 8750 oersteds and $\Theta = -50^{\circ}$.
73	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.0	W 13a	The above specimen measured at H = 10880 oersteds and $\Theta = -50^{\circ}$.
74	436	Grüneisen, E. and Adenstedt, H.	1938	L	21.1	W 13a	The above specimen measured at H = 12200 oersteds and $\Theta = -50^{\circ}$.
75	449	Weber, S.	1917	L	274.2		Tempered for 20 hrs at 225 C.
76	602	Gumenyuk, V. G. and Lebedev, V. V.	1961	E	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; measured in a high vacuum.
77	579	deHaas, W. J. and Biermasz, Th.	1936	L	16-22		
78	669	Platunov, E. S. and Fedorov, V. B.	1964	L	1283-3223		Tungsten rod; photographic recording was used for the measurement of temperature distribution above 1500 C.

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*See TPRC Data Book Vol. 1, Chapter 1, References

TABLE 13. SPECIFICATIONS OF THE SPECIMENS OF TUNGSTEN (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
79	667	Rudkin, R. L., Parker, W. J., and Jenkins, R. J	1962	E	1615-2780		Spectrographically pure wire, 0. 10 in. in diameter, suspended vertically in a vacuum of better than 10^{-5} mm Hg.
80	603	Neel, D. S , Pears, C. D., and Oglesby, S., Jr.	1962	R	1555-1872		0. 003 Fe, 0. 0026 Si, 0. 0020 O, 0. 0010 S, 0. 0010 P, Ni, Cu, H, N; arc-cast; specimen 3/4 in. in diameter and 3/4 in. long; maximum exposure temperature 3040 K; density 18. 87 g cm^{-3}; 98. 4% of theoretical density.
81	603	Neel, D. S., Pears, C. D., and Oglesby, S., Jr.	1962	R	1571-2939		Similar to the above specimen; evidence that melting had occurred during test.
82	651	Zwikker, C.	1925		1800-2800		Pure wire.
83	652	Tye, R. P.	1961	L	323-673		Spectrographically standardized tungsten; JM740 of Johnson, Matthey and Co.; rod of about 4 mm in diameter and 10 cm in length.
84	653	Cutler, M. and Cheney, G. T.	1963		645-1660		Single crystal.
85	654	Wheeler, M. J.	1965		1300-2900		99. 5 W, undoped; impurities: Fe, Mo, and traces of other elements; 1. 5 mm thick disc cut from a swaged rod as used in the manufacture of lamp filaments; from General Electric Co. Osram Lamp Works; average grain size (after testing) 46 μ; density 19. 3 g cm^{-3}; data calculated from thermal diffusivity measurements using specific heat data of Kubaschewski, O. and Evans, L. L. (Metallurgical Thermochemistry, Pergamon Press, Ltd., 1956).
86	**	Bäcklund, N. G.	1965		104-380		Spectroscopically standardized; from Johnson, Matthey and Co.; bar of 4 mm in diameter and 10 cm in length; residual electrical resistivity $\rho_0 = 0.22$ μohm cm.
87	656	Timrot, D. L. and Poletskii, V. E.	1963		1473-3273		Pure tungsten containing no more than 0. 1% impurities.
88	668	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μ thick; wire rider of 0. 2 mm in diameter placed on that part of the foil where temperature was constant; circular diaphragms used in optical pyrometer system.
89	668	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μ thick; rider diameter 0.3 mm, circular diaphragms in system.
90	668	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Foil of 60 μ thick; rider diameter 0. 2 mm, slit diaphragms in system.
91	668	Filippov, L. P. and Simonova, Yu. N.	1964	E	1900		Wire of 0. 2 mm in diameter; rider diameter 0. 2 mm. slit diaphragms in system.
92	†	Powell, R. W and Tye, R. P.	1966	C	323-1023		About 0. 01 Mo; spectrographically standardized; from Johnson, Matthey and Co.; catalog No. JM740; two rods 0. 4 cm in diameter and 10 cm long; electrical resistivity ratio $\rho(273K)/\rho(4.2K) = 150$; electrical resistivity at 273, 323, 373, 473, 573, 673, 773, 873, 973, and 1023 K were, respectively, 5. 0, 6. 1, 7. 3, 9. 8, 12. 6, 15. 5, 18. 3, 21. 4, 24. 6, and 26. 2 μohm cm.
93	‡	Moore, J. P., Graves, R S., Fulkerson, W., and McElroy, D. L.	1965	R	323-1273		99.983^+ pure; <0.0030 C, <0.0029 O, <0.0010 Al, Ca, Cr, Cu, Fe, Mg, Mn, Mo, Ni, Si, Sn each, <0.0005 H, N each; machined from a 3. 5 in. diameter billet which had been hot extruded at 1800 C for a 3-to-1 reduction in area of the original pressed and sintered powder metallurgy billet; specimen density 19. 077 g cm^{-3} or approximately 99. 8% of theoretical; grain size 5 to 25 μ in average dimension; electrial resistivity ratio $\rho(300K)/\rho(4K) = 35$; electrical resistivity at 273, 323, 373, 473, 573, 673, 773, 873, 973, 1073, 1173, 1273, 1373, 1473, 1573, and 1673 K were, respectively, 5. 002, 6. 157, 7. 344, 9. 822, 12. 436, 15. 186, 18. 073, 21. 041, 24. 070, 27. 151, 30. 286, 33. 477, 36. 717, 40. 013, 43. 362, and 50. 216 μohm cm.

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*See TPRC Data Book Vol. 1, Chapter 1, References

**Private communication, Nov. 16, 1965

†In course of publication

‡Unpublished data

TABLE 13. SPECIFICATIONS OF THE SPECIMENS OF TUNGSTEN (continued)

Cur. No.	Ref. No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
94	688	Kulcinski, G. L , Wagner, P., and Cowder, L.R.	1964	L	317. 2	LASL; Set No. I, Sample 1	An oxide layer on the surface and less than 0. 0050 oxide inside the specimen; specimen in the form of porous right circular cylinder obtained from Powder Metallurgical Group of LASL and prepared from tungsten powder, which was 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 atmosphere; particle size 0. 8 micron; 72. 3% theoretical density; the ratio of isolated pores to total pores 0. 7 ± 0. 1; electrical resistivity 10. 4 μohm cm at 20 C.
95	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	323. 2	LASL; Set No. I, Sample 2	Same as the above specimen except 72. 1% theoretical density and 10. 6 μohm cm electrical resistivity at 20 C.
96	688	Kulcinski, G. L , Wagner, P., and Cowder, L.R	1964	L	326. 2	LASL; Set No. I, Sample 3	Same as sample 1 except 1350 C sintering temperature, 63. 2% theoretical density, and 13. 3 μohm cm electrical resistivity at 20 C.
97	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	311. 2	LASL; Set No. I, Sample 6	Same as sample 1 except 1575 C sintering temperature, 78. 1% theoretical density, and 9. 1 μohm cm electrical resistivity at 20 C.
98	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	311. 2	LASL; Set No. I, Sample 7	Same as sample 1 except 1625 C sintering temperature, 83. 6% theoretical density, and 8. 2 μohm cm electrical resistivity at 20 C.
99	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	308. 2	LASL; Set No. I, Sample 11	Same as sample 1 except sintered at 1700 C for 9 hrs, 95. 3% theoretical density, the ratio of isolated pores to total pores ≈0. 9, and 6. 2 μohm cm electrical resistivity at 20 C.
100	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	320. 2	LASL; Set No. I, Sample 12	Same as sample 11 except 95 5% theoretical density and 6. 3 μohm cm electrical resistivity at 20 C.
101	688	Kulcinski, G. L., Wagner, P., and Cowder, L.R.	1964	L	319. 2	LASL; Set No. II, Sample 2	Same as sample 1 except sintered at 1700 C for 3 hrs, particle size 2 - 4. 5 microns, 74. 4% theoretical density, and 10. 5 μohm cm electrical resistivity at 20 C.
102	‡	Pears, C.D.	1965	C, R	533-2755		Hot pressed polycrystalline disc of 1 in. in diameter 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.
103	544	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 3/4 in. in diameter and 3/4 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.

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[*] See TPRC Data Book Vol. 1, Chapter 1, References

[‡] Private communication, Oct. 7, 1965

C. References

1. Cezairliyan, A., "Prediction of Thermal Conductivity of Metallic Elements and Their Dilute Alloys at Cryogenic Temperatures", Purdue University, Thermophysical Properties Research Center, TPRC Rept. 14, 1-140, 1962.
2. Cezairliyan, A., and Touloukian, Y. S., "Generalization and Calculation of the Thermal Conductivity of Metals by means of the Law of Corresponding States", High Temperature, 3, 63-75, 1965; A translation of Teplofizika Vysokikh Temperatur, 3, 75-85, 1965.
3. Cezairliyan, A., and Touloukian, Y. S., "Correlation and Prediction of Thermal Conductivity of Metals Through the Application of the Principle of Corresponding States", Advances in Thermophysical Properties at Extreme Temperatures and Pressures, 3rd Symposium on Thermophysical Properties, A. S. M. E., March 22-25, 1965, 301-313.
4. Touloukian, Y. S, Thermophysical Properties Research Center Data Book, Volume I. Metallic Elements and Their Alloys, Chapter 1. Thermal Conductivity. Data sheets updated twice a year; 850 pages in Chapter 1 as of June 1965, 11" x 17".
5. Powell, R. W., Tye, R. P., and Woodman, Margaret J., "The Thermal Conductivity of Pure and Alloyed Aluminum: I. Solid Aluminum as a Reference Material", Advances in Thermophysical Properties at Extreme Temperatures and Pressures, 3rd Symposium on Thermophysical Properties, ASME, March 22-25, 1965, 277-88.
6. Flynn, D. R., National Bureau of Standards, Private communication, March, 1965.
7. Lees, C. H., Bakerian Lexture - "The Effect of Temperature and Pressure on the Thermal Conductivities of Solids. Part II. The Effect 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.
8. 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., ASTIA TR-264-7, ATI 105 924, 1-13, 1951.
9. 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.
10. 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 available from Clearinghouse for Federal Scientific and Technical Information, T T-65-63678).
11. Powell, R. W., Tye, R. P., and Metcalf, S. C., "The Thermal Conductivity of Pure and Alloyed Aluminum: II. Molten Aluminum and Aluminum Alloys", Advances in Thermophysical Properties at Extreme Temperatures and Pressures, 3rd Symposium on Thermophysical Properties, ASME, March 22-25, 1965, 289-95.
12. 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., December 7, 1964, 71 pp.
13. 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., November 22, 1964, 40 pp.
14. Roll, A. and Motz, H., "The Electrical Resistivity of Molten Metals", Z. Metallkde, 48, 272-280, 1957.
15. Konno, S., "On the Variation of Thermal Conductivity during the Fusion of Metals", Sci. Reports Tohoku Imp. Univ., 8, 169-179, 1919.
16. Meissner, W., "Thermal and Electrical Conductivity of Several Metals between 20 and 373 K", Ann. Physik., 4, 47, 1001-58, 1915.
17. 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.
18. Schofield, F. H., "The Thermal and Electrical Conductivities of Some Pure Metals", Proc. Roy. Soc. (London), A107, 206-27, 1925.
19. Smith, C S. and Palmer, E. W., "Thermal and Electrical Conductivities of Copper Alloys", AIMME Tech. Publ. No. 648, 1-19, 1935.
20. Mikryukov, V. E. and Rabotnov, S. N., "Thermal and Electrical Conductivities of Mono- and Polycrystalline Substances from 100 C to the Melting Point", Uchenye Zapiski Moskov. Ordena Lenina Gosudarst Univ. Mv Lomonosova Fiz., 74, 167-79, 1944.
21. Powell, R. W. and Tye, R. P., "New Measurements on Thermal Conductivity Reference Materials", In course of publication.

22. Fieldhouse, I. B., Hedge, J. C., Lang, J. I., Takata, A. N., and Waterman, T. E., "Measurements of Thermal Properties", WADC TR 55-495, Part I, 1-64, 1956.

23. Meechan, C. J. and Eggleston, R. R., "Formation Energies of Vacancies in Copper and Gold", Acta Met., 2, 680-3, 1954.

24. Powell, R. W., "Correlation of Metallic Thermal and Electrical Conductivities for both Solid and Liquid Phases", Intern. J. Heat Mass Transfer, 8, 1033-1045, 1965.

25. Mokrovskii, N. P. and Regel, A. R., "The Electrical Conductivity of Copper, Nickel, Cobalt, Iron and Manganese in the Solid and Liquid States", J. Tech. Phys., U. S. S. R., 23, 2121-5, 1953.

26. White, G. K. and Tainsh, R. J., "Lorenz Number for High-Purity Copper", Phys. Rev., 119, 1869-71, 1960.

27. 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.

28. White, G. K., "The Thermal and Electrical Conductivity of Copper at Low Temperatures", Austral. J. Phys., 6, 397-404, 1953.

29. Powell, R. L., Rogers, W. M., and Coffin, D. O., "An Apparatus for Measurement of Thermal Conductivity of Solids at Low Temperatures", J. Res. NBS, 59 (5), 349-55, 1957.

30. 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.

31. White, G. K., "The Thermal Conductivity of Gold at Low Temperatures", Proc. Phys. Soc. (London), A66, 559-64, 1953.

32. White, G. K., Private communication, CSIRO, National Standards Laboratory, Australia, Nov. 30, 1965.

33. Kannuluik, W. G., "On the Thermal Conductivity of Some Metal Wires", Proc. Roy. Soc. (London), A131, 320-335, 1931.

34. 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, 615-642, 1927.

35. 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-A1394, 1965.

36. Powell, R. W., "Armco Iron as a Thermal Conductivity Standard; Review of Published Data" Progress in International Research on Thermodynamic and Transport Properties, 2nd Symposium on Thermophysical Properties, ASME, Jan. 24-26, 1962, Academic Press, 1962, 454-65.

37. 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", Ibid, 466-473.

38. Laubitz, M. J., "The Unmatched Guard Method for Measuring Thermal Conductivity at High Temperatures", Canadian Jnl. of Physics, 41 (10), 1663-78, 1963.

39. 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.

40. Flynn, D. R., Robinson, H. E., and Watson, T. W., Heat Transfer Section, National Bureau of Standards, Private communication.

41. 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", Accepted for publication, J. Appl. Phys.

42. Powell, R. W., "The Electrical Resistivity of Liquid Iron", Phil. Mag., 7, 44, 772-5, 1953.

43. 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.

44. Zavaritskii, N. V. and Zeldovich, A. G., "Thermal Conductivity of Technical Materials at Low Temperatures", Soviet Phys. Tech. Phys., 1, 1970-1974, 1956.

45. 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.

46. Powell, R. W. and Tye, R. P., "The Thermal and Electrical Conductivity of Liquid Mercury", International Developments in Heat Transfer, Part IV, ASME Symposium, 856-62, 1961.

47. Vel'tishcheva, V. A., Kalakutskaya, N. A., and Nikol'skii, N. A., "The Heat conductivity of Mercury", Teploenergetika, 10, 80-2, 1958; and 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. Krzhizharovoskogo, 11-45, 1959.

48. Ewing. C. T., Seebold, R. E., Grand, J. A., and Miller, R. R., "Thermal Conductivity of Mercury", NRL-4506, 1-11, 1955.

49. Birch, F., "The Electrical Resistance and the Critical Point of Mercury", Phys. Rev., 41, 641-648, 1932.

50. 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.

51. Slack, G. A., "Platinum as a Thermal Conductivity Standard", J. Appl. Phys., 35, 339-44, 1964.

52. 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), 312-322, 1930.

53. Powell, R. W., Tye, R. P., and Woodman, Margaret J., "The Thermal Conductivity and Electrical Resistivity and Electrical Resistivity of Polycrystalline Metals of the Platinum Group and of Single Crystals of Ruthenium", In course of publication.

54. Flynn, D. R., "Thermal Conductivity of a 2-cm diam. Bar of Engelhard E-2 Grade Platinum", National Bureau of Standards, Washington, D. C., U. S. A., Private communication, Jan. 20, 1966.

55. Laubitz, M. J., "The Thermal Conductivity of Platinum from 300 to 1000 K", Division of Applied Physics, National Research Council, Ottawa, Ontario, Canada, Private communication, Oct. 1965.

56. Martin, J. J. and Sidles, P. H., "Thermal Diffusivity of Platinum from 300 to 1300 K", Iowa State Univ., Ames Laboratory Contribution No. 1614, 1964.

57. Hopkins, M. R. and Griffith, R. L., "The Determination of the Lorenz Number at High Temperatures", Z. Physik., 150, 325-31, 1958.

58. Wheeler, M. J., "Thermal Diffusivity at Incandescent Temperature by a Modulated Electron Beam Technique", Brit. J. Appl. Phys., 16 (3), 365-76, 1965.

59. Kobushko, V. S., Merisov, B. A., and Khotkevich, V. I., "A Method of Determining the Thermal Conductivity of Metals at High Temperature", Inzhenerno-Fizicheskii Zhurnal, 8 (1), 58-63, 1965. Translated in International Chemical Engineering, 5 (3), 485-488, 1965; and J. Eng. Phys., 8 (1), 43-6, 1965.

60. Vargaftik, N. B., "Teplofizicheskie Svoistova Veshchestv" Gosenergoizdat, 1-368, 1956.

61. Flynn, D. R., "Thermal Conductivity of Semiconductive Solids, Method for Steady-State Measurements on Small Disk Reference Samples", NBS Rept. 7740, 1-41, 1962.

62. Bailey, L. C., "The Thermal Conductivities of Certain Approximately Pure Metals and Alloys at High Temperatures", Proc. Roy. Soc. (London), A134, 57-76, 1931.

63. Evans, J. E., Jr., "Thermal Conductivity of 14 Metals and Alloys up to 1100 F [595 C]", NACA Research Memo. E50L07, 1-15, 1951.

64. deHaas, W. J. and deNobel, 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.

65. White, G. K. and Woods, S. B., "Low-Temperature Resistivity of the Transition Elements: Cobalt, Tungsten, Rhenium", Can. J. Phys., 35, 656-65, 1957.

66. Tye, R. P., "Preliminary Measurements of the Thermal and Electrical Conductivities of Molybdenum, Niobium, Tantalum and Tungsten", J. Less-Common Metals, 3, 13-18, 1961.

67. Moore, J. P., Graves, R. S., Fulkerson, W. and McElroy, D. L., "The Physical Properties of Tungsten", Metals and Ceramics Div., Oak Ridge National Laboratory, Private communication, 1965.

68. Osborn, R. H., "Thermal Conductivities of Tungsten and Molybdenum at Incandescent Temperatures", J. Optical Soc. Am., 31, 428-32, 1941.

69. Gumenyuk, V. S. and Lebedev, V. V., "Investigation of the Thermal and Electrical Conductivity of Tungsten and Graphite at High Temperatures", Phys. Metals and Metallog. USSR, 11 (1), 30-5, 1961.

70. Timrot, D. L. and Poletskii, V. E., "Use of Heating by Electron Bombardment to Investigate the Coefficient of Heat Conductivity in High-Melting-point Alloys and Compounds", High Temperature, USSR, 1 (2), 147-51, 1963.

71. Platunov, E. S. and Federov, V. B., "Use of Photographic Pyrometry in Thermal Studies", High Temperature, 2, 568-572, 1964.

72. Revel, G., "Aluminum of High Purity obtained by Zone Melting", Compt. Rend., 259, 4031-3, 1964.

73. Gniewek, J. J. and Clark, A. F., "Preparation of Copper Crystals with Low Electrical Resistivity", J. Appl. Phys., 36 (10), 3358-9, 1965.

74. Schmidt, P. H., "Purification and Crystal Growth of Gold", J. of Electrochemical Soc., 112 (6), 631-2, 1965.

75. Isin, A. and Coleman, R. V., "Magnetoresistance of Iron Whiskers", Phys. Rev., 137 (5A), A1609-13, 1965.

76. Jackson, J. J., Argonne National Lab., Private communication to T. F. Connolly, Research Materials Information Center, ORNL, June, 1965.

77. Coleman, R V., Private communication to D. C. Lawson and B. T. Boiko, cited as Ref. 11 in Appl. Phys. Letters, 5 (8), 155-6, 1964.

78. Appel, J. C., Chambers, R. H., and Trozera, T. A., "A Program of Basic Research on Mechanical Properties of Reactor Materials", General Atomic, Quarterly Progress Rept. on Contract AT (04-3)-167 for the period ending Jan. 31, 1965, 1-28, 1965.

PART II

THERMAL CONDUCTIVITY OF NONMETALLIC SOLIDS

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A. Introduction

The nonmetallic solids treated in this part include aluminum oxide, beryllium oxide, Corning code 7740 glass, diamond, magnesium oxide, Pyroceram brand glass-ceramic code 9606, quartz, thorium dioxide, and titanium dioxide. The thermal conductivities of these solids cover a fairly wide range.

A thorough literature search was conducted for the thermal conductivities of these solids. The available experimental data are collected and shown in Figures 15 to 23. Each figure is followed by a specification table giving information on the specimens corresponding to the respective curves in the figure. For curves listed in the specification table but not shown in the figure, particularly in the low temperature region, one is referred to the TPRC Data Book Volume III, Chapter 1 [1], in which complete numerical data tables are also given. The heavy broken line shown in the figure represents the recommended curve of thermal conductivity versus temperature. For each of the oxides, except quartz, the recommended curve is for a 99.5% pure, 98% dense polycrystalline specimen. In all the oxide single crystals, only the data for quartz single crystals are analyzed at this time.

The recommended values are the results of critical analysis of available data from all sources. The analysis procedure involves careful evaluation of the validity of available data and related information, resolution and reconciliation of the disagreements of conflicting data, correlation of data with affecting parameters, comparison of the resulting values with theoretical predictions and so forth.

According to theory, the thermal conductivity of nonmetallic crystals is determined both by the specific heat and the mean free path of the phonons. At temperatures close to absolute zero the phonons are scattered by the boundaries: the thermal conductivity varies as T^3 and is size dependent. As the temperature is increased, other scattering mechanisms become effective: scattering of phonons by static imperfections (impurities, isotopes and all kinds of defects) and scattering of phonons by other phonons (Umklapp processes). The last mentioned process increases rapidly with temperature, until the mean free path decreases more rapidly with temperature than the specific heat increases. At this point, still at very low temperatures (usually below $\theta/20$), the thermal conductivity passes through a maximum, and then decreases again, in some perfect crystals exponentially. Around the Debye temperature and above, it should vary as T^{-1}.

However, experimental thermal conductivity data measured at high temperatures show numerous exceptions to this T^{-1} rule. In some cases the thermal conductivity varies more slowly than T^{-1}. This can be ascribed to scattering by imperfections. At high temperatures the resistance due to Umklapp processes varies as T, that due to imperfections is more or less independent of temperature, and the combined resistance has an intermediate variation, hence the conductivity varies more slowly than T^{-1}. This is particularly pronounced in mixed crystals and in highly disordered crystals. Furthermore, in the extreme case of disorder such as in glasses and in vitreous materials, the disorder determines the phonon mean free path which consequently becomes constant at high temperatures. Hence the thermal conductivity increases with temperature, being roughly proportional to the specific heat of the material.

Other cases of departure from the theoretical behavior may be explained in terms of a radiative component of heat transfer. In porous materials, a radiative heat transfer across the pores acts as a shunt. In some cases the crystals are at least partly transparent to infrared radiation, and there is an internal radiation component. In either case the additional thermal conductivity is proportional to the specific heat of the radiation component (proportional to T^3) and the mean free path of the photons. In some cases this mean free path is governed by internal absorption and scattering processes; the radiation component is then an intrinsic property of the material. In other cases the material is transparent, and the photons traverse the specimen. The corresponding component of heat transfer is thus dependent on the dimensions of the specimen, analogous to the case of phonon heat transport near absolute zero. Finally, it may happen that photons move from the heat source in the measuring apparatus to the heat sink, partly going through the specimen and partly through free space. In this case it seems difficult to separate radiative measurement error from internal radiative heat transport. To compound the conceptual difficulty, since the internal absorption and scattering probabilities depend on photon frequency, it may happen that part of the radiative conductivity is intrinsic and part dependent on specimen dimensions. To sum up, the radiative component of the thermal conductivity can be extremely complex, is generally not well understood, and often increases rapidly with temperature, though in principle it may also decrease over some range of temperatures, depending on the photon absorption coefficient.

In analysing the available data, attempts were made to consider all parameters likely to affect the thermal conductivity, such as purity, crystal imperfection, crystal axes orientation, density (or porosity), thermal history, microstructure, etc. However, it is very unfortunate that in the majority of cases the authors do not report all necessary pertinent information to fully characterize the materials for which their data are reported. Data for unspecified materials are of little utility. The recommended values have therefore at times been based on scanty information and should be accepted as an attempt to make the most of existing knowledge and subject to modification in the light of further work.

For a material to be used as a reference standard, the chemical and physical stability is a major requirement. The stability of a material is very much dependent on the environment in which heating to high temperatures takes place. For instance, the stoichiometric composition of titanium dioxide is affected by heating to high temperatures in reducing environment and consequently its thermal conductivity is likely to change after such heating. Therefore, selection of a suitable environment is important in using a reference material.

Some pertinent comments regarding the thermal conductivity of each solid are given in the following section, and the recommended values are reported collectively in Table 14 and in Figure 14. In the table, the third significant figure is given only for the purpose of comparison and for smoothness and is not indicative of the degree of accuracy. The recommended values for most of these materials do not cover the low temperature region. This is because either there are no experimental data available in the low temperature region for some of the materials or the pertinent information on specimen characterization is inadequate. It is noted that in the low temperature region the thermal conductivity of a crystal is very strongly dependent on its purity and perfection, among other parameters, and therefore knowledge of the sample characterization is particularly important at low temperatures.

B. Thermal Conductivity of A Group of Selected Nonmetallic Solids

Aluminum Oxide. - There are 169 sets of experimental thermal conductivity data available for aluminum oxide, of which 34 sets are for single crystals and the remaining 135 sets are mostly for polycrystalline specimens and for some alumina powder. Despite these large numbers, the specimen purity and density (or porosity) are known for only one set of data for the single crystals, and for only 25 sets of data for the polycrystalline specimens. It is indeed a waste of effort to make such extensive measurements on specimens whose major specification and characterization are not known.

The available data for polycrystalline specimens cover the temperature range from 2.5 to 2030 K. There are four sets of data below room temperature. One set of data (curve 130) bridges the gap and covers the low, normal, and moderately high temperature regions. However, the latter appeared to be not of the correct trend. All the remaining data are above room temperature. They spread into a wide band, as shown in Figure 15, over the entire temperature range where data are available. The spreading of the curves is mainly due to the differences in purity and density of the specimens measured, and therefore effectively each curve represents a different material. It should be noted here that, because of the nature of these different curves, an average curve obtained through some form of statistical fit of all these data points would have little meaning.

From the inadequate information available on specimen specification and characterization, the analysis of thermal conductivity data can be based only on porosity and purity. The thermal conductivity values of various curves at each of several selected temperatures were read off a large working-graph, and were used to determine the relationship between thermal conductivity versus porosity and purity by means of an iteration technique. The procedure used was as follows.

The thermal conductivity values were first plotted against porosity of the specimens neglecting at first the differences in specimen purity. A preliminary curve was thus obtained at each temperature representing the tentative relationship between thermal conductivity and porosity. Using this preliminary result the thermal conductivity values were adjusted to zero porosity, and the resulting zero-porosity thermal conductivity values were plotted against specimen purity. Thus a second generation preliminary curve was obtained at each temperature representing the tentative relationship between thermal conductivity and purity. Again using this second generation preliminary result the thermal conductivity values were adjusted to zero impurity, and the resulting zero-impurity thermal conductivity values were plotted against porosity. By repeating this procedure, two final curves were obtained representing the relationships between thermal conductivity versus purity and porosity. It must be pointed out that the resulting relationships are still very preliminary in nature due to the inadequacy of available information.

The relationship between thermal conductivity and porosity derived from experimental data is found in closer agreement with the relationship derived by Euler [2] from the theoretical model of Maxwell [3] than with the simplified relation derived by Loeb [4, 5].

Using the above correlation procedure, at each of the several selected temperatures, a point was obtained corresponding to the thermal conductivity of a 99.5% pure, 98% dense polycrystalline specimen. A mean curve was subsequently drawn through these points to serve as the recommended curve.

The recommended curve has a minimum at about 1700 K, in agreement with the general trend of the experimental data. Above 1700 K it turns up probably mainly due to the increasing contribution of the radiation component. The uncertainty of the recommended values should be within ± 8% at temperatures from 500 to 1000 K and increases to about ± 15% below 250 K and above 1800 K.

Beryllium Oxide. - The thermal conductivity of beryllium oxide is exceptionally high, in fact, higher than that of most refractory materials. At temperatures below about 500 K it exceeds the thermal conductivity of beryllium.

There are 58 sets of data available for polycrystalline beryllia. No data are available for single crystals. Four sets of data are below room temperature and the rest are above. Out of the 58 sets of available data, only 15 sets are for specimens of known purity and density (or porosity). The purity and density of most specimens are low.

In the measurements of the thermal conductivity of five specimens of beryllium oxide of different density, Powell [6] found that, within the temperature range studied (325 to 825 K), the thermal conductivity of beryllia varies approximately inversely as the absolute temperature and, at any one temperature, varies approximately linearly with the density.

The thermal conductivity data were correlated with porosity and purity. Several points corresponding to a 99.5% pure, 98% dense polycrystalline specimen were obtained at several selected temperatures. The recommended curve, as shown in Figure 16, has been drawn through these points. It has a minimum at about 2100 K and turns up above this temperature. This trend of the thermal conductivity curve has been investigated and confirmed experimentally by several workers including Taylor [7].

The uncertainty of the recommended values is thought to be within ± 8% at temperatures from 500 to 1000 K and increases to ± 15% below 300 K and above 1800 K. Beryllium oxide has a phase transformation at about 2370 K. This may limit the use of beryllia as a high-temperature thermal conductivity standard.

Corning Code 7740 Glass. - This glass is produced by Corning Glass Works and is a particular kind of borosilicate glass, commercially known as Pyrex glass. It is composed approximately of 80.6% SiO_2, 13% B_2O_3, 4.3% Na_2O, and 2.1% Al_2O_3, which is the average of the compositions reported for four of the specimens measured.

The spreading of the thermal conductivity curves as shown in Figure 17 is probably mainly due to experimental errors since small variations of chemical composition or microstructure in different specimens of this glass are unlikely to cause very large differences in thermal conductivity*.

There are 12 sets of thermal conductivity data available for this glass. The specimen measured by Birch and Clark [8] (Curve 10) was stated as No. 774 Pyrex glass from Corning Glass Works instead of No. 7740, but was actually the same kind of glass, since No. 774 was the old designation. The data of curves 2 and 6, which spread out the most, were derived from thermal diffusivity measurements and appear to be in error. The recommended curve has been drawn through the mean of the remaining 10 curves.

The recommendations are thought to be accurate to within ± 5% at moderate temperatures and within ± 10% below 200 K and above 700 K.

Diamond. - Despite its high cost, diamond is, from a theoretical standpoint, the obvious choice for a reference standard due to the fact that it forms a monatomic, isotropic crystal lattice, reasonably free from defects and most close to the simple crystalline model on which the theory of thermal conductivity is based. Furthermore, diamond retains rather well its geometry and degree of perfection. At room and moderate temperatures diamond has the highest thermal conductivity of all materials.

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 [9, 10]. Type II diamonds are in turn subdivided into two kinds: type IIa which refers to the insulating variety and type IIb to the good conductors of electricity.

There are 14 sets of data available for diamond as shown in Figure 18. It can be seen that only for type I does more than one experimental curve exist. Moreover, most of the measurements have come from the Clarendon Laboratory, Oxford [11, 12], and for type I the workers concerned regarded the newer measurements (curve 14) as being more accurate. Therefore, there is no comparison or choice that can be made from the existing data for diamond. It is very tentatively recommended that the values represented by the three smooth curves for the three types of diamond, in the temperature range from 150 to 400 K, be provisionally accepted as most probable values pending the availability of further experimental data. Until further data are available an attempt to estimate the accuracy of the present values does not seem justified.

Magnesium Oxide. - Fifty-two sets of experimental data are available, in which six sets are for single crystals and the remaining 46 sets are mostly for polycrystalline specimens and for some magnesia powder. All data available for polycrystalline specimens are at temperatures above room temperature. Out of the 52 sets of available data, only 13 sets are for specimens of known purity and density (or porosity). The purity and density of most specimens are low.

Charvat and Kingery [5] have investigated the effect of purity, porosity, and microstructure on the thermal conductivity of magnesium oxide among other materials. They give fairly complete information on the specification and characterization of their specimens, which many other workers fail to do. However, their data appear to be high and the inclusion of their data in the correlation of thermal conductivity with purity and porosity would probably lead to high results.

The recommended curve as shown in Figure 19 is for a 99.5% pure, 98% dense polycrystalline specimen, and is the result of the correlation of thermal conductivity with purity and porosity. This curve has a minimum at about 1650 K and turns up at higher temperatures. The uncertainty of the recommended values is thought to be within ± 8% at temperatures from 500 to 1000 K and increases to ± 15% below 300 K and from 1650 to 2000 K. The uncertainty increases to about ± 20% above 2100 K.

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*Dr. P. G. Klemens (private communication) suggests that even at ordinary temperatures the thermal conductivity of glass is governed by the mean free path of relatively long wave phonons, and that this mean free path may be sensitive to the occurrence of very small crystallites. This may be a greater source of variability in the thermal conductivity than chemical composition.

Pyroceram Brand Glass-Ceramic Code 9606. - This is a microcrystalline material composed of silicon dioxide, aluminum oxide, magnesium oxide, and a small amount of titanium dioxide, and is produced by Corning Glass Works.

There are eight sets of experimental data available. As shown in Figure 20, six curves are in the temperature range from 93 to 1433 K. Of these six curves only two (curves 1 and 2) were obtained by direct measurements of thermal conductivity. The other four curves were derived from thermal diffusivity data. In view of the fact that these curves were obtained by completely different methods, the agreement of the data with one another is rather good.

Curves 1 and 2 were produced by Robinson and Flynn [13] and their experimental data are usually reliable. The recommended curve has been drawn closely following these two curves. At temperatures above 500 K the recommended curve deviates slightly from curve 1 to follow the general trend of all the curves, since at temperatures above 600 K curve 1 is essentially a straight line which is deemed not very likely. Flieger [14] observed a small jump in his thermal diffusivity data. This jump is ignored at this time pending further confirmation.

The recommended values should be accurate to within ± 5% at temperatures from 200 to 1000 K. The uncertainty increases to ± 10% at 100 K and 1400 K.

Quartz. - There are 45 sets of experimental thermal conductivity data available for quartz single crystals, of which 13 sets, 22 sets, and one set are, respectively, for single crystals measured with the heat flow direction parallel, perpendicular, and at 45 degrees to the c-axis of the crystal, and nine sets for single crystals of unknown axis orientation. Four sets of data are available for quartz powder and 78 sets of data available for fused quartz. which is called by various commercial names such as fused quartz quartz glass, fused silica, vitreous silica, silica glass etc. It is surprising to note that out of these 127 sets of data only one set is for a specimen whose purity and density are both known. The specimen purity is known for only two other curves and the specimen density is known for only 28 other curves.

The available data and pertinent information were studied, critically evaluated, and selected. The recommended curve as shown in Figure 21 for a high-purity ($99.99^{+}\%$) quartz single crystal measured with the heat flow direction parallel to the c-axis has been drawn as the mean of curves 39, 14, 49, 51, 24, and 54. The recommended curve for a high-purity ($99.99^{+}\%$) quartz single crystal measured with the heat flow direction perpendicular to the c-axis has been drawn as the mean of curves 6, 15, 50, 53, 23, 17, 3, 2, and 55. The recommended curve for high-purity ($99.99^{+}\%$) clear fused quartz has been drawn as the mean of curves 45, 46, 47, 48, 110, 12, 13, 11, 16, 111, 120, 66, 67, 68, 30, 84, and 29. The above curve numbers are listed in such an order that the curves commence at increasing temperatures.

Quartz crystal has a phase transformation which occurs at about 848 K. Experimental specific heat data [15, 16, 17] and thermal expansion data [18] indicate a pronounced discontinuity at the transition temperature. The effect of this phase transformation on the thermal conductivity of quartz crystal is not known, since no measurement has ever been made above 750 K.

The uncertainty of the recommended values for quartz single crystal is thought to be within ± 5% at temperatures from 300 to 500 K and increases at lower and higher temperatures up to ± 10% at 40 and 800 K. The uncertainty of the recommended values for fused quartz should be within ± 4% at temperatures from 200 to 500 K, and increases to ± 8% at 50 K and 900 K and up to ± 15% below 10 K and at 1400 K.

Thorium Dioxide. - There are only six sets of experimental thermal conductivity data available for thorium dioxide over the temperature range from 304 to 379 K and from 527 to 1821 K. No data are available below room temperature and between 379 and 527 K. Furthermore, all the available data are for polycrystalline specimens and no measurements have yet been made on thoria single crystal.

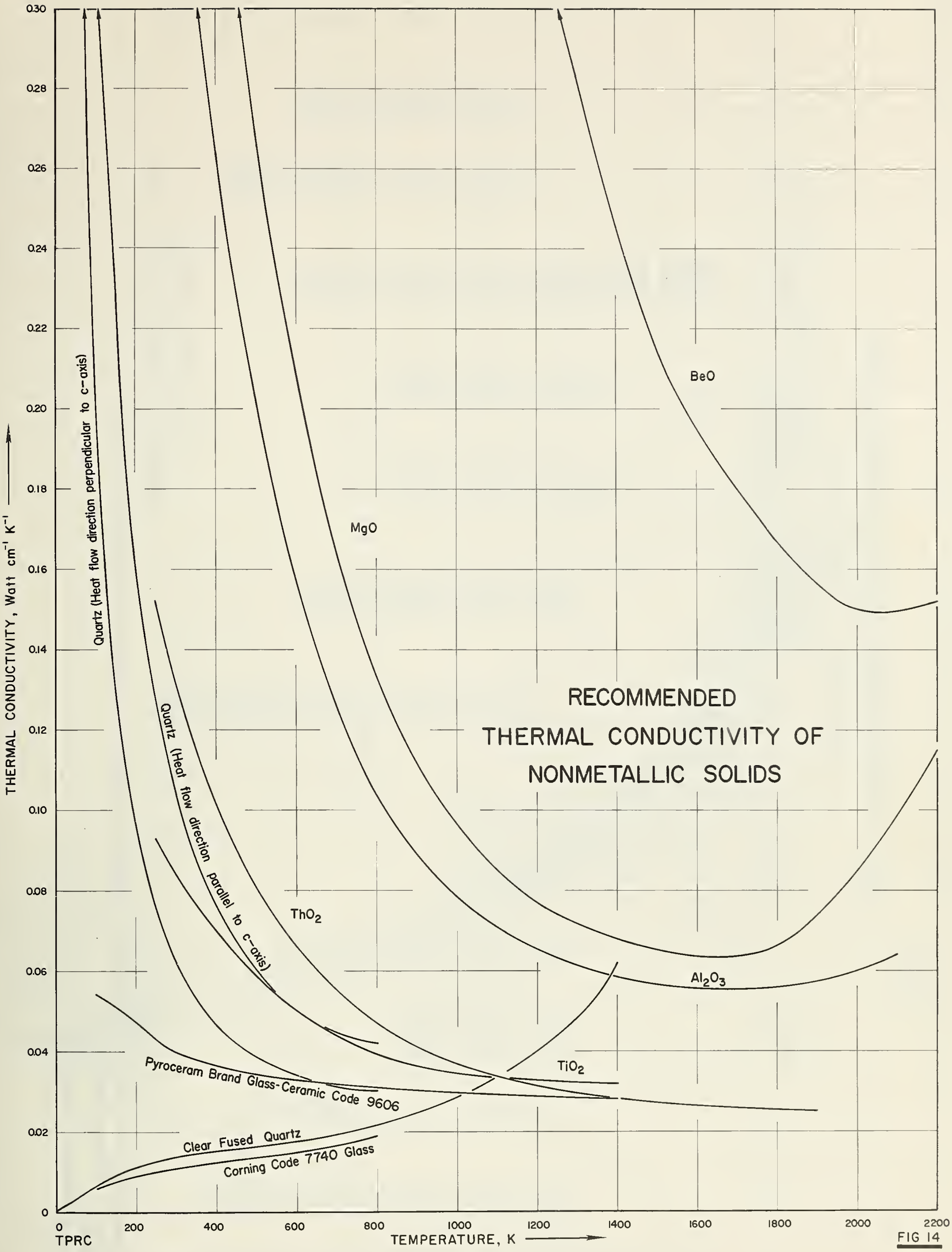
From the available inadequate information, the specimen purity and density are known for only one set of data, and density is known for the other curves. Below 380 K the only two available curves, 1 and 2, were produced by the same author on the same specimen. The difference in the experimental results was attributed by the author to the difference in the coatings used on the end faces of the cylindrical specimen in separate runs, and he pointed out that the data obtained during the second run (curve 2) using a platinum alloy glaze on the faces of the cylinder were more accurate than those obtained during the first run (curve 1) in which a gold coating was used. The recommended values at the lower temperatures are therefore based on curve 2.

Several points, each at one of the several selected temperatures, were derived from the available meager information to correspond to a 99.5% pure, 98% dense polycrystalline specimen, and the recommended curve has been drawn through these points. The uncertainty of the recommended values is thought to be within ± 15% at temperatures from 350 to 1000 K and increases at lower and higher temperatures up to ± 20% at 250 K and ± 25% at 1900 K.

Titanium Dioxide. - There are 36 sets of experimental thermal conductivity data available for titanium dioxide, of which 21 sets are for single crystals, 13 sets for polycrystalline specimens and 2 sets are for an unspecified specimen measured before and after irradiation. The specimen purity and density (or porosity) are both known for only six sets of data.

For the polycrystalline titania all available data are at temperatures above 350 K, and it is interesting to note that all curves except two were produced by workers of the same institution. Their later results [5] were 10% to 50% higher than earlier ones, which was attributed partially to the use of dense high-purity specimens and partially to the improved design of the thermal conductivity apparatus used in their later measurements. However, on comparison of their results with the recently published data for extremely high-purity titania single crystals [19], their later results [5] appear to be somewhat too high. On account of this fact, adjustments and modifications have been made in deriving the recommended values from their data.

The recommended values are for a 99.5% pure, 98% dense polycrystalline specimen. The uncertainty of the recommended values should be within ± 10% at temperatures from 400 to 1000 K and increases to ± 15% at 250 K and 1400 K.



RECOMMENDED
THERMAL CONDUCTIVITY OF
NONMETALLIC SOLIDS

FIG 14

TABLE 14. RECOMMENDED THERMAL CONDUCTIVITY OF NONMETALLIC SOLIDS*

Thermal Conductivity, k, Watt cm^{-1} K^{-1}

T, K	Al_2O_3**	BeO**	Corning Code 7740 Glass	Diamond†			MgO**	Pyroceram Brand Glass-Ceramic Code 9606	Quartz† (Single Crystal)		Quartz† (Clear Fused)	ThO_2**	TiO_2**	T, K
				Type I	Type IIa	Type IIb			∥ to c-axis	⊥ to c-axis				
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1											(0.00024)			1
2											(0.00054)			2
3											0.00080			3
5											0.00118			5
10											0.00127			10
20											0.00153			20
40									1.79	0.89	0.00266			40
60									0.85	0.429	0.0041			60
80									0.54	0.279	0.0055			80
100	1.33		0.0058	30	100	54.5		0.0542	0.39	0.208	0.0069			100
150	0.77		0.0076	20	60.5	31.7		0.0550	0.231	0.130	0.0095			150
200	0.55	4.24	0.0090	14.2	40.4	22.0		0.0474	0.164	0.095	0.0114			200
250	0.434	3.34	0.0101	11.0	29.7	16.7	(0.580)	0.0428	0.127	0.075	0.0128	(0.152)	(0.093)	250
273	0.397	3.02	0.0106	10.0	26.5	15.1	(0.531)	0.0413	0.116	0.0684	0.0133	(0.142)	(0.089)	273
300	0.360	2.72	0.0110	9.0	23.5	13.5	0.484	0.0399	0.104	0.0621	0.0138	(0.132)	(0.084)	300
350	0.307	2.28	0.0117	(7.6)	(19.5)	(11.3)	0.412	0.0379	0.088	0.0530	0.0145	0.115	(0.0767)	350
400	0.264	1.96	0.0124	(6.6)	(16.6)	(9.7)	0.356	0.0365	0.076	0.0470	0.0151	0.102	0.0701	400
500	0.202	1.46	0.0136				0.269	0.0345	0.060	0.0388	0.0162	0.081	0.0588	500
600	0.158	1.11	0.0149				0.207	0.0331	0.050	0.0340	0.0175	0.066	0.0502	600
700	0.126	0.87	0.0165				0.165	0.0319	0.0447	0.0314	0.0192	0.055	0.0439	700
800	0.104	0.70	(0.0189)				0.134	0.0310	(0.0420)	(0.0306)	0.0217	0.047	0.0394	800
900	0.089	0.57					0.112	0.0303			0.0248	0.041	0.0365	900
1000	0.0785	0.47					0.097	0.0297			0.0287	0.0368	0.0346	1000
1100	0.0710	0.39					0.085	0.0291			0.0336	0.0336	0.0335	1100
1200	0.0655	0.33					0.077	0.0287			0.0400	0.0312	0.0328	1200
1300	0.0613	0.283					0.072	0.0284			0.0482	0.0296	0.0323	1300
1400	0.0585	0.245					0.068	0.0282			0.0620	0.0284	0.0321	1400
1500	0.0566	0.215					0.065					0.0273		1500
1600	0.0556	0.195					0.064					0.0266		1600
1700	0.0554	0.180					0.064					0.0259		1700
1800	0.0559	0.167					0.066					0.0254		1800
1900	0.0574	0.156					0.074					(0.0252)		1900
2000	0.0600	0.150					0.085							2000
2100	(0.0644)‡	0.150					0.099							2100
2200		0.152					0.115							2200
2300		0.164					0.132							2300

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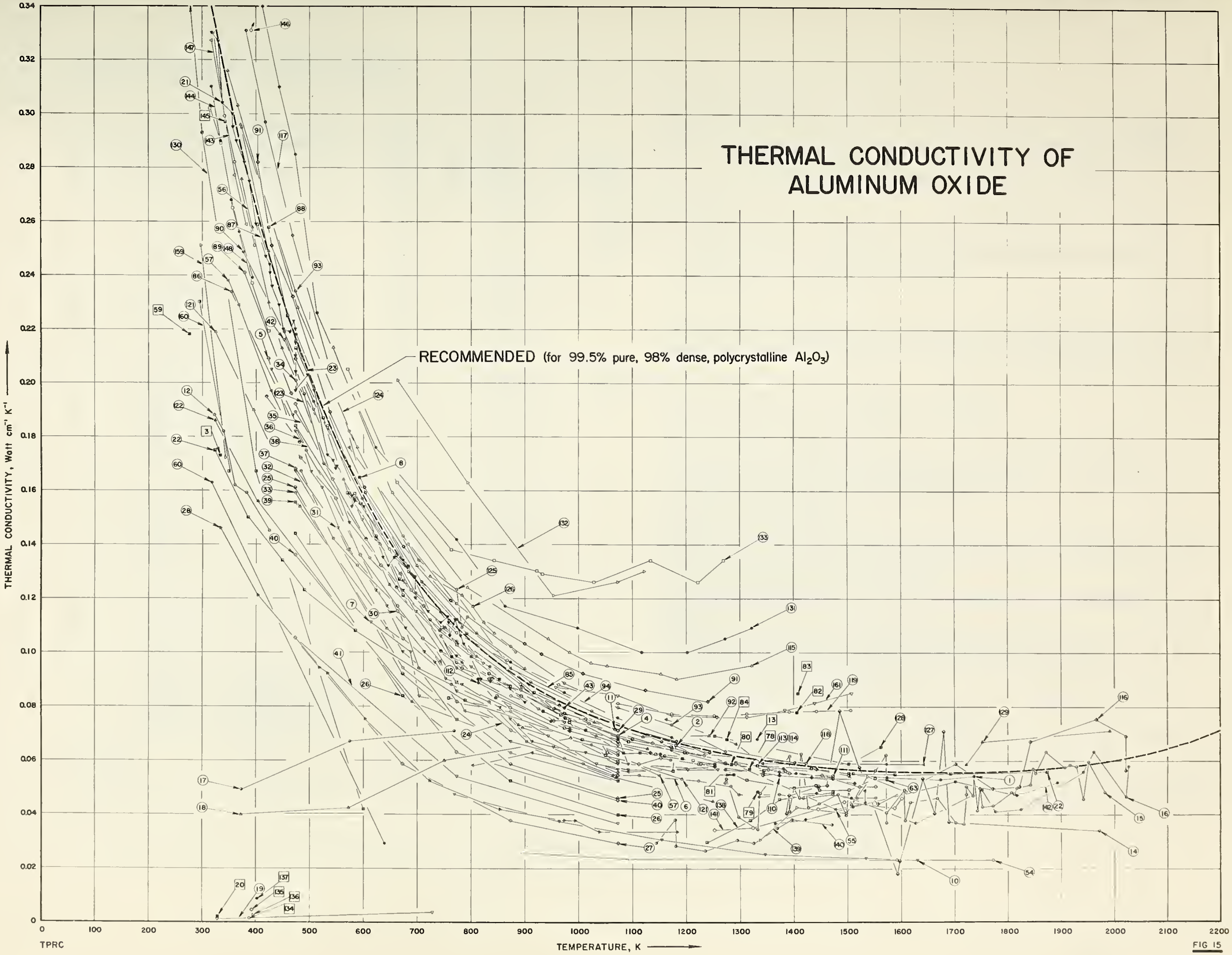
*In the table the third significant figure is given only for the purpose of comparison and for smoothness and is not indicative of the degree of accuracy.

**99.5% pure, 98% dense, polycrystalline.

†High-purity.

‡Values in parentheses are extrapolated.


THERMAL CONDUCTIVITY OF
ALUMINUM OXIDE
RECOMMENDED (for 99.5% pure, 98% dense, polycrystalline Al_2O_3)
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
2100
2200
146
147
21
144
145
91
117
130
143
56
88
87
90
89
148
159
57
93
86
59
121
160
42
5
34
23
12
124
122
123
3
35
36
38
22
37
8
60
32
25
33
39
28
31
132
133
40
125
126
131
7
30
115
41
112
83
26
85
43
94
91
82
161
119
116
11
29
93
92
84
129
4
2
13
24
78
113
114
118
128
127
80
111
17
81
1
25
40
57
6
121
138
63
18
26
141
79
110
142
22
15
16
27
139
140
55
14
54
137
20
19
135
136
134
10

TPRC

FIG 15

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	1	Norton, F.H., Fellows, D.M., Adams, M., and McQuarrie, M.	1950	R	846-1737		Sintered.
2	2	Norton, F.H., Kingery, W.D., Fellows, D.M., Adams, M., et al	1951	R	758-1535		Pure; polycrystalline; heat-treated.
3	3	Koenig, J.H.	1953		333.2		Maximum moisture absorption = 0.05%; flexural strength = 33,000 psi; coefficient of expansion (25-700 C) = 8.0 x 10^{-6}.
4	4	Norton, F.H.	1951	R	873-1473		Sintered.
5	5	Kingery, W.D.	1954	R	423-1553		Hemispherical samples prepared by slip-casting in plaster molds and refiring to 1100 C; 1.75 in. inside dia and 3.5 in. outside dia.
6	5	Kingery, W.D.	1954	R	483-1553		Same as the above specimen.
7	5	Kingery, W.D.	1954	R	613-1258		Made by slip-casting; hollow cylinder with inside dia 0.6 in., outside dia 1.5 in., entire length 18 in., test zone 4 in.
8	5	Kingery, W.D.	1954	R	593-1253		Same as the above specimen.
9	293	Charvat, F.R. and Kingery, W.D.	1957	C	583-1473	No. 2	Polycrystalline; 99.5^+ pure; gravimetric porosity 12.09%; microscopic porosity 15%; average grain size 17 μ; data corrected to zero porosity.
10	7	Norton, F.H., Fellows, D.M., Adams, M., McQuarrie, M., and Fullerton, C.P.	1949	R	769-1631		Sintered; open pores 10.65%, closed pores 2.35%; bulk density 3.48 g cm^{-3}.
11	8	Sutton, W.H.	1960	L	419-1067	AP-30	99.5 Al_2O_3; 25.69% porosity; bulk density 2.95 g cm^{-3}.
12	9	Koenig, J.H.	1953	C	322-425	Hi alumina; 6 NI-1	
13	294	Laubitz, M.J.	1963		1333		Dense alumina; measured by the "Unmatched Guard Method", the given value is the average of 5 runs of two specimens; R.M.S. deviation from average 1.9%.
14	89	Norton, F.H. and Kingery, W.D.	1952	R	1387-1973	M-2	
15	89	Norton, F.H. and Kingery, W.D.	1952	R	1273-1983	M-4	
16	89	Norton, F.H. and Kingery, W.D.	1952	R	1336-2028	M-5	
17	34	Knapp, W.J.	1943	C	373-769	Corundum (African)	Red; single crystal; measured parallel to c-axis; 18-8 stainless steel as standard.
18	34	Knapp, W.J.	1943	C	372-985	Corundum (African)	Red; single crystal; measured normal to c-axis; 18-8 stainless steel as standard.
19	79	Griffiths, E., Powell, R.W., and Hickman, M.J.	1942	L	328, 728		Porous; measured in the presence of air atmosphere; density 0.77 g cm^{-3}.
20	79	Griffiths, E., Powell, R.W., et al.	1942	L	328.2		Same as the above specimen but measured in the presence of hydrogen atmosphere.
21	131	Francl, J., and Kingery, W.D.	1954	C	318-900		Slip-cast from suspension of finely ground material; fired to zero apparent porosity; bulk density 3.79 g cm^{-3}.

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* See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	132	Fieldhouse, I. B., Hedge, J. C., and Lang, J. I.	1958	R	323-1876		Polycrystal.
23	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		1 in. cube; prepared from Norton Co. 38X 220F alumina by grinding in steel mills, acid-treating to remove iron impurities introduced in milling, and casting in plaster mold from an acid suspension; zero porosity.
24	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 12. 3% porosity with spherical isometric pores.
25	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 23. 4% porosity with spherical isometric pores.
26	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 30. 0% porosity with spherical isometric pores.
27	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 44. 2% porosity with spherical isometric pores.
28	133	Francl, J., and Kingery, W. D.	1954	C	333-1183		Same preparation as the above specimen; 48. 7% porosity with spherical isometric pores.
29	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; zero porosity.
30	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 7. 54% porosity with cylindrical pores of dia 0. 082 cm; cylinders parallel to heat flow.
31	133	Francl, J., and Kingery, W. D.	1954	C	428-1093		Same preparation as the above specimen; 11. 97% porosity with cylindrical pores of dia 0. 082 cm; cylinders parallel to heat flow.
32	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 17. 95% porosity with cylindrical pores of dia 0. 082 cm; cylinders parallel to heat flow.
33	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 22. 4% porosity with cylindrical pores of dia 0. 082 cm; cylinders parallel to heat flow.
34	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 4. 5% porosity with cylindrical pores of dia 0. 146 cm; cylinders parallel to heat flow.
35	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 9. 75% porosity with cylindrical pores of dia 0. 146 cm; cylinders parallel to heat flow.
36	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 13. 5% porosity with cylindrical pores of dia 0. 146 cm; cylinders parallel to heat flow.
37	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 19. 75% porosity with cylindrical pores of dia 0. 146 cm; cylinders parallel to heat flow.
38	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 4. 5% porosity with cylindrical pores of dia 0. 146 cm; cylinders perpendicular to heat flow.
39	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 9. 75% porosity with cylindrical pores of dia 0. 146 cm; cylinders perpendicular to heat flow.
40	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 13. 5% porosity with cylindrical pores of dia 0. 146 cm; cylinders perpendicular to heat flow.
41	133	Francl, J., and Kingery, W. D.	1954	C	473-1073		Same preparation as the above specimen; 19. 75% porosity with cylindrical pores of dia 0. 146 cm; cylinders perpendicular to heat flow.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	65	Francis, R.K., Brown, R., McNamara, E. P., and Tinklepaugh, J.R.	1958	C	452-973	Wesgo Alumina (Al-300)	97.6 Al_2O_3; bulk density 3.70 g cm^{-3}; porosity 6.8%.
43	65	Francis, R.K., Brown, R., McNamara, E.P., and Tinklepaugh, J.R.	1958	C	452-973	Wesgo Alumina (Al-300)	2nd run of above specimen using different alumina as the comparative standard.
44	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1193-2093		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
45	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1248-2083		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
46	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1268-2143		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
47	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1243-2143		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
48	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1223-2093		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
49	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1233-2143		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
50	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1193-2123		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
51	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1173-2043		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
52	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1173-2043		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
53	134	Schul'man, A.R., Fedorov, V.N., and Shepsenvol, M.A.	1952	R	1193-2193		Porous layer coated cataphoretically on a tungsten wire and then heated to 1600-1700 C.
54	135	Shakhtin, D.M. and Vishnevskii, I.I.	1957	R	893-1773		In cylindrical form 30 mm long, inside dia 30 mm, outside dia 60 mm; porosity 22%.
55	135	Shakhtin, D.M. and Vishnevskii, I.I.	1957	R	803-1533		Same as the above specimen except 10% porosity.
56	136	Kingery, W.D.	1959	C	373-1128		Polycrystalline; containing 0.30 vol % Cr_2O_3; prepared by mixing calcined Cr_2O_3 and Al_2O_3 in a water suspension and either slip-casting or hydrostatically pressing, and fired at 1800 C to total porosity of 17.2%.
57	136	Kingery, W.D.	1959	C	348-1150		Polycrystalline; preparation same as the above specimen; containing 1.26 vol % Cr_2O_3; total porosity 19.8%.
58	137	Soxman, E.J.	1957	P	84-249	AV30	96.0 Al_2O_3; in vitreous form; 2.95 cm long.
59	137	Soxman, E.J.	1957	P	276	AV30	Same as the above specimen; 2.95 cm long.
60	137	Soxman, E.J.	1957	P	317, 639	AV30	Same as the above specimen; 1.93 cm long.
61	158	Berman, R.	1952	L	2.5-94		Ground to a dia of 1.5 mm rod from a 3 mm-dia artificial sapphire, single crystal.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	158	Berman, R.	1952	L	2.8-200		Sintered; a rod of 1/4 in. dia; density 3.70 g cm^{-3} (95% of the single crystal value).
63	72	Kingery, W.D. and Norton, F.H.	1955		573-1573		Polycrystalline; prepared from high purity powders; calcined, hydrostatically pressed, and fired.
64	170	Norton, F.H. and Kingery, W.D.	1953	R	473.2		Four specimens with porosity 7.5 to 22.3%; heat flow perpendicular to the 0.82 mm diameter cylindrical pores.
65	170	Norton, F.H. and Kingery, W.D.	1953	R	773.2		Four specimens with porosity 7.5 to 22.1%; heat flow perpendicular to the 0.82 mm diameter cylindrical pores.
66	170	Norton, F.H. and Kingery, W.D.	1953	R	1073.2		Four specimens with porosity 7.5 to 22.2%; heat flow perpendicular to the 0.82 mm diameter cylindrical pores.
67	170	Norton, F.H. and Kingery, W.D.	1953	R	473.2		Four specimens with porosity 4.6 to 19.6%; heat flow perpendicular to the 1.46 mm diameter cylindrical pores.
68	170	Norton, F.H. and Kingery, W.D.	1953	R	473.2		Four specimens with porosity 4.5 to 19.7%; heat flow parallel to the 1.46 mm diameter cylindrical pores.
69	170	Norton, F.H. and Kingery, W.D.	1953	R	773.2		Four specimens with porosity 4.3 to 19.8%; heat flow perpendicular to the 1.46 mm diameter cylindrical pores.
70	170	Norton, F.H. and Kingery, W.D.	1953	R	773.2		Four specimens with porosity 4.5 to 19.7%; heat flow parallel to the 1.46 mm diameter cylindrical pores.
71	170	Norton, F.H. and Kingery, W.D.	1953	R	1073.2		Four specimens with porosity 4.7 to 19.7%; heat flow perpendicular to the 1.46 mm diameter cylindrical pores.
72	170	Norton, F.H. and Kingery, W.D.	1953	R	1073.2		Four specimens with porosity 4.7 to 19.7%; heat flow parallel to the 1.46 mm diameter cylindrical pores.
73	215	Berman, R., Foster, E.L., Schneidmesser, B., and Tirmizi, S.M.A.	1960		4.5-86		Sintered.
74	215	Berman, R., Foster, E.L., Schneidmesser, B., and Tirmizi, S.M.A.	1960		2.5-89		γ - irradiated sintered alumina.
75	216	Salmon, D.F. and Bailey, J.F.	1951	R	763.7		No. 8 grain; measured from the inner half of test annulus.
76	216	Salmon, D.F. and Bailey, J.F.	1951	R	977.6		Measured from the outer half of the above test annulus.
77	216	Salmon, D.F. and Bailey, J.F.	1951	R	901.5		Measured from the entire above annulus.
78	184	Childer, H.M. and Cerceo, J.M.	1961	P	1318		Polycrystalline; measured in a vacuum of 10^{-5} mm Hg, run No. 1.
79	184	Childer, H.M. and Cerceo, J.M.	1961	P	1333.5		The above specimen run No. 2.
80	184	Childer, H.M. and Cerceo, J.M.	1961	P	1284		The above specimen run No. 3.
81	184	Childer, H.M. and Cerceo, J.M.	1961	P	1289.5		The above specimen run No. 4.
82	184	Childer, H.M. and Cerceo, J.M.	1961	P	1407.7		The above specimen run No. 5.

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[*] See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (continued)

Cur. No.	Ref.* Ref.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
83	184	Childer, H.M. and Cerceo, J.M.	1961	P	1409		The above specimen run No. 6.
84	184	Childer, H.M. and Cerceo, J.M.	1961	P	1276		The above specimen run No. 7.
85	157	Norton, F.H. and Kingery, W.D.	1954	C	573-1473		No details.
86	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	354-1171	Gulton HS. B Alumina No. 1	99.3 Al_2O_3, 0.23 Fe_2O_3, 0.22 SiO_2, 0.5 C, 0.05 C, 0.05 CaO, 0.05 TiO_2, 0.02 MgO, 0.01 Na_2O, and 0.07 others; polycrystalline with average grain dia 2μ; hot pressed and heat treated; density 3.86 g cm^{-3} and 2.6% porosity; impurity analysis made after heat treatment.
87	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	403-1213	Gulton HS. B Alumina No. 2	Same composition as the above specimen except with average grain dia 3μ; density 3.90 g cm^{-3} and porosity 1.5%.
88	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	423-1292	Gulton HS. B Alumina No. 3	The above specimen heat treated for 100 hrs at 1500 C; average grain dia 6μ; density 3.84 g cm^{-3} and porosity 3.0%.
89	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	379-1234	Gulton HS. B Alumina No. 4	Same composition as the above specimen except average grain dia 4μ; density 3.90 g cm^{-3} and porosity 1.6%.
90	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	376-1243	Gulton HS. B Alumina No. 5	Same composition as the above specimen except average grain dia 10μ; density 3.91 g cm^{-3} and porosity 1.4%.
91	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	403-1241	Norton H. P. Alundum	99.5 Al_2O_3, 0.40 MgO, 0.05 C, 0.01 SiO_2, 0.01 Fe_2O_3, 0.01 CaO, 0.01 Na_2O, and 0.05 others; polycrystalline with average grain dia 3μ; hot pressed and heat treated; density 3.97 g cm^{-3} and zero porosity; impurity analysis made after heat treatment.
92	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	371-1243	Norton H. P. Alundum	The above specimen heat treated for 100 hrs at 1500 C in helium; average grain dia 5μ; density 3.83 g cm^{-3} and porosity 3.3%.
93	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	373-1273	Norton 38-900	99.8 Al_2O_3, 0.05 Fe_2O_3, 0.05 Na_2O, 0.05 C, 0.03 CaO, 0.02 SiO_2, 0.01 MgO, and 0.04 others; polycrystalline with average grain dia 10-11μ; hot pressed; density 3.89 g cm^{-3} and porosity 1.8%; data corrected to theoretical density.
94	217	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1960	C	373-1273	Norton 38-900 + 1/2% MgO	99.3 Al_2O_3, 0.44 MgO, 0.05 Fe_2O_3, 0.05 C, 0.05 Na_2O, 0.03 CaO, 0.02 SiO_2, and 0.04 others; polycrystalline with average grain dia 8-9μ; hot pressed; density 3.92 g cm^{-3} and porosity 1.1%; data corrected to theoretical density.
95	272	Michke, R.A. and Smith, J.M.	1962	R	318-417	FW-5	Prepared from the spray-dried alumina powder supplied by the American Cyanamid Co.; Alpha-monohydrate (böhmite) structure; drying loss: 16.4 wt % at 500 F, and 27.0 wt % at 1800 F, true density of solid (monohydrate) 2.45 g cm^{-3}, B. E. T. surface area 362 m^2g^{-1} and pore volume 0.475 cm^3g^{-1}; particle size distribution: 90 μ mesh 61.0% through, 60 32.5%, 45 23.5%, 20 11.5%, 10 7.0%; first dried at 500 F for 24 hrs and the powder pelleted (in a Carver Model B press) while hot; pellet density 1.211 g cm^{-3}, micro pore volume 0.365 cm^3g^{-1}, macro pore volume 0.120 cm^3g^{-1}, micro void fraction 0.134; measured in vacuum (pressure 10-25 microns of Hg).

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	272	Michke, R.A. and Smith, J.M.	1962	R	315-400	FW-4.5	Prepared from the same powder as the above specimen; pellet density 1.010 g cm^{-3}, micro pore volume 0.383 cm^3g^{-1}, macro pore volume 0.198 cm^3g^{-1}, micro void fraction 0.387, and macro void fraction 0.200; measured in vacuum (pressure 10-25 microns of Hg).
97	272	Michke, R.A. and Smith, J.M.	1962	R	322-437	FW-4	Prepared from the same powder as the above specimen; pellet density 0.896 g cm^{-3}, micro pore volume 0.400 cm^3g^{-1}, macro pore volume 0.308 cm^3g^{-1}, micro void fraction 0.359; and macro void fraction 0.275; measured in vacuum (pressure 10-25 microns of Hg).
98	272	Michke, R.A. and Smith, J.M.	1962	R	318-444	FW-3.5	Prepared from the same powder as the above specimen; pellet density 0.785 g cm^{-3}, micro pore volume 0.416 cm^3g^{-1}, macro pore volume 0.451 cm^3g^{-1}, micro void fraction 0.327, and macro void fraction 0.353; measured in vacuum (pressure 10-25 microns of Hg).
99	272	Michke, R.A. and Smith, J.M.	1962	R	318-378	FW-3	Prepared from the same powder as the above specimen; pellet density 0.672 g cm^{-3}, micro pore volume 0.434 cm^3g^{-1}, macro pore volume 0.670 cm^3g^{-1}, micro void fraction 0.275, and macro void fraction 0.450; measured in vacuum (pressure 10-25 microns of Hg).
100	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-5	Same as the above specimen FW-5 but measured in helium at 1 atm pressure.
101	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-4	Same as the above specimen FW-4 but measured in helium at 1 atm pressure.
102	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-3	Same as the above specimen FW-3 but measured in helium at 1 atm pressure.
103	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-5	Same as the above specimen FW-5 but measured in air at 1 atm pressure.
104	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-4	Same as the above specimen FW-4 but measured in air at 1 atm pressure.
105	272	Michke, R.A. and Smith, J.M.	1962	R	322.1	FW-3	Same as the above specimen FW-3 but measured in air at 1 atm pressure.
106	273	Flynn, D.R.	1963	L	293, 313	Powder	Produced at the NBS by ignition of hydrated aluminum chloride in a muffle furnace at 1150 C: density 0.41 g cm^{-3}.
107	273	Flynn, D.R.	1963	L	313.2		Powder; same method of production as the above except density 0.46 g cm^{-3}.
108	273	Flynn, D.R.	1963	R	413-1363		Powder; same method of production as the above except density 0.44 g cm^{-3}.
109	273	Flynn, D.R.	1963	R	413-1198		Powder; same method of production as the above except density 0.40 g cm^{-3}.
110	274	Norton, F.H., Kingery, W.D., McQuarrie, M.C., Adams, M., Loeb, A.L., and Francl, J.	1953	R	813-1513		Fired to a total porosity of 6.35 - 7.11% with a bulk density of 3.66 - 3.69 g cc^{-1}.
111	274	Norton, F.H., Kingery, W.D., et al	1953	R	848-1473		Same material as the above; separate run.
112	274	Norton, F.H., Kingery, W.D., et al	1953	R	813-1403		Same material as the above; separate run.

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TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	274	Norton, F.H., Kingery, W.D., et al.	1953	R	833-1503		Same material as the above; separate run.
114	274	Norton, F.H., Kingery, W.D., et al.	1953	R	813-1513		Same material as the above; separate run.
115	295	Lee, D.W. and Kingery, W.D.	1960	C	543-1323	A-4	Polycrystalline specimen fabricated by pressing hydrostatically and sintering; grain size 13 μ; gravimetric density 3.97 g cm^{-3}; microscopic porosity 0.5%; gravimetric porosity 0.25%; pore size 1.0 to 1.5 μ; data corrected for the effect of porosity and presented as at zero porosity.
116	274	Norton, F.H., Kingery, W.D., et al.	1953	R	1343-2023		0.31 Fe_2O_3, 0.245 O_2, and 0.01 TiO_2; slip-cast; fired to zero apparent porosity at 1850 C and had a final total porosity of 5-10%.
117	295	Lee, D.W. and Kingery, W.D.	1960	C	383-1403	A-5	Polycrystalline specimen fabricated by pressing hydrostatically and sintering; grain size 28 μ; gravimetric density 3.86 g cm^{-3}; microscopic porosity 3.3%; gravimetric porosity 3.0%; pore size 4.0 μ; data corrected for the effect of porosity and presented as at zero porosity.
118	295	Lee, D.W. and Kingery, W.D.	1960	C	683-1423	A-6	Polycrystalline specimen fabricated by pressing hydrostatically and sintering; grain size 19 μ; gravimetric density 3.48 g cm^{-3}; microscopic porosity 14.0%; gravimetric porosity 12.5%; pore size 6 to 10 μ; data corrected for the effect of porosity and presented as at zero porosity.
119	293	Charvat, F.R. and Kingery, W.D.	1957	C	533-1508		Single crystal; 99.5^+ pure; data corrected to zero porosity.
120	293	Charvat, F.R. and Kingery, W.D.	1957	C	548-1158	No. 1	Polycrystalline; 99.5^+ pure; gravimetric porosity 3.78%; microscopic porosity 4%; average grain size 9 μ; data corrected to zero porosity.
121	136	Kingery, W.D.	1959	C	325-1193		2.88 Cr_2O_3 by volume; polycrystalline solid solution; prepared by mixing calcined Cr_2O_3 and Al_2O_3 in a water suspension and either slip casting or hydrodynamically pressing and fired at 1800 C; total porosity 20.1%; data corrected to theoretical density.
122	136	Kingery, W.D.	1959	C	323-1249		6.42 Cr_2O_3 by volume; same description as the above specimen except total porosity 22.1%; data corrected to theoretical density.
123	284	Francis, R.K., McNarmara, E.P., and Tinklepaugh, J.R.	1958	C	473-973	Wesgo Al-300	97.6 Al_2O_3; 1 in. cube ground and polished on diamond laps.
124	286	Truesdale, R.S., Swica, J.J., and Tinklepaugh, J.R.	1958	C	347-900	Norton 38-900	One in. cube; grain size distribution ranging from 5 to 9 microns with a peak at 7.5 microns; hot pressed.
125	287	Nishijima, T., Kawada, T., and Ishihata, A.	1965	L	683-883	Specimen a	0.1 MgO, 0.1 NiO; sintered; 99.5% theoretical density; specimen size = 12.70 mm in dia, 25 mm long.
126	287	Nishijima, T., Kawada, T., et al.	1965	L	723-843	Specimen b	Similar to above specimen.
127	287	Nishijima, T., Kawada, T., et al.	1965	R	1163-1643	Specimen c	Similar to above specimen except with 24.00 mm in dia, 25 mm long.
128	287	Nishijima, T., Kawada, T., et al.	1965	R	1253-1563	Specimen d	Similar to above specimen with 24.00 mm in dia, 25 mm long; slight melting and cracking were found around the center of the specimen after the measurement.
129	287	Nishijima, T., Kawada, T., et al.	1965	R	1723-1993	Specimen e	Similar to above specimen.
130	288	General Electric Co.	1963		15-600	Lucalox	Polycrystalline; 99.9% Al_2O_3; density 3.98 gm cm^{-3}; gas-tight, essentially zero porosity; melting point 2040 C; manufactured by General Electric Co.

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TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	295	Lee, D.W. and Kingery, W.D.	1960	C	323-1323	A-1	Commercial single crystal; gravimetric density 3.98 g cm^{-3}; zero porosity; c axis inclined 60 degrees to the direction of heat flow (this corresponds to the average conductivity of the crystal); platinum foil used at the interface between specimens; polycrystalline Al_2O_3 and ZrO_2 used as reference materials.
132	295	Lee, D.W. and Kingery, W.D.	1960	C	663-1123	A-2	Commercial single crystal; gravimetric density not determined; c axis inclined 60 degrees to the direction of heat flow; platinum foil used at the interface between specimens; polycrystalline Al_2O_3 and ZrO_2 used as reference materials.
133	295	Lee, D.W. and Kingery, W.D.	1960	C	571-1271	A-3	Commercial single crystal; gravimetric density 3.98 g cm^{-3}; zero porosity; c axis inclined 60 degrees to the direction of heat flow; graphite used at the interface between specimens; polycrystalline Al_2O_3 and ZrO_2 used as reference materials.
134	314	Charlesworth, D.H.	1959	L	387.8	Ignited alumina	Compressed powder; supplied by Anachemia Chemicals, Ltd.; specimen in the shape of a disc of 0.182 in. thick and 9 in. dia, pressed at 63 psi; bulk density 1.02 g cm^{-3}; load reduced to 0.5 lb in.$^{-2}$ prior to making measurements.
135	314	Charlesworth, D.H.	1959	L	393.2	Ignited alumina	Compressed powder; same as the above specimen except 0.145 in. thick; pressed at 940 lb in.$^{-2}$; density 1.27 g cm^{-3}.
136	314	Charlesworth, D.H.	1959	L	396.5	Norton Alundum R.R.	Powder; -90 mesh; supplied by Fisher Scientific Co.; disc of 0.189 in. thick and 9 in. dia, pressed at 63 psi; bulk density 1.92 g cm^{-3}; load reduced to 0.5 lb in.$^{-2}$ prior to making measurements.
137	314	Charlesworth, D.H.	1959	L	403.2	Norton Alundum R.R.	Compressed powder; same as the above specimen except 0.166 in. thick; pressed at 940 psi; density 2.19 g cm^{-3}.
138	317	JPL, Pasadena, Calif.	1960	R	1233-1473	TC 352	99.3 pure; sintered; bulk density 3.8 g cm^{-3}; 95% theoretical density; supplied by Gladding McBean; run no. 6.
139	317	JPL, Pasadena, Calif.	1960	R	1336-1609	TC 352	The above specimen; run No. 7.
140	317	JPL, Pasadena, Calif.	1960	R	1144-1471	TC 352	The above specimen; run No. 14.
141	317	JPL, Pasadena, Calif.	1960	R	1252-1601	TC 352	The above specimen; run No. 15.
142	317	JPL, Pasadena, Calif.	1960	R	1365-1895	TC 352	The above specimen; run No. 16.
143	42	Koenig, J.H.	1953	C	322-399	Sapphire; 93 B-1	Single crystal; heat flow direction parallel to the c-axis.
144	42	Koenig, J.H.	1953	C	318-394	Sapphire; 93 C-1	Single crystal; the a-axis was parallel ± 3 degrees to the specimen axis; 0.250 ± 0.001 in. in length; negative optical sign; indices of refraction: e = 1.760 and w = 1.768; heat flow direction within 3 degrees to the a-axis.
145	13	Weeks, J.L. and Seifert, R.L.	1952	C	343.2	Sapphire	Heat flow direction at 60 degrees to the c-axis; density 4.0 g cm^{-3}.
146	34	Knapp, W.J.	1943	C	392-763	Sapphire	Synthetic, colorless 1 cm cube cut from a single crystal with c-axis normal to two opposite faces and parallel to other surfaces; heat flow direction perpendicular to c-axis.

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TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (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	68	Koenig, J. H.	1954	C	319-382	Sapphire; 93 B-2	Single crystal; measured in the direction of c-axis.
148	68	Koenig, J. H.	1954	C	316-424	Sapphire; 93 C-2	Single crystal; measured in the direction of a-axis.
149	69	Berman, R.	1951	L	2.5-100	Corundum	Single crystal; specimen diameter 3 mm, length 6 cm; rod axis at 36 degrees to the principal axis.
150	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.4-90	Specimen I-b	Pure Al_2O_3 crystal; 1.55 mm diameter, 6 cm long; with mat surfaces; rod axis at 36 degrees to the optic axis.
151	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.3-90	Specimen I-c	Pure Al_2O_3 crystal: 1.02 mm diameter, 13 mm long; with mat surfaces; rod axis at 36 degrees to the optic axis.
152	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	6.0-100	Specimen II	Pure Al_2O_3 crystal; 2.8 mm diameter, 15 mm long; with marked mosaic structure shown by X-rays.
153	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.3-90	Specimen IIIa	Pure Al_2O_3 crystal; 2.52 mm diameter, 6 cm long; with polished surfaces; annealed at a temperature slightly below melting point.
154	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.3-90	Specimen IIIb	Pure Al_2O_3 crystal; 2.47 mm diameter, 6 cm long; with mat surfaces; annealed at a temperature slightly below melting point.
155	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.3-90	Specimen IV	Pure Al_2O_3 crystal; 2.54 mm diameter, 6 cm long; with polished surfaces.
156	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	3.4-25	Specimen V	Pure Al_2O_3 crystal; 2.54 mm diameter, 6 cm long; with mat surfaces.
157	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.9-60	Specimen VI	Pure Al_2O_3 crystal; 2.54 mm diameter, 6 cm long; with polished surfaces; annealed at a temperature slightly below melting point.
158	70	Berman, R., Foster, E. L., and Ziman, J. M.	1955	L	2.3-35		Pure Al_2O_3 crystal; 2.54 mm diameter, 6 cm long; with mat surfaces; annealed at a temperature slightly below melting point.
159	71	McCarthy, K. A. and Ballard, S. S.	1951	C	299, 343		Linde synthetic sapphire single crystal; measured with heat flow parallel to the optic axis.
160	71	McCarthy, K. A. and Ballard, S. S.	1951	C	296, 350		As above, but heat flow perpendicular to the optic axis.
161	72	Kingery, W. E. and Norton, F. H.	1955		592-1508	Linde synthetic sapphire	Single crystal; measured with heat flow direction at about 60 degrees with the c-axis.
162	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		2.3-34	Synthetic sapphire	Single crystal.
163	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		2.5-91	Synthetic sapphire	Single crystal; measured after receiving 3×10^7 roentgens γ-ray dose.
164	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		4.5-21	Synthetic sapphire	Single crystal; measured after reactor irradiation.
165	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		3.4-93	Synthetic sapphire	Single crystal; measured after some annealing.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 15. SPECIFICATIONS OF THE SPECIMENS OF ALUMINUM OXIDE (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
166	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		2.8-92	Synthetic sapphire	Partially annealed single crystal; measured after γ-ray irradiation.
167	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		5.5-90	Synthetic sapphire	Single crystal.
168	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		2.5-87	Synthetic sapphire	Single crystal; stretched at 1400 C.
169	215	Berman, R., Foster, E. L., Schneidmesser, B. and Tirmizi, S. M. A.	1960		4.4-31	Synthetic	Single crystal; γ-ray irradiated and stretched.

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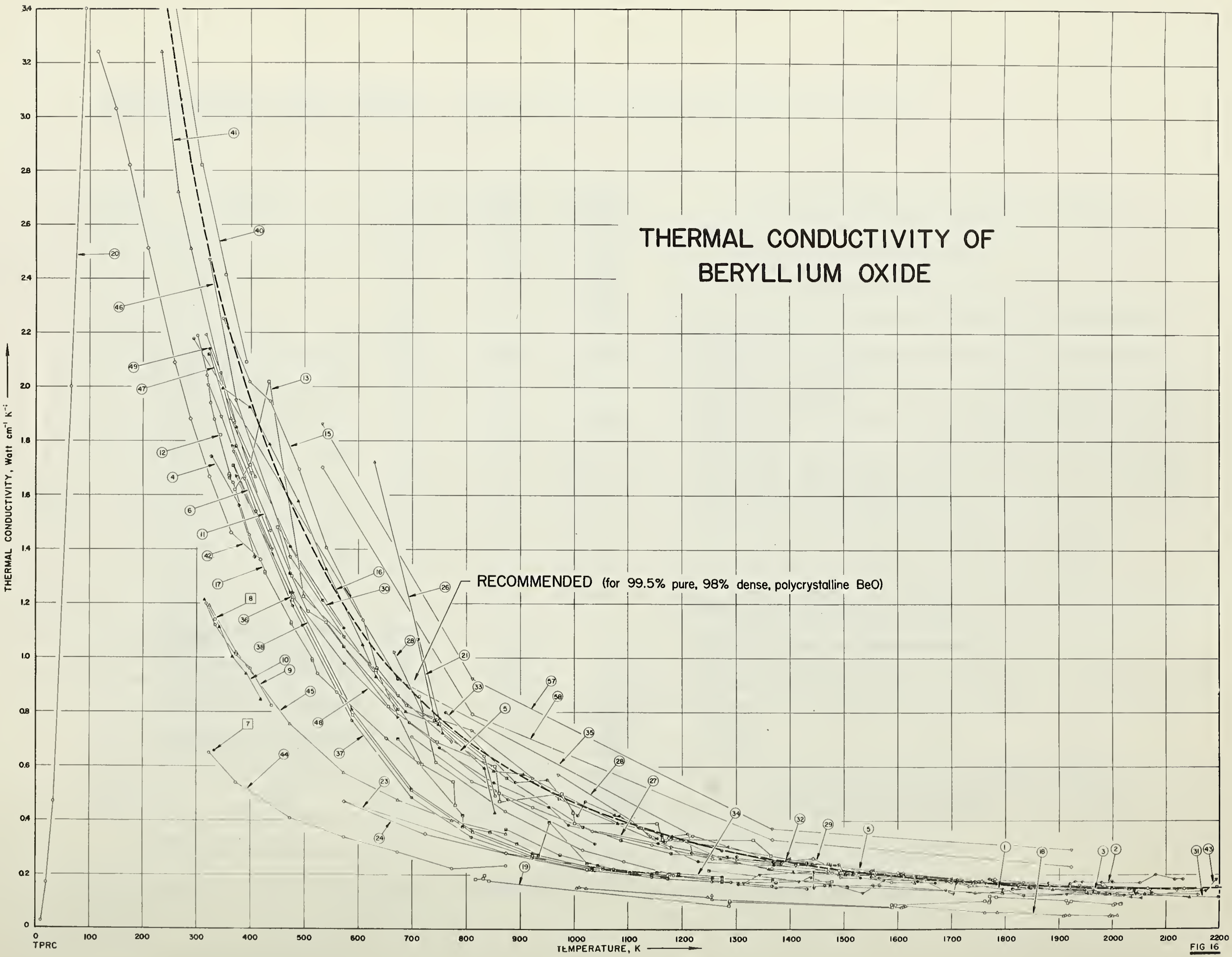
*See TPRC Data Book Vol. 3, Chapter 1, References


THERMAL CONDUCTIVITY OF BERYLLIUM OXIDE
RECOMMENDED (for 99.5% pure, 98% dense, polycrystalline BeO)
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
TPRC
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
3.2
3.4
100
200
300
400
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1100
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2200
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FIG 16

TABLE 16. SPECIFICATIONS OF THE SPECIMENS OF BERYLLIUM OXIDE

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	Norton, F.H., Kingery, W.D., et al.	1953	R	1303-2041	M-14	0.01 Fe_2O_3, 0.08 Al_2O_3, and 0.18 MgO; slip cast; fired to zero apparent porosity at 1850 C and had a final total porosity of 5-10%.
2	274	Norton, F.H., Kingery, W.D., et al.	1953	R	1303-1998	M-13	Same material as the above; separate run.
3	274	Norton, F.H., Kingery, W.D., et al.	1953	R	1813-2073	M-15	Same material as the above; separate run.
4	11	Scholes, W.A.	1950	L	326-407	BeO porcelain	Pure BeO porcelain; density (25C) = 2.969 g cm^{-3}; water absorption 0.03%.
5	†	Harrington, L.C. and Rowe, G.H.	1964	L	449-1364		Specimen fabricated by the National Beryllia Corp. by cold pressing 99.9 pure BeO and sintering at about 1650 C, and then grinding to approximately 0.5 in. dia and 7 in. long; final density was 99% of theoretical.
6	12	Koenig, J.H.	1953	C	322-439	94A-1	Pure; hot-pressed; water absorption 0.03%; density 2.97 g cm^{-3}.
7	3	Koenig, J.H.	1953	C	333.2		65% Beryllia in unfired state; max water absorption = 0.05%; flexural strength 34,000 psi; coefficient of expansion (25-700 C) = 8.4×10^{-6}.
8	3	Koenig, J.H.	1953	C	333.2		88% Beryllia in unfired state; max water absorption = 0.05%; flexural strength 34,500 psi; coefficient of expansion (25-700 C) = 8.2×10^{-6}.
9	9	Koenig, J.H.	1953	C	318-439	273A-1	4811 BeO porcelain from Coors Co.; 0.09% water absorption; density 2.90 g cm^{-3}.
10	9	Koenig, J.H.	1953	C	315-420	273A-2	Same as the above specimen.
11	9	Koenig, J.H.	1953	C	317-436	94A-3	Same as the above specimen.
12	13	Weeks, J.L. and Seifert, R.L.	1953	C	343.2		Hot-pressed; density = 3.0 g cm^{-3}; Armco iron used as standard.
13	89	Norton, F.H. and Kingery, W.D.	1952	C	370-780		No details.
14	89	Norton, F.H. and Kingery, W.D.	1952	R	873-1373		No details.
15	131	Francl, J. and Kingery, W.D.	1954	C	348-853		Slip-cast from suspensions of finely ground material; fired to zero apparent porosity; bulk density 2.86 g cm^{-3}.
16	131	Francl, J. and Kingery, W.D.	1954	C	348-853		Second run of the above specimen.
17	138	Ditmars, D.A. and Ginnings, D.C.	1957	L	301-712		Impurities (other than carbon) less than 0.2%; hot-pressed and fired at about 1700 C; dia 0.4524 in.; density 2.62 g cm^{-3}.
18	144	Pears, C.D. and Neel, D.S.	1962	R	1006-2009	1	Pressed and sintered; with poorly bonded structure; supplied by Zirconium Corp. of America; specimen 3/4 in. long, 3/4 in. outside dia, and 1/4 in. inner dia; density 3.00 g cm^{-3} at 25 C; specimen found broken on post inspection.
19	144	Pears, C.D. and Neel, D.S.	1962	R	818-2018	2	Same as the above specimen except specimen found cracked on post inspection.
20	158	Berman, R.	1952	L	2.6-93		A rod with a square cross section of side 5 mm; density 2.94 g cm^{-3} (97% of the single crystal value).
21	72	Kingery, W.D. and Norton, F.H.	1955		710-1431		Prepared by K. A. P. L.; density 2.78 cm^{-3}.
22	72	Kingery, W.D. and Norton, F.H.	1955		713-1431		Same as the above specimen.

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* See TPRC Data Book Vol. 3, Chapter 1, References

† Private communication

TABLE 16. SPECIFICATIONS OF THE SPECIMENS OF BERYLLIUM OXIDE (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	219	Schofield, H. Z., Duckworth, W. H., and Long, R. E.	1949		573-1173		Extruded from refractory-grade beryllia of minus 325 mesh.
24	220	Nelson, A. R.	1947		573-1173	3008-13-3	Extruded from refractory-grade BeO of minus 200 mesh and followed by burning three hrs at 1978 K density 2.18 g cm^{-3}.
25	218	Taylor, R. E.	1960	R	665-2290	ORNL-1	Brush SP grade of 2700 PPM metallic impurities; hot pressed; average grain size 50; density 2.89 g cm^{-3}; specimen 3 in. long with 2 in. O.D. and 1/2 in. I.D. .
26	218	Taylor, R. E.	1960	R	630-2242	ORNL-2	Same as the above specimen except density of 2.87 g cm^{-3}.
27	218	Taylor, R. E.	1960	R	750-1669	NBC-1	"Pure beryles" of the National Beryllia Corp; slip cast; density 2.72 g cm^{-3}.
28	218	Taylor, R. E.	1960	R	970-2256	AI -1	700 PPM metallic impurities; average grain size 60; hot pressed at 1700 C and 4000 psi for 4 hrs; density 2.98 g cm^{-3}.
29	218	Taylor, R. E.	1960	R	1175-2293	AI -2	Same description as the above specimen; separate run.
30	251	Hedge, J. C., Kostenko, C., and Lang, J. I.	1963	C	450-1039		99.5 BeO, 0.005 Al, 0.001 Fe, 0.002 Mo, 0.001 Ni, 0.0003 Mn, 0.001 Cr, 0.001 Ca, 0.009 Si, 0.001 Na, ≤0.0001 B, Cd, Li, Co, Cu; cold pressed; firing temperature 1855 K; specimen 2 in. dia by 1 in. thick with both faces of the disk ground flat and parallel; density 2.87 g cm^{-3}.
31	251	Hedge, J. C., Kostenko, C., and Lang, J. I.	1963	P	1250-2200		The above specimen measured by another method.
32	275	Rudkin, R. L.	1963	P	1073-2053	BD-98	97% of the theoretical density; manufactured by The Coors Porcelain Co.
33	218	Taylor, R. E.	1960	R	761-2131	AI -3	1.0 MgO; hot-pressed at 1700 C and 4000 psi for 4 hrs; average grain size 60; specimen 3 in. long with 2 in. O.D. and 1/2 in. I.D.; density 2.99 g cm^{-3}.
34	316	Norton, F. H., Kingery, W. D., et al	1951	R	673-1473		99.6^{+} pure; slip-cast; density 2.65 g cm^{-3}; total porosity 10%; apparent porosity < 1%.
35	296	Sibley, L. B., et al	1958		293-1273		Sintered; 93.5% of theoretical density.
36	292	Fitzsimmons, E. S.	1961	C	367-1478	No. 1	Fabricated by dry pressing followed by isostatic compaction and sintered at 1894 K in H_2 for 2 hrs and then heat treated at 2032 K in H_2 for one hr; 96-97% of theoretical density; specimen size: 1/2 x 1/2 x 7/8 in. rectangular prisms, manufactured by Brush.
37	292	Fitzsimmons, E. S.	1961	C	367-1478	No. 2	Same as the above specimen.
38	292	Fitzsimmons, E. S.	1961	C	367-1367		Average value of the above specimens No. 1 and No. 2 and then corrected to zero porosity.
39	276	Booker, J., Paine, R. M., and Stonehouse, A. J.	1961	R	700-1700		No details.
40	290	Burk, M.	1963	L	88-398		99 BeO, 1 Al_2O_3; density (25C) 2.89 g cm^{-3}; ground cylinder 3.4 ±0.01 cm in dia and 11 cm long; prepared from isostatically pressed bodies using a wax emulsion as a binder; calcinated at 1740 C for 2 hrs; measured in a vacuum of 10^{-4}mm Hg.
41	290	Burk, M.	1963	L	85-408		98 BeO, 1 Al_2O_3, 0.5 MgO + CaO, 0.5 SiO_2; density (25 C) 2.87 g cm^{-3}; ground cylinder 3.4 ± 0.01 cm in dia and 11 cm long; prepared from isostatically pressed bodies using a wax emulsion as a binder; calcinated at 1730 C for 3 hrs; measured in a vacuum of 10^{-4} mm Hg.

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[*] See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 16. SPECIFICATIONS OF THE SPECIMENS OF BERYLLIUM OXIDE (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	290	Burk, M	1963	L	88-418		96 BeO, 1 Al_2O_3, 1.5 MgO + CaO, 1.5 SiO_2; density (25 C) 2.87 g cm^{-3}; ground cylinder 3.4 ± 0.01 cm in dia and 11 cm long; prepared from isostatically pressed bodies using a wax emulsion as a binder; calcinated at 1690 C for 2 hrs; measured in a vacuum of 10^{-4} mm Hg.
43	291	Feith, A.D.	1964	R	1273-2493		Made of UOX-grade BeO powder isostatically pressed at 7000 psi; the cold compacts were crushed and screened through a 20-mesh sieve and then a 2.5 in. dia steel die was charged with 85 grams of the material and cold-pressed at about 6500 psi; the compacts were then isostatically pressed into discs at 20,000 psi; the discs were sintered in dry hydrogen at 1700 C for approximately 6 hrs and then machined to the final configuration: 2.00 in. O.D. and 0.375 in. I.D.; measured is effective conductivity; data corrected to 100% theoretical density (original: 97.8% theoretical density).
44	297	Powell, R.W.	1954	C	323-873	"Triangle" Beryllia; 1	99^+ BeO, main impurity being Al_2O_3; square sectioned bar cut from the center of a "Triangle" beryllia disc, type Y. 1029 having been fired at 1750 C; before measurement the specimen baked to about 800 C to drive off moisture introduced during cutting; length 10.84 cm, breadth 0.883 cm, width 0.801 cm, weight 14.155 g, and mean density 1.85 g cm^{-3}; iron used as comparative reference standard.
45	297	Powell, R.W.	1954	C	323-873	"Triangle" Beryllia; 2	99^+ BeO, main impurity being Al_2O_3; square sectioned bar cut from the center of a "Triangle" beryllia disc, type Y. 1033 having been fired at 1750 C; after baking to about 800 C, the specimen length 11.41 cm, breadth 1.006 cm, width 1.002 cm, weight 26.395 g, and mean density 2.3 g cm^{-3}; iron used as comparative reference standard.
46	297	Powell, R.W.	1954	C	323-773	Hot-molded Beryllia; 3	A rod of hot-molded beryllia; length 9.94 cm, dia 1.00 cm, weight 21.703 g, mean density 2.82 g cm^{-3}; iron used as comparative reference standard.
47	297	Powell, R.W.	1954	C	323-673	Hot-molded Beryllia; 4a	The heavier portion of specimen No. 4 of hot-molded beryllia; mean density 2.80 g cm^{-3}; iron used as a comparative reference standard.
48	297	Powell, R.W.	1954	C	373-673	Hot-molded Beryllia; 4b	The lighter portion of specimen No. 4 of hot-molded beryllia; mean density 2.72 g cm^{-3}; iron used as comparative reference standard.
49	297	Powell, R. W.	1954	C	323-573	Norton's Beryllia; 5	Norton's BeO, Shipment B. 1866, Clifton metal grade; hot-molded; specimen was a strip 0.5 cm wide cut from the center of a disc; density 3.0 g cm^{-3}; iron used as comparative reference standard.
50	319	General Electric	1962	C	339-568	AOX-BeO (329)	AOX-grade BeO; cylinder of 1 in. long and 0.238 in. dia; about 97.5% theoretical density; grain size 20 microns; pressed between two standard high density graphite (AGOT) probes.
51	319	General Electric	1962	C	335-525	AOX-BeO(329)	Same as the above specimen except with 8.6 x 10^{18} nvt ($E_n \geq 1$ Mev) irradiation.
52	319	General Electric	1962	C	348-548	AOX-BeO(329)	Same as the above specimen except with 2.0 x 10^{20} nvt ($E_n \geq 1$ Mev) irradiation.
53	319	General Electric	1962	C	328-560	AOX-BeO(329)	Same as the above specimen except with 3.7 x 10^{20} nvt ($E_n \geq 1$ Mev) irradiation.
54	320	General Electric	1962	R	1118-1773	Sample 23	Wafer of about 2 in. outside dia, 3/8 in. inside dia, and 1/2 to 2 in. thick; density ~0.9 g cm^{-3}; pore size 0.010 to 0.025 cm.

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* See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 16. SPECIFICATIONS OF THE SPECIMENS OF BERYLLIUM OXIDE (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
55	320	General Electric	1962	R	1133-1833	Sample 23	The above specimen (after the above measurement) sintered again in hydrogen for 1.5 hrs at 1590 C to eliminate contained phosphates; density 0.75 g cm^{-3}; pore size 0.01 to 0.025 cm.
56	320	General Electric	1962	R	1118-1798	Sample 25	Same as the above specimen except density ~1.0 g cm^{-3}; pore size 0.01 to 0.02 cm, and sintered at 1566 C for 1.5 hrs.
57	331	Pears, C. D.	1963	R	533-1922		99 pure; specimen of 1 in. in diameter and 1 in. long, hot pressed in graphite dies; 98% theoretical density; specimen equally guarded during measurement.
58	331	Pears, C. D.	1963	R	533-1922		98 pure; specimen of 1 in. in diameter and 1 in. long, cold pressed and fired; 96% theoretical density; specimen equally guarded during measurement.

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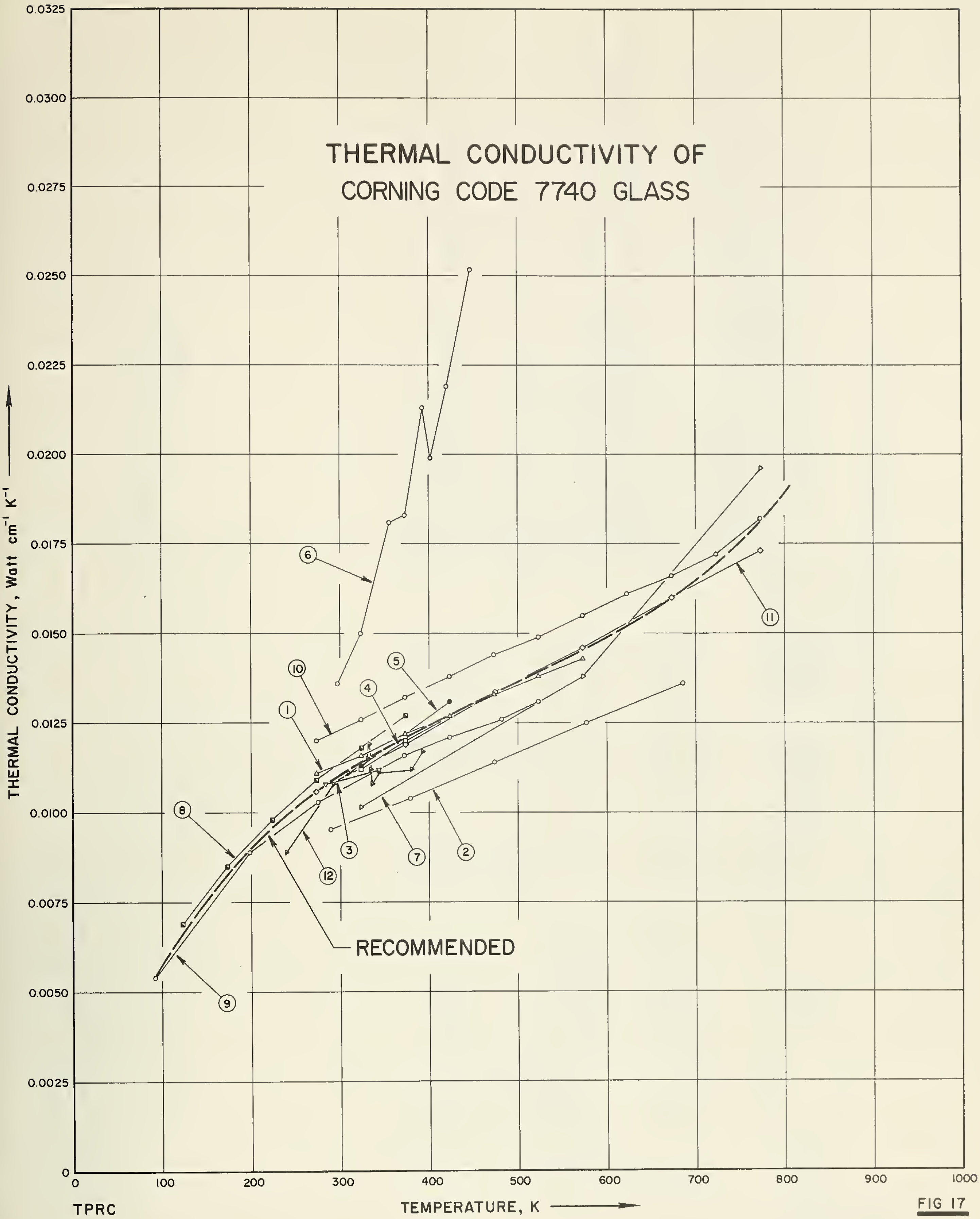
*See TPRC Data Book Vol. 3, Chapter 1, References



THERMAL CONDUCTIVITY OF CORNING CODE 7740 GLASS

TPRC

FIG 17

TABLE 17. SPECIFICATIONS OF THE SPECIMENS OF CORNING CODE 7740 GLASS

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	301	Flynn, D. R.	1963	L	273-773	Pyrex 7740	Density 2. 2258 g cm^{-3} at 24. 3 C; refractive index 1. 47257 ± 0. 00003 at 23 C for the D lines of sodium (5893 Å); specimen was somewhat strained; after the thermal conductivity measurement, the glass was annealed and the index of refraction decreased to 1. 47211 ± 0. 00003; data reported are the deduced probable values.
2	302	Plummer, W. A., et al	1962	P	289-685	Pyrex 7740	Pyrex glass Corning Code 7740; approximate composition: 80. 4 SiO_2, 13. 3 B_2O_3, 2. 0 Al_2O_3, and 4. 4 Na_2O.
3	†	Lucks, C. F. and Deem, H. W.	1961	L	283-323	Pyrex 7740	Measured by guarded hot plate method.
4	†	Lucks, C. F. and Deem, H. W.	1961	C	323-423	Pyrex 7740	Specimen from the same lot of material as the above specimen; measured by comparative method using Armco iron as reference standard; specimen temperature measured by inserted thermocouples.
5	†	Lucks, C. F. and Deem, H. W.	1961	C	323-423	Pyrex 7740	The above specimen measured by comparative method using Armco iron as reference standard; specimen surface temperatures obtained by extrapolation technique.
6	267	Hartunian, R. A. and Varwig, R. L.	1962	P	297-447	Pyrex 7740	Corning Pyrex 7740 glass tubing.
7	136	Kingery, W. D.	1959	R	373-773		Approximate composition: 81. 0 SiO_2, 12. 5 B_2O_3, 4. 5 Na_2O, and 2. 0 Al_2O_3.
8	147	Ratcliffe, E. H.	1960		123-373	A	Approximate composition: 80. 0 SiO_2, 12. 8 B_2O_3, 4. 2 Na_2O, and 2. 2 Al_2O_3; density 2. 22 g cm^{-3}.
9	187	Stephens, R. W. B.	1932		92-523	Pyrex 7740	80. 5 SiO_2, 12. 5 B_2O_3, 4. 0 Na_2O, and 2. 0 Al_2O_3; density 2. 233 g cm^{-3} at 21 C.
10	303	Birch, F. and Clark, H.	1940	L	273-773	774 Pyrex	No. 774 Pyrex Glass from Corning Glass Co.; density 2. 229 g cm^{-3}.
11	304	Flynn, D. R. and Robinson, H. E.	1961	L	273-773	Pyrex 7740	Pyrex No. 7740; tentative data.
12	331	Pears, C. D.	1963	L	239-393	Pyrex 7740	Pyrex glass Corning Code 7740; 1 in. thick, 7 in. diameter; tested in ASTM C177 apparatus.

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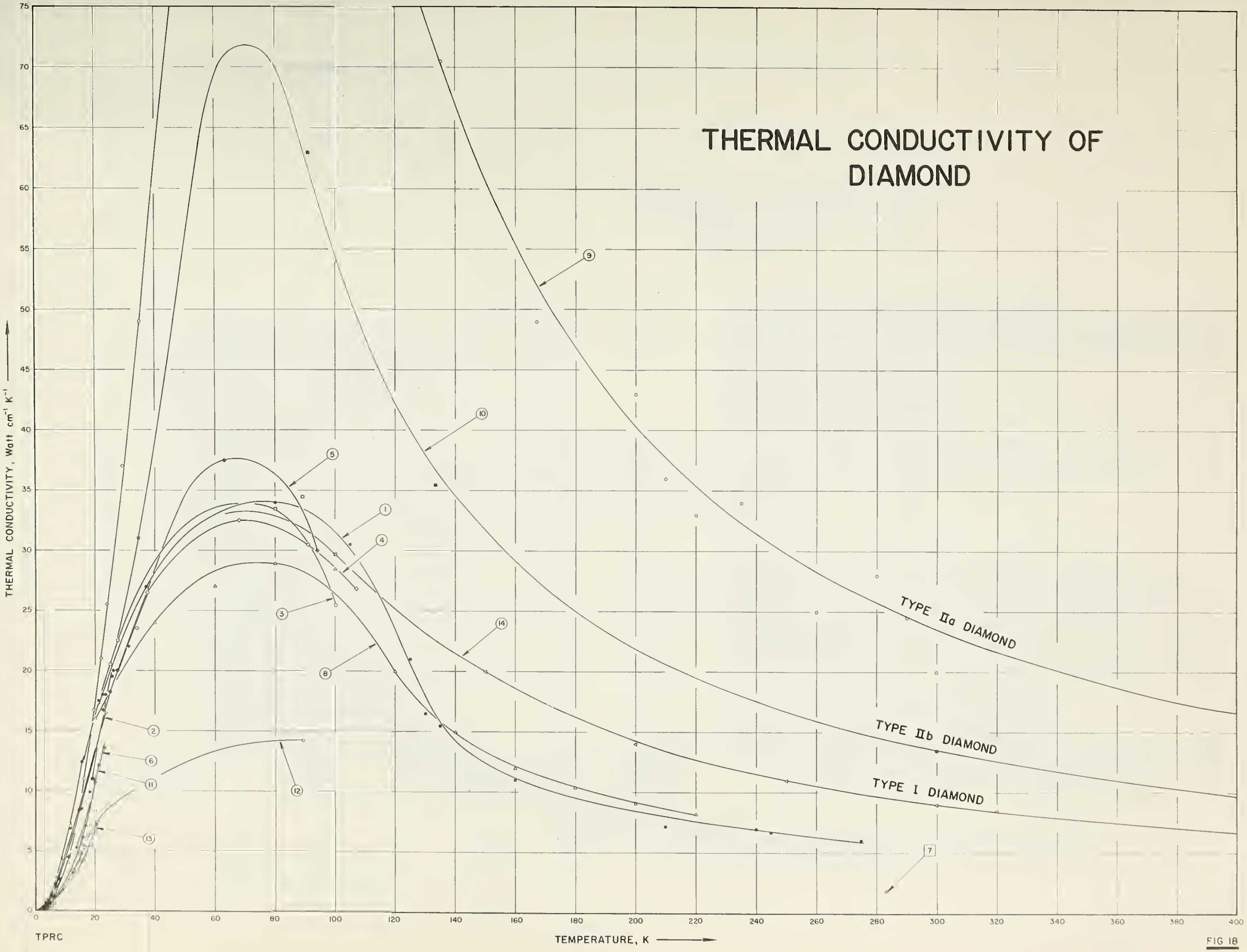
[*] See TPRC Data Book Vol. 3, Chapter 1, References

[†] Private communication


THERMAL CONDUCTIVITY OF DIAMOND
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
0
5
10
15
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25
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35
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80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
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TYPE IIa DIAMOND
TYPE IIb DIAMOND
TYPE I DIAMOND
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TPRC

FIG 18

TABLE 18. SPECIFICATIONS OF THE SPECIMENS OF DIAMOND

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	2.8-275	Type I stone	Name classified according to its ultra-violet transparancy limit; sawn and ground; 3.9 mm square cross-section and 6.8 mm in length.
2	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	5.4-24	Type I stone	Same as the above specimen except 5.8 mm in length.
3	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	3.2-100	Type I stone	Same as the above specimen except 3.1 mm square cross-section; no information concerning length.
4	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	2.4-107	Type I stone	Same as the above specimen except 1.7 mm square cross-section; no information concerning length.
5	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	2.8-94	Type I stone	Same as the above specimen except 1.1 mm square cross-section; and 6.9 mm in length.
6	25	Berman, R., Simon, F.E. and Ziman, J.M.	1953	L	14-23	Type I stone	Same as the above specimen except 1.1 mm square cross-section; and 5.2 mm in length.
7	26	Ioffe, A.V. and Ioffe, A.F.	1954		283.2		
8	27	Berman, R., Simon, F.E., and Wilks, J.	1951		20-220		Single crystal.
9	28	Berman, R., Foster, E.L., and Ziman, J.M.	1956	L	2.7-300	Type II a	An electrical insulator; 10 mm long with a cross-section approximately 0.7 x 1.25 mm.
10	28	Berman, R., Foster, E.L., and Ziman, J.M.	1956	L	3.0-300	Type II b	An electrical conductor; 7 mm long with a cross-section approximately 1.1 x 1.2 mm.
11	231	DeHass, W.J. and Biermasz, Th.	1938		2.99-22		Single crystal; length 6 mm, triangular cross-section 0.59 mm^2; presented by the firm I. J. Asscher at Amsterdam.
12	231	DeHass, W.J. and Biermasz, Th.	1938		11.4-89		Same as the above specimen.
13	231	DeHass, W.J. and Biermasz, Th.	1938		18-21		Same source as the above specimen but with length 9 mm, cross-section 0.82 mm^2.
14	28	Berman, R., Foster, E.L., and Ziman, J.M.	1956	L	100-320	Type I stone	Single crystal; 11 mm long of nearly square cross-section with side about 1.1 mm; measurements made in a new apparatus in which the corrections for radiation heat losses could be determined more accurately.

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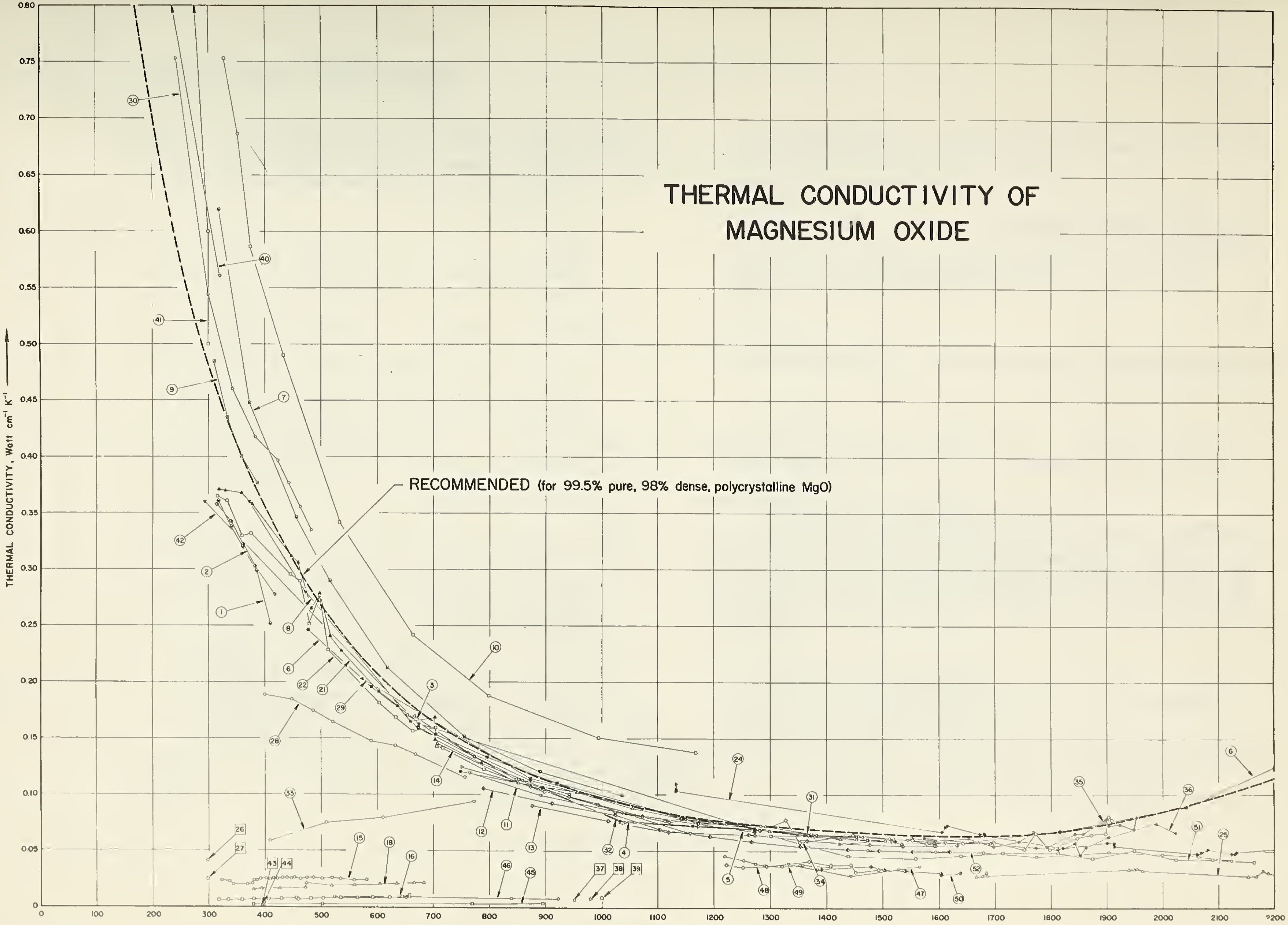
* See TPRC Data Book Vol. 3, Chapter 1, References



THERMAL CONDUCTIVITY OF MAGNESIUM OXIDE

RECOMMENDED (for 99.5% pure, 98% dense, polycrystalline MgO)

TPRC

FIG 19

TABLE 19. SPECIFICATIONS OF THE SPECIMENS OF MAGNESIUM OXIDE

Cur. No.	Ref.* No.	Author(s)	Year	Met'd Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	3	Koenig, J.H.	1953	C	319-411	236A-1	Spectroscopically pure; density (25 C) = 3.21 g cm^{-3}; water absorption = 0.83%.
2	3	Koenig, J.H.	1953	C	315-419	236A-2	Same sample as above; separate run.
3	2	Norton, F.H., Kingery, W.D. and others.	1951	R	666-1520		Polycrystalline; 0.30 SiO_2, 0.14 Al_2O_3, 0.35 CaO, 0.05 Fe_2O_3; hydrostatically pressed (30,000 psi); test run No. 1.
4	2	Norton, F.H., Kingery, W.D. and others.	1951	R	751-1517		Same specimen as above; test run No. 2.
5	4	Norton, F.H.	1951	R	673-1473		Sintered.
6	298	Fieldhouse, I.B. and Lang, J.I.	1961	R	478-2264		99^{+} MgO, 0.5>Si, 0.3>Mn; specimen contained 5 one-inch disks; density 2.98 g cm^{-3}.
7	293	Charvat, F.R. and Kingery, W.D.	1957	C	323-1033	No. 1	Polycrystalline; 99.54 pure, 0.20 SiO_2; 0.12 Al_2O_3, 0.11 total Na_2O, CaO, and K_2O, 0.02 Fe_2O_3, 0.01 TiO_2; gravimetric porosity 4.75%; microscopic porosity 6%; average grain size 8 μ; data corrected to zero porosity.
8	293	Charvat, F.R. and Kingery, W.D.	1957	C	373-1073	No. 2	Polycrystalline; 99.16 pure, 0.30 SiO_2, 0.14 Al_2O_3, 0.35 total Na_2O, CaO, and K_2O, 0.05 Fe_2O_3, trace TiO_2; gravimetric porosity 13.7%; microscopic porosity 14%; average grain size 12 μ; data corrected to zero porosity.
9	23	Koenig, J.H.	1952	C	312-388	83A-1	Single crystal.
10	293	Charvat, F.R. and Kingery, W.D.	1957	C	328-1168		Single crystal; 99.92 pure, 0.02 SiO_2, 0.05 total Na_2O, CaO, and K_2O, 0.01 Fe_2O_3; data corrected to zero porosity.
11	57	Norton, F.H., Kingery, W.D. and others.	1950	R	764-1611	A	Sintered; open pores 0.49%, closed pores 8.44%, total porosity 8.93%bulk density 3.26 g cm^{-3}.
12	57	Norton, F.H., Kingery, W.D. and others.	1950	R	789-1619	A	The second run of the above specimen.
13	57	Norton, F.H., Kingery, W.D. and others.	1950	R	876-1633	B	Sintered; without open pores, closed pores 8.66%, total porosity 8.66%; bulk density 3.27 g cm^{-3}.
14	57	Norton, F.H., Kingery, W.D. and others.	1950	R	707-1692	B	The second run of the above specimen.
15	166	Eian, C.S. and Deissler, R.G.	1953	R	324-583		Powder form; 0.64 volume fraction occupied by solid particles; measured in helium.
16	166	Eian, C.S. and Deissler, R.G.	1953	R	335-658		Same as the above specimen except measured in air.
17	166	Eian, C.S. and Deissler, R.G.	1953	R	371-620		Same as the above specimen except measured in argon.
18	239	Deissler, R.G. and Eian, C.S.	1952	R	380-683		Powder form; 0.58 fractional volume occupied by the solid particles; measured in He; gas pressure in range where pressure change does not affect conductivity of powder.
19	239	Deissler, R.G. and Eian, C.S.	1952	R	372-694		Same as the above specimen except measured in air.
20	239	Deissler, R.G. and Eian, C.S.	1952	R	378-611		Same as the above specimen except measured in argon.
21	131	Francl, J. and Kingery, W.D.	1954	C	318-896		Slip cast from suspensions of finely ground material; fired to zero apparent porosity; bulk density 3.48 g cm^{-3}.

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[*] See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 19. SPECIFICATIONS OF THE SPECIMENS OF MAGNESIUM OXIDE (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	131	Francl, J. and Kingery, W.D.	1954	C	316-898		The second run of the above specimen.
23	240	Thomas, R.	1919	R	429, 453		Sample size: 12.2 mm inside diameter, 19 mm outside diameter, and 8 cm long.
24	144	Pears, C.D. and Neel, D.S.	1962	R	1133-2322	1	0.3 Fe, 0.3 Si, 0.2 Ca, 0.1 Al; pressed and sintered, poorly bonded structure; supplied by Zirconium Corp. of America; density 3.51 g cm^{-3}; 3/4 in. long, 3/4 in. o.d. dia, and 1/4 in. i.d. dia; specimen found broken and partially melted on post insp.
25	144	Pears, C.D. and Neel, D.S.	1962	R	1668-2269		Same as above specimen except dimensions: 3 in. long, 2.5 in. outside diameter, and 3/4 in. inner diameter; specimen found cracked and color changed on post inspection.
26	152	Bopp, C.D., Sisman, O., and Towns, R.L.	1955	L	298.2	MgO	No details given.
27	152	Bopp, C.D., Sisman, O., and Towns, R.L.	1955	L	298.2	MgO	The above specimen exposed with 3 x 10^{19} epithermal neutrons per cm^2 for 480 megawatt day in the Material Testing Reactor.
28	153	Norton, F.H. and Kingery, W.D., et. al.	1951	C	400-756		
29	211	Norton, F.H. and Kingery, W.D.	1954		573-1473		
30	285	Makarounis, O. and Jenkins, R.J.	1962	P	111-483	MgO	Single crystal.
31	274	Norton, F.H., Kingery, W.D., et. al.	1953	R	653-1513	Run 1	Fired to total porosity of 8.10 - 8.93% with a bulk density of 3.26 - 3.29 g cm^{-3}.
32	274	Norton, F.H., Kingery, W.D., et. al.	1953	R	748-1523	Run 2	Same material as the above; separate run.
33	34	Knapp, W.J.	1943	C	409-772	Periclase	Synthetic, colorless, isotropic 1 cm cube; cut from a single crystal.
34	274	Norton, F.H., Kingery, W.D., et. al.	1953	R	1283-1908	M-10	0.05 Fe_2O_3, 0.30 SiO_2, 0.14 Al_2O_3, and 0.35 CaO; slip cast; fired to zero apparent porosity at 1850 C; final total porosity 5 - 10%.
35	274	Norton, F.H., Kingery, W.D., et. al.	1953	R	1423-1953	M-11	Same material as the above; separate run.
36	274	Norton, F.H., Kingery, W.D., et. al.	1953	R	1573-2023	M-12	Same material as the above; separate run.
37	299	Karpinski, J.M., Hasselman, D.P.H. Tervo, R., and Fetterley, G.H.	1958	R	951.7	Periclase	Compressed granular specimen; porosity 23.5%.
38	299	Karpinski, J.M., Hasselman, D.P.H. Tervo, R., and Fetterley, G.H.	1958	R	980.7	Periclase	Compressed granular specimen; porosity 15.2%.
39	299	Karpinski, J.M., Hasselman, D.P.H. Tervo, R., and Fetterley, G.H.	1958	R	1000.7	Periclase	Compressed granular specimen; porosity 13.7%.

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* See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 19. SPECIFICATIONS OF THE SPECIMENS OF MAGNESIUM OXIDE (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	300	Slack, G. A.	1962	L	2.4-305	R-38	Single, synthetic crystal; transparent, colorless, well-formed and free of visible defects; grown from the melt in an arc furnace using carbon electrodes and a self-crucible technique by R. L. Hansler, Lamp Division, General Electric Co.; specimen 1.11 cm long and 0.28 cm average dia; 4.213 Angstrom lattice constant; impurity (e_{pj} in atms cm^{-3}) given in $\log_{10} e_{pj}$ = 18.9 Al, 18.4 Be, 18.7 Ca, 17.6 Cr; 17.6 Fe, <18.4 K, 17.5 Li, <17.3 Mn, 18.7 Na, <17.2 Ni, 17.9 Si, <17.6 Ti, <17.3 V, <17.8 Zn, <17.7 Zr.
41	300	Slack, G. A.	1962	L	2.9-300	R-14	Similar to above specimen except 1.24 cm long and 0.41 cm average diameter; impurity (e_{pj} in atms cm^{-3}) given in $\log_{10} e_{pj}$ = 18.4 Al, 18.4 Be, 18.3 Ca, 17.6 Cr, 17.6 Fe, 18.4 K, 17.5 Li, <17.3 Mn, 18.7 Na, <17.2 Ni, 18.7 Si, <17.6 Ti, <17.3 V, <17.8 Zn, 18.1 Zr.
42	296	Sibley, L. B., et al.	1958		293-1273		Sintered; 97% of theoretical density; with an average grain size of about 15 microns.
43	314	Charlesworth, D. H.	1959	L	395.9		Compressed powder; calcined; manufactured by Fisher Scientific Co.; specimen of 0.152 in. thick and 9 in. dia; pressed at 63 psi; bulk density 0.73 g cm^{-3}; heat flow parallel to the axis of the specimen; load reduced to 0.5 lb $in.^{-2}$ prior to making measurements.
44	314	Charlesworth, D. H.	1959	L	398.2		Same as the above specimen except 0.089 in. thick, 1.25 g cm^{-3} bulk density, and 940 psi load.
45	315	Nonken, G. C.	1948	R	380-894		Powder; ≤200 mesh; porosity 47%; tested in air atmosphere.
46	315	Nonken, G C.	1948	R	525-922		Same as the above specimen except in hydrogen atmosphere.
47	317	JPL, Pasadena, Calif.	1960	R	1332-1565	MgO FPM-1	Fused MgO; 98.9 overall purity; composition: 45% fused MgO with -40 + 60 mesh and 99.0 purity, 15% fused MgO with -80 + 100 mesh and 99.0 purity, 35% fused MgO with -325 mesh and 98.5 purity, and 5% precipitated MgO with 0.02 - 0.03 μ, and 99.5 purity; bulk density 2.95 g cm^{-3} (83.5% theoretical density); fabricated at JPL; cold pressed at 30 k psi and sintered at 2750 F for 3 hrs; run No. 11.
48	317	JPL, Pasadena, Calif.	1960	R	1221-1492	MgO FPM-1	The above specimen run No. 12.
49	317	JPL, Pasadena, Calif.	1960	R	1219-1409	MgO FPM-1	The above specimen run No. 20.
50	317	JPL, Pasadena, Calif.	1960	R	1390-1638	MgO FPM-1	The above specimen run No. 21.
51	318	McCleland, J. D. and Zehms, E. H.	1960	R	1301-2163		Polycrystalline; right cylinder 3 in. long, 2 in. dia with coaxial hole of 0.5 in. dia; density 3.22 g cm^{-3}; supplied by Norton Co.; all data corrected to theoretical density of 3.58 g cm^{-3}; measured at increasing temperatures.
52	318	McCleland, J. D. and Zehms, E. H.	1960	R	1358-2122		The above specimen measured at decreasing temperatures.

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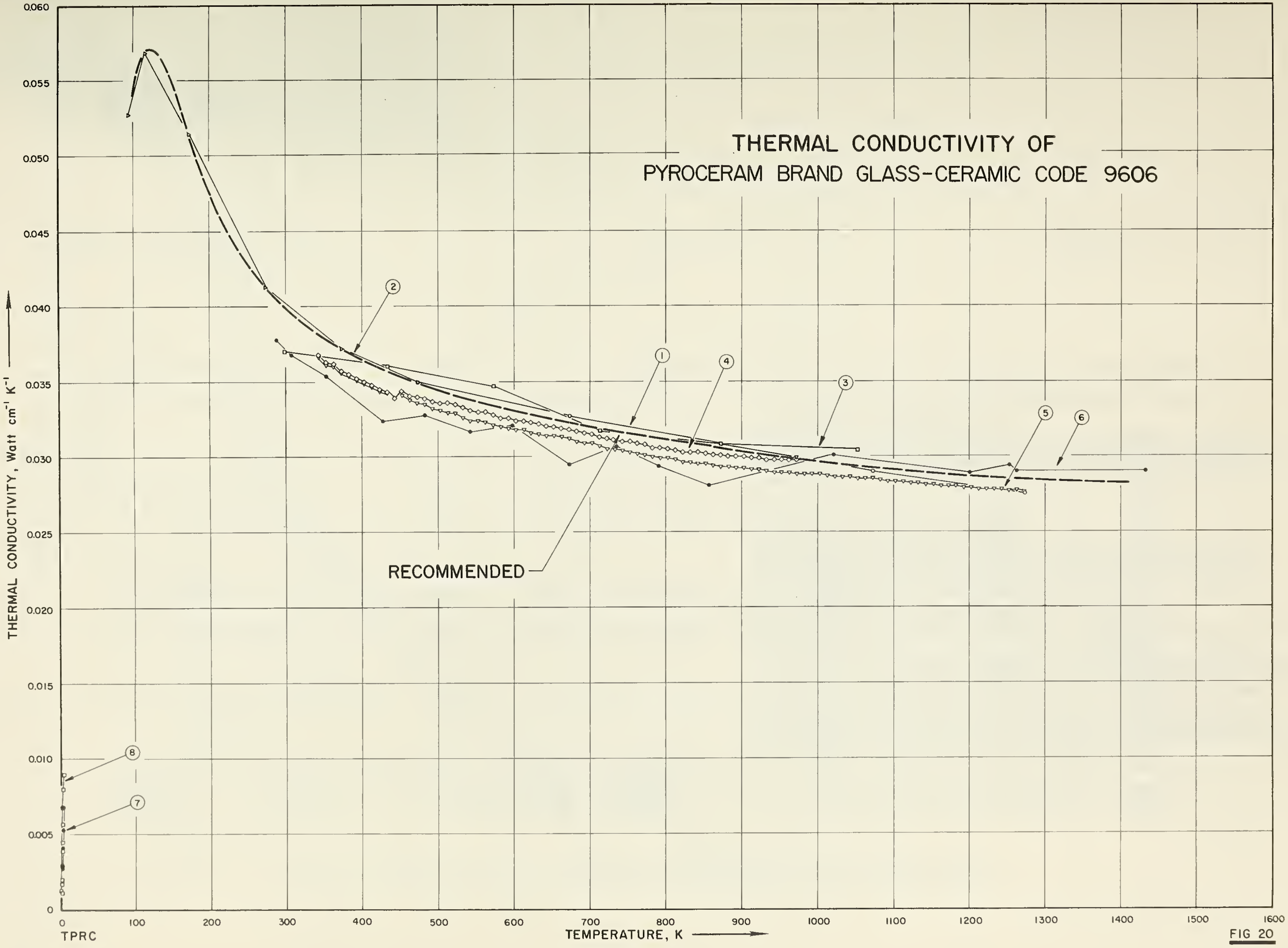
*See TPRC Data Book Vol. 3, Chapter 1, References



THERMAL CONDUCTIVITY OF
PYROCERAM BRAND GLASS-CERAMIC CODE 9606

TPRC

FIG 20

TABLE 20. SPECIFICATIONS OF THE SPECIMENS OF PYROCERAM BRAND GLASS - CERAMIC CODE 9606

Cur. No.	Ref. No.[*]	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	†	Flynn, D. R.	1962	L	473-1273	Pyroceram 9606	Pyroceram 9606 (a microcrystalline glass), product of Corning Glass Works; specimen 2.540 cm in dia and 1.269 cm in length; density 2.601 g cm^{-3}; data obtained before and after the specimen held at 1000 C for about 275 hrs agree with each other.
2	†	Robinson, H. E. and Flynn, D. R.	1963	L	93-473	Pyroceram 9606	Pyroceram 9606 of Corning Glass Works; specimen 4.44 cm in dia and 31 cm long from same bar as above; diatomaceous earth used as powder insulation surrounding the specimen inside the guard-tube of the NBS low-temperature model long-bar apparatus for metals.
3	†	Plummer, W. A.	1963	P	298-1053	Pyroceram 9606	Corning Code 9606 glass-ceramic; 0.5 cm thick planar specimen; thermal conductivity values calculated from thermal diffusivity data.
4	‡	Flieger, H. W., Jr.	1963	P	343-973	Pyroceram 9606	Pyroceram 9606 produced by Corning Glass Works; specimen 2 in. in diameter and 14 in. in length from the same lot as that measured by Flynn, D. R. (Curve 1); thermal conductivity values calculated from thermal diffusivity data (measured by radial heat flow technique) using a constant density of 2.60 g cm^{-3} and using W. A. Plummer's unpublished specific heat data.
5	‡	Flieger, H. W., Jr.	1963	P	343-1273	Pyroceram 9606	The above specimen measured (thermal diffusivity) after heating at 1000 C for about 10 hrs.
6	275	Rudkin, R. L.	1962	P	288-1433	Pyroceram 9606	Pyroceram 9606 from Corning Glass Works; specimen 3/4 in. in diameter and about 0.045 in. thick, coated on both sides to opacity with electron beam evaporated tungsten; thermal conductivity values calculated from thermal diffusivity data (measured by flash method) using a constant density of 2.60 g cm^{-3} and using W. A. Plummer's unpublished specific heat data.
7	306	Chang, G. K. and Jones, R. E.	1962	L	2.7-3.9	Pyroceram 9606 (a)	From Corning Glass Works; specimen cross-section 0.034 cm x 1.666 cm.
8	306	Chang, G. K. and Jones, R. E.	1962	L	1.6-3.9	Pyroceram 9606 (b)	From Corning Glass Works; specimen cross-section 0.130 cm x 1.607 cm.

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[*] See TPRC Data Book Vol. 3, Chapter 1, References

[†] Private communication

[‡] Unpublished data

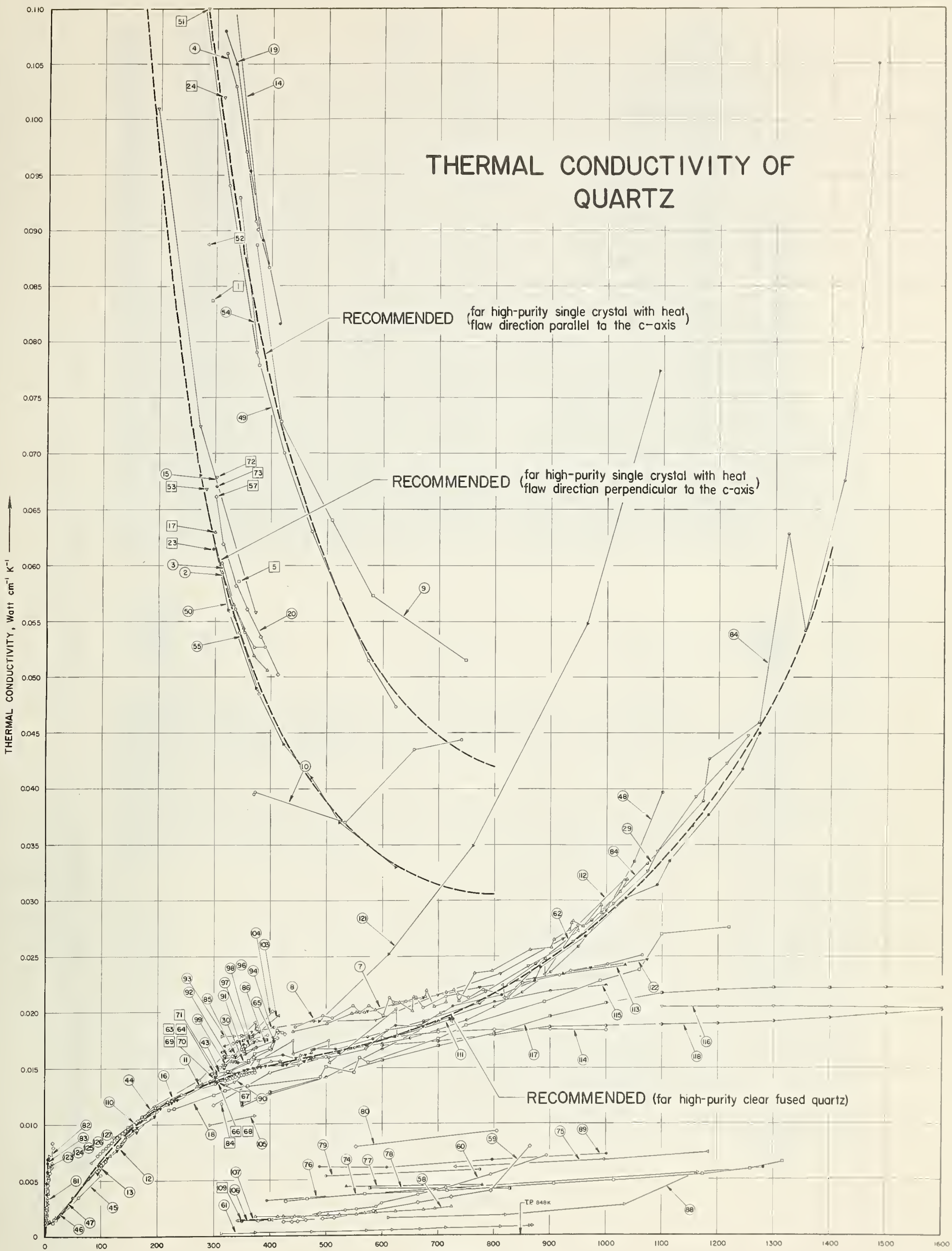
THERMAL CONDUCTIVITY OF QUARTZ
RECOMMENDED (for high-purity single crystal with heat flow direction parallel to the c-axis)
RECOMMENDED (for high-purity single crystal with heat flow direction perpendicular to the c-axis)
RECOMMENDED (for high-purity clear fused quartz)
THERMAL CONDUCTIVITY, Watt cm⁻¹ K⁻¹
TEMPERATURE, K
0
0.005
0.010
0.015
0.020
0.025
0.030
0.035
0.040
0.045
0.050
0.055
0.060
0.065
0.070
0.075
0.080
0.085
0.090
0.095
0.100
0.105
0.110
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600
T.P. 848K
TPRC

FIG 21

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	31	Vries, D. A. and Peck, A. J.	1958	R	293.2		Single crystal; density 2.65 g cm^{-3}.
2	23, 35	Koenig, J. H. Colosky, B. P.	1952	C	314-394	162A-2	Clear single crystal; ground and polished; free from twinning and inclusions; the base of the 1/2 in. cylindrical specimen was coated with a special silver paste (No. 45a); heat flow direction parallel to the a-axis.
3	23, 35	Koenig, J. H. Colosky, B. P.	1952	C	313-390	162B-2	Cut from the same crystal as the above specimen; preparation same as above; specimen axis parallel to the Y mechanical axis (a line intermediate between two a-axes).
4	23, 35	Koenig, J. H. Colosky, B. P.	1952	C	318-395	162C-2	Cut from the same crystal as the above specimen; preparation same as above; heat flow direction parallel to the c-axis (oriented to ± 5 minutes).
5	13	Weeks, J. L. and Seifert, R. L.	1953	C	343.2		Single crystal; measured perpendicular to optical axis; density = 2.6 g cm^{-3}; Armco iron used as standard.
6	32	deHaas, W. J. and Biermasz, Th.	1937	L	1.7-89		Single crystal; measured perpendicular to the principal axis and in the direction of a binary axis; length 3.20 cm and dia 0.216 cm.
7	33	Lucks, C. F., Matolich, J., and Van Velzor, J. A.	1954	C	441-1037		Clear fused quartz.
8	33	Lucks, C. F., Matolich, J., et al.	1954	C	445-1065		The above specimen measured with low emissivity foil adjacent to the surface.
9	34	Knapp, W. J.	1943	C	373-748	domestic	Single crystal; 1-cm colorless cube; cut from a single crystal; heat flow direction parallel to the c-(principal) axis, which is normal to two surfaces and parallel to others.
10	34	Knapp, W. J.	1943	C	370-741	domestic	The above specimen measured with heat flow direction perpendicular to the c-(principal) axis.
11	246	Kamilov, I. K.	1963	L	116-474		Fused quartz; d/s = 0.4 (d, the sample thickness and s, its transverse cross-sectional area); ΔT (the temperature drop across the sample) = 7 - 10 C.
12	246	Kamilov, I. K.	1963	L	94-463		Fused quartz; d/s = 0.4, ΔT = 2 - 4 C.
13	246	Kamilov, I. K.	1963	L	96-305		Fused quartz; d/s = 0.2, ΔT = 4 - 6 C.
14	22	Eucken, A.	1911	L	83-373		Single crystal; measured in the direction of the principal axis.
15	22	Eucken, A.	1911	L	83-373		Single crystal; measured perpendicular to the principal axis.
16	222	Ratcliffe, E. H.	1959	L	123-323		Fused quartz.
17	222	Ratcliffe, E. H.	1959	L	302.1		Single crystal; heat-flow at 90 degrees with the optic axis.
18	223	Seemann, H. E.	1928	R	220-1220		Clear fused quartz; hollow cylindrical specimen with one end closed hemispherically.
19	68	Koenig, J. H.	1954	C	314-415	162D-1	Natural single crystal of hexagonal crystal system; measured along c-(principal) axis; copper used as reference standard (thermal conductivity data of cooper taken from International Critical Tables, 1929).
20	68	Koenig, J. H.	1954	C	315-413	162E-1	The above specimen measured along a-axis.
21	69	Berman, R.	1951	L	6.5-90		Single crystal; 5 mm square cross-section and 5 cm length; temperature difference measured on length of 3.05 cm; heat flow direction perpendicular to the principal axis.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (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	69	Berman, R.	1951	L	28, 60		As above but temperature difference measured on length of 2.15 cm.
23	125	Griffiths, E. and Kaye, G. W. C.	1923	L	298.2		Single crystal; 0.253 cm thick with heat flow perpendicular to the principal axis and measured under pressure 21 lb in.$^{-2}$.
24	125	Griffiths, E. and Kaye, G. W. C.	1923	L	313.2		Single crystal 0.253 cm thick with heat flow parallel to the principal axis and measured as above.
25	224	deHaas, W. J. and Biermasz, Th.	1938	L	2.6–20	IIA	Single crystal; length 4.48 cm, dia 0.359 cm; measured perpendicular to the principal axis.
26	224	deHaas, W. J. and Biermasz, Th.	1938	L	2.3–20	II	Single crystal; length 4.80 cm, dia 0.454 cm; measured perpendicular to the principal axis.
27	224	deHaas, W. J. and Biermasz, Th.	1938	L	2.7–20		Single crystal; length 4.40 cm, dia 0.775 cm; measured perpendicular to the principal axis.
28	225	deHaas, W. J. and Biermasz, Th.	1938	L	1.7–20		Single crystal; specimen dia 0.216 cm; heat flow in the direction of the bisector of the angle between the two binary axes.
29	170	Norton, F. H. and Kingery, W. D.	1953	R	418–1253		Fused quartz; prepared by grinding the ellipsoid shape from a block.
30	170	Norton, F. H. and Kingery, W. D.	1953	R	343–1273		Same as the above specimen.
31	226	Berman, R., Klemens, P. G., Simon, F. E., and Fry, T. M.	1950		5–94	1	Single crystal irradiated with 1.8×10^{18} thermal neutrons cm^{-2} in a pile.
32	226	Berman, R., Klemens, P. G., et al.	1950		2–94	2	Above specimen re-irradiated again with cumulative irradiation dose $2.4 \times 1.8 \times 10^{18}$ neutrons cm^{-2}.
33	226	Berman, R., Klemens, P. G., et al.	1950		3.5–94	3	The above specimen No. 1 irradiated again with cumulative irradiation dose $19 \times 1.8 \times 10^{18}$ neutrons cm^{-2}.
34	226	Berman, R., Klemens, P. G., et al.	1950		10–20	1	The above specimen annealed at 300 C for 8 hrs.
35	226	Berman, R., Klemens, P. G., et al.	1950		10–20	2	The above specimen annealed again at 400 C for 6 hrs.
36	226	Berman, R., Klemens, P. G., et al.	1950		6–92	3	After 2nd annealing, the above specimen annealed again at 510 C for 6 hrs.
37	226	Berman, R., Klemens, P. G., et al.	1950		4.5–93	4	After 3rd annealing, the above specimen annealed again at 565 C for 6 hrs.
38	226	Berman, R., Klemens, P. G., et al.	1950		4.9–93	5	After 4th annealing, the above specimen annealed again at 540 C for 60 hrs.
39	227	deHaas, W. J. and Biermasz, Th.	1936	L	2.8–87	Rod I	Single crystal; specimen 0.308 cm in dia and 5.0 cm in length in the first part of the measurements; later specimen cut to 0.1336 cm dia and 3.033 cm length when being measured at lower temperatures; heat flow direction parallel to the c-axis of the crystal.
40	227	deHaas, W. J. and Biermasz, Th.	1936	L	15–89	Rod II	Single crystal; cut out of the same crystal as the above specimen; 0.1356 cm in dia and 5.58 cm in length; heat flow direction parallel to the c-axis of the crystal.
41	227	deHaas, W. J. and Biermasz, Th.	1936	L	15–20	Rod II	The above specimen heated at 340 C for 8 hrs.
42	227	deHaas, W. J. and Biermasz, Th.	1936	L	15–20	Rod II	The above specimen heated again at 570 C for 5 hrs.
43	267	Hartunian, R. A. and Varwig, R. L.	1962	P	297–422		Clear fused quartz.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (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	22	Eucken, A.	1911	L	83-373		Quartz glass.
45	69	Berman, R.	1951	L	2. 5-100		Quartz glass; specimen diameter 6. 1 mm, length 2. 3 cm.
46	69	Berman, R.	1951	L	5. 0-100		Quartz glass; specimen diameter 7. 7 mm, length 2. 25 cm.
47	69	Berman, R.	1951	L	5. 0-100		Quartz glass; specimen diameter 7. 4 mm, length 4. 6 cm.
48	309	Devyatkova, E. D., Petrov, A. V., Smirnov, I. A., and Moizhes, B. Ya.	1960	L	50-1100		Fused quartz; five specimens of dimensions 1 by 1 by 1 cm cut out of a single piece obtained from the M. V. Lomonosov Factory in Leningrad; data obtained with three different experimental arrangements.
49	303	Birch, F. and Clark, H.	1940	L	273-623		Single crystal; less than 0. 01 Cu; measured with heat flow direction parallel to the optic axis; specimen in the shape of a flat circular disc of 0. 25 in. thickness and 1. 5 in. dia cut from a single crystal originally nearly a foot long with well-developed external form obtained from the Harvard Mineralogical Museum; the whole crystal was perfectly transparent except for a few visible fractures; the deviation from the intended orientation was less than one degree.
50	303	Birch, F. and Clark, H.	1940	L	273-613		Similar to above specimen except for the specimen orientation so that heat flow direction perpendicular to the optic axis.
51	324	Tuchschmid, A.	1884		285	I	Heat flow direction parallel to the optic axis.
52	324	Tuchschmid, A.	1884		285	II	Heat flow direction at 45 degrees with the optic axis.
53	324	Tuchschmid, A.	1884		285	III	Heat flow direction perpendicular to the optic axis.
54	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	341, 378		Clear quartz (rock crystal) of 1. 25 in. in dia and 0. 10 in. thick; the faces of the disc were made optically flat and parallel; heat flow direction parallel to the optic axis; aluminum used as comparative reference standard.
55	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	343, 379		Similar to above specimen except heat flow direction perpendicular to the optic axis.
56	325	Lees, C. H.	1892	C	302		Quartz disc of 1. 91 cm dia and 1. 005 cm thick; heat flow direction parallel to the optic axis.
57	325	Lees, C. H.	1892	C	303		Quartz disc of 1. 93 cm dia and 0. 811 cm thick; heat flow direction perpendicular to the optic axis.
58	326	Kozak, M. I.	1952	R	373-723	Sample I	Powder; derived from coarse grain quartz of about 50% grains of 0. 3 mm dia, 40% of 0. 6 mm dia, and 10% of 1 mm dia; density 0. 54 g cm^{-3}.
59	326	Kozak, M. I.	1952	R	423-863	Sample II	Powder; derived from coarse grain quartz of 1. 0 - 1. 8 mm dia; density 0. 44 g cm^{-3}.
60	326	Kozak, M. I.	1952	R	378-893	Sample III	Coarse grains of cylindrical form of 3 mm dia and 3 - 7 mm long; density 0. 45 g cm^{-3}.
61	327	Sinel'nikov, N. N. and Filipovich, V. N.	1958	R	313-868		Powder; grain size 100 - 200 μ; density 1. 35 g cm^{-3}; measured in vacuum.
62	45	Norton, F. N. and Kingery, W. D.	1953	C	328-949		Fused quartz.
63	152	Bopp, C. D., Sisman, O., and Towns, R. L.	1955		298	Silica glass	Silica glass.
64	152	Bopp, C. D., Sisman, O., et al.	1955		298	Silica glass	The above specimen exposed to 7 x 10^{19} epithermal neutrons per cm^2 for 480 megawatt day in the Material Testing Reactor.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (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	321	Hartunian, R.A. and Varwig, R. L.	1961	P	300-426	Fused quartz	Clear fused quartz tubing; electrical resistence 10. 88 ohm; values of (dck) measured with platinum film gage deposited parallel to axis of tube; value of specific heat, c, taken from correlated data of Lord, R.C. and Morrow, J.C., J. Chem. Phys., 26, 230-2, 1957; the source of density, d, not given.
66	328	Gafner, G.	1957	P	303. 2	Fused quartz; 1	Fused quartz; disc of 7 cm in dia and 2. 406 cm thick; lapped planes parallel to better than 0. 02 mm; temperature rise in copper heat sink approx. 0. 5 d per 2 min; temperature measurement continued for 20 min after initial heat transient.
67	328	Gafner, G.	1957	P	303. 2	Fused quartz; 2	Same as the above specimen except thickness 1. 518 cm.
68	328	Gafner, G.	1957	P	303. 2	Fused quartz; 3	Same as the above specimen except thickness 0. 732 cm.
69	328	Gafner, G.	1957	P	303. 2	Fused quartz; 4	Same as the above specimen except thickness 1. 206 cm.
70	328	Gafner, G.	1957	P	303. 2	Fused quartz; 5	Same as the above specimen except thickness 0. 507 cm.
71	328	Gafner, G.	1957	P	303. 2	Fused quartz; 6	Same as the above specimen except thickness 0. 305 cm.
72	328	Gafner, G.	1957	P	303. 2	Single crystal; 7	Single crystal; disk of 7 cm in dia and 0. 952 cm thick; lapped planes parallel to better than 0. 02 min; temperature rise in copper heat sink 0. 5 C per min; temperature measurement continued for 20 min after initial transient; heat flow direction perpendicular to the optic axis.
73	328	Gafner, G.	1957	P	303. 2	Single crystal; 8	Single crystal; same as the above specimen except thickness 0. 635 cm.
74	311	Mason, C.R., Walton, J.D., Bowen, M.D. and Teague, W.T.	1959	E	417-1317	Fused silica; A	Slip cast from fused silica; dried 4 days at 333 K before being tested; 9 in. in dia and 1 in. thick; unfired; density 1. 78 g cm^{-3}.
75	311	Mason, C.R., Walton, J.D., et al.	1959	E	730-1182	Fused silica; A	The above specimen, 2nd run.
76	311	Mason, C.R., Walton, J.D., et al.	1959	E	393. 2, 1282. 1	Fused silica; B	Similar to above specimen A; unfired.
77	311	Mason, C.R., Walton, J.D., et al.	1959	E	537. 1, 778. 2	Fused silica	Similar to above specimen; fired at 1100 K for 3. 5 hrs.
78	311	Mason, C.R., Walton, J.D., et al.	1959	E	578. 2, 828. 7	Fused silica	Similar to above specimen; fired at 1200 K for 3. 5 hrs.
79	311	Mason, C.R., Walton, J.D., et al.	1959	E	499. 3, 774. 8	Fused silica	Similar to above specimen; fired at 1400 K for 3. 5 hrs.
80	311	Mason, C.R., Walton, J.D., et al.	1959	E	552. 6, 804. 8	Fused silica	Similar to above specimen; fired at 1500 K for 3. 5 hrs; fine cracks appeared over all surfaces.
81	322	Cohen, A. F.	1957		2. 9-13. 2	Vitreous silica	High purity fused silica; obtained from Corning Glass Works; square cross-sectional area 19. 8 mm^2; unirradiated; density (determined by hydrostatic weighing) 2. 1994 g cm^{-3}; measured by a steady state method.
82	322	Cohen, A. F.	1957		3. 30-14. 0	Vitreous silica	The above specimen irradiated to 1. 71 x 10^{19} fast neutrons cm^{-2}; density after irradiation 2. 2412 g cm^{-3}; measured by a steady state method.
83	322	Cohen, A. F.	1957		3. 2-6. 0	Vitreous silica	The above specimen after an additional exposure to 4. 13 x 10^{19} neutrons cm^{-2}; density after second irradiation 2. 2602 g cm^{-3}; measured by a steady state method.
84	72	Kingery, W. D. and Norton, F. H.	1955	C	373-1483	Clear fused silica	Specimen obtained from commercial source; cut and polished; data corrected to zero porosity using Loeb's expression (Loeb, A. L., J. Am. Ceram. Soc., 37(2), Pt. II, 96-99, 1954).

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (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	3	Koenig, J. H.	1953	L	311-412	53R-1	Silky fused vitreous silica.
86	3	Koenig, J. H.	1953	L	317-406	53J-1	Silky fused vitreous silica.
87	312	Ballard, S. S., McCarthy, K. A., and Davis, W. C.	1950	C	314.2	Fused silica	High optical homogeneity; variety of "Homosil", manufactured by the W. C. Heraeus Co. of Hanau, Germany; 10 mm^2 cross-sectional area and 2 - 10 mm thick; crystalline quartz used as reference standard.
88	313	Mason, C. R., Walton, J. D., Bowen, M. D. and Teague, W. T.	1959		611-1165	Foamed fused silica	Density 0.74 g cm^{-3}.
89	313	Mason, C. R., Walton, J. D., et al.	1959		489-1002	Fused silica	Density 1.91 g cm^{-3}.
90	42	Koenig, J. H.	1953		322-375	53M-1	Vitreous silica; 0.350 in. in dia and 0.499 in. in length.
91	42	Koenig, J. H.	1953		318-408	53P-1	Vitreous silica; 0.449 in. in dia and 0.498 in. in length.
92	42	Koenig, J. H.	1953		319-373	53J-1	Vitreous silica; 0.251 in. in dia and 0.250 in. in length.
93	42	Koenig, J. H.	1953		314-375	53L-1	Vitreous silica; 0.303 in. in dia and 0.500 in. in length.
94	42	Koenig, J. H.	1953		314-406	53N-1	Vitreous silica; 0.409 in. in dia and 0.500 in. in length.
95	42	Koenig, J. H.	1953		319-394	53Q-1	Vitreous silica; 0.500 in. in dia and 0.500 in. in length.
96	42	Koenig, J. H.	1953		318-397	53Q-2	Vitreous silica; 0.500 in. in dia and 0.499 in. in length.
97	23, 35	Koenig, J. H.	1952		319-394	53C-2	Clear vitreous silica sample with platinum alloy glaze on its end faces.
98	23, 35	Koenig, J. H.	1952		318-397	53D-2	Clear vitreous silica sample with silver glaze on its end faces.
99	23, 35	Koenig, J. H.	1952		316-397	53E-2	Silky vitreous silica sample with platinum alloy glaze on its end faces.
100	23, 35	Koenig, J. H.	1952		314-398	53F-2	Silky vitreous silica sample with platinum alloy glaze on its end faces.
101	23, 35	Koenig, J. H.	1952		318-394	53G-2	Silky vitreous silica sample with silver alloy glaze on its end faces.
102	23, 35	Koenig, J. H.	1952		320-393	53H-2	Silky vitreous silica sample with silver alloy glaze on its end faces.
103	9	Koenig, J. H.	1953	C	319-417	53NI-1	Vitreous silica.
104	9	Koenig, J. H.	1953	C	316-407	53NI-2	Vitreous silica.
105	44	Barratt, T.	1914	F	293, 373		Fused silica; density 2.17 g cm^{-3}.
106	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	342-510		Clear transparent vitreous silica; obtained from Thermal Syndicate; circular plate of 1.25 in. in dia and 1.000 mm in thickness; surfaces optically flat and parallel to a high degree of accuracy; density 2.205 g cm^{-3}.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (continued)

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
107	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	344-510		Same as the above specimen except 1. 503 mm thickness and 2. 204 g cm^{-3} density.
108	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	345-509		Same as the above specimen except 2. 002 mm thickness and 2. 203 g cm^{-3} density.
109	140	Kaye, G. W. C. and Higgins, W. F.	1926	C	348. 3		Same as the above specimen except with glycerine films on the surfaces and 1. 503 mm thickness and 2. 204 g cm^{-3} density.
110	147	Ratcliffe, E. H.	1960		93-373	Glass M	99. 9^+ SiO_2, less than 0. 1 other oxides; sample in the form of a pair of 3 in. dia discs; density 2. 20 g cm^{-3}.
111	303	Birch, F. and Clark H.	1940	L	273-773	Silica glass	1. 5 in. in dia and 0. 25 in. thick; density 2. 199 g cm^{-3}; obtained from Thermal Syndicate, Ltd.
112	39	Lucks, C. F., Deem, H. W., and Wood, W. D.	1960	C	367-1033	Fused silica	Clear fused silica; specimen 3 in. in dia and 0. 25 in. in thickness; density 2. 203 g cm^{-3} at 0 C; prepared by Hanovia Chemical Co.
113	39	Lucks, C. F., Deem, H. W., and Wood, W. D.	1960	C	367-1033	Fused silica	Same as the above specimen except having low-emissivity aluminum foil discs adjacent to the specimen surface.
114	237	Wray, K. L. and Connolly, T.	1959	E	300-1000	Fused silica; CQ3	Clear fused silica; cylindrical specimen of 0. 549 cm in dia and 10. 20 cm long; tungsten wire heater of 0. 00763 cm in dia embedded along the axis of the specimen.
115	237	Wray, K. L. and Connolly, T.	1959	E	350-1000	Fused silica; CQ3	The third run of the above specimen, CQ3.
116	237	Wray, K. L. and Connolly, T.	1959	E	1100-1750	Fused silica; CQ3	The fourth run of the above specimen, CQ3.
117	237	Wray, K. L. and Connolly, T.	1959	E	350-2100	Fused silica; CQ4	Clear fused silica; cylindrical specimen with 0. 478 cm in dia and 8. 30 cm long; tungsten wire heater of 0. 00763 cm in dia embedded along the axis of the specimen.
118	237	Wray, K. L. and Connolly, T.	1959	E	300-1700	Fused silica; CQ7	Clear fused silica; cylindrical specimen with 0. 598 cm in dia and 5. 34 cm long; tungsten wire heater of 0. 00508 cm in dia embedded along the axis of the specimen.
119	330	Powell, R. W.	1957	C	298	Single crystal	Quartz single crystal; disc of 1-3/8 in. in dia and 1/4 in. thick; disc axis perpendicular to the c-axis of the crystal; measured with thermal comparator.
120	330	Powell, R. W	1957	C	298	Fused silica	Disc of 3 in. in dia and 3/16 in. thick; measured with thermal comparator.
121	34	Knapp, W. J.	1943	C	377-1092	Silica glass	Pure; fused silica glass.
122	39	Lucks, C F., Deem, H. W., et al.	1960	C	423-1073	Fused silica	Specimen of 3 in. in dia and 0. 25 in. in thickness.
123	188	Crawford, J. H., Jr. and Cohen, A. F.	1958	L	3. 2-7. 2	Silica glass	High-purity Corning fused silica; square rod of 19. 8 mm^2 cross section; unirradiated; density 2. 2002 g cm^{-3}.
124	188	Crawford, J. H., Jr. and Cohen, A. F.	1958	L	3. 3-7. 4	Silica glass	The above specimen irradiated with 1. 71×10^{19} neutrons cm^{-2}; density 2. 24 g cm^{-3}.
125	188	Crawford, J. H., Jr. and Cohen, A. F.	1958	L	3. 3-6. 5	Silica glass	The above specimen again irradiated with 4. 13×10^{19} neutrons cm^{-2} (total irradiation 5. 84×10^{19} neutrons cm^{-2}); density 2. 26 g cm^{-3}.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 21. SPECIFICATIONS OF THE SPECIMENS OF QUARTZ (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	188	Crawford, J. H., Jr., and Cohen, A. F.	1958	L	3.5-5.7	Silica glass	The above specimen again irradiated with 3.5×10^{19} neutrons cm^{-2} (total irradiation 9.34×10^{19} neutrons cm^{-2}); density 2.26 g cm^{-3}.
127	188	Crawford, J. H., Jr. and Cohen, A. F.	1958	L	3.3-7.4	Silica glass	The above specimen annealed in air at 925 C for 9 hrs; density 2.2045 g cm^{-3}.

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*See TPRC Data Book Vol. 3, Chapter 1, References

THERMAL CONDUCTIVITY OF THORIUM DIOXIDE

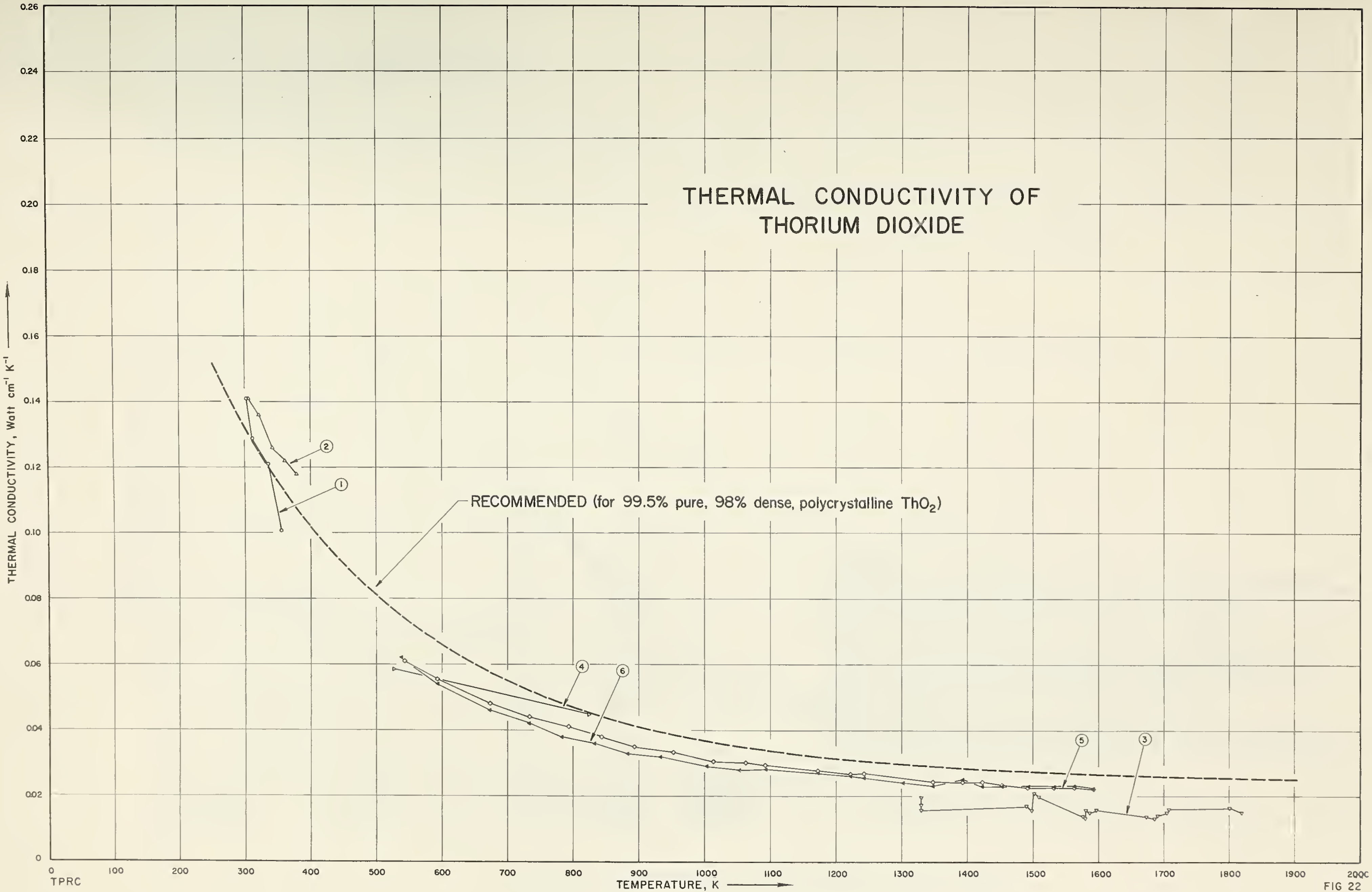

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FIG 22

TABLE 22. SPECIFICATIONS OF THE SPECIMENS OF THORIUM DIOXIDE

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	3	Koenig, J. H.	1953	C	304-356	239A-1	Spectroscopically pure; formed by hot pressing at 1790 - 1820 C; density (25C) = 9.58 g cm^{-3}; measurements made when using gold coatings on the end faces of the cylindrical specimen.
2	3	Koenig, J. H.	1953	C	306-379	239A-2	The above specimen remeasured, using platinum alloy glaze.
3	144	Pears, C. D. and Neel, D. S.	1962	R	1331-1821	1	Pressed and sintered; poorly bonded structure; supplied by Zirconium Corp. of America; 3/4 in. long, 3/4 in. outer dia, and 1/4 in. inner dia; density 9.69 g cm^{-3} at 25 C; specimen found broken on post inspection.
4	204	Armour Research Fdn., ARF Project	1957	R	527, 824		0.5 CaF_2; hot-pressed at 1500 ± 50 C and at pressure of about 100 psi for 30 min; average bulk density 9.37 g cm^{-3}.
5	307	Adams, M.	1954	R	543-1593		Specimen in the shape of prolate spheroid prepared by slip casting from suspension of finely ground thoria; total porosity 16.7% and bulk density 8.07 g cm^{-3}; the first run.
6	307	Adams, M	1954	R	538-1593		The above specimen second run.

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*See TPRC Data Book Vol. 3, Chapter 1, References

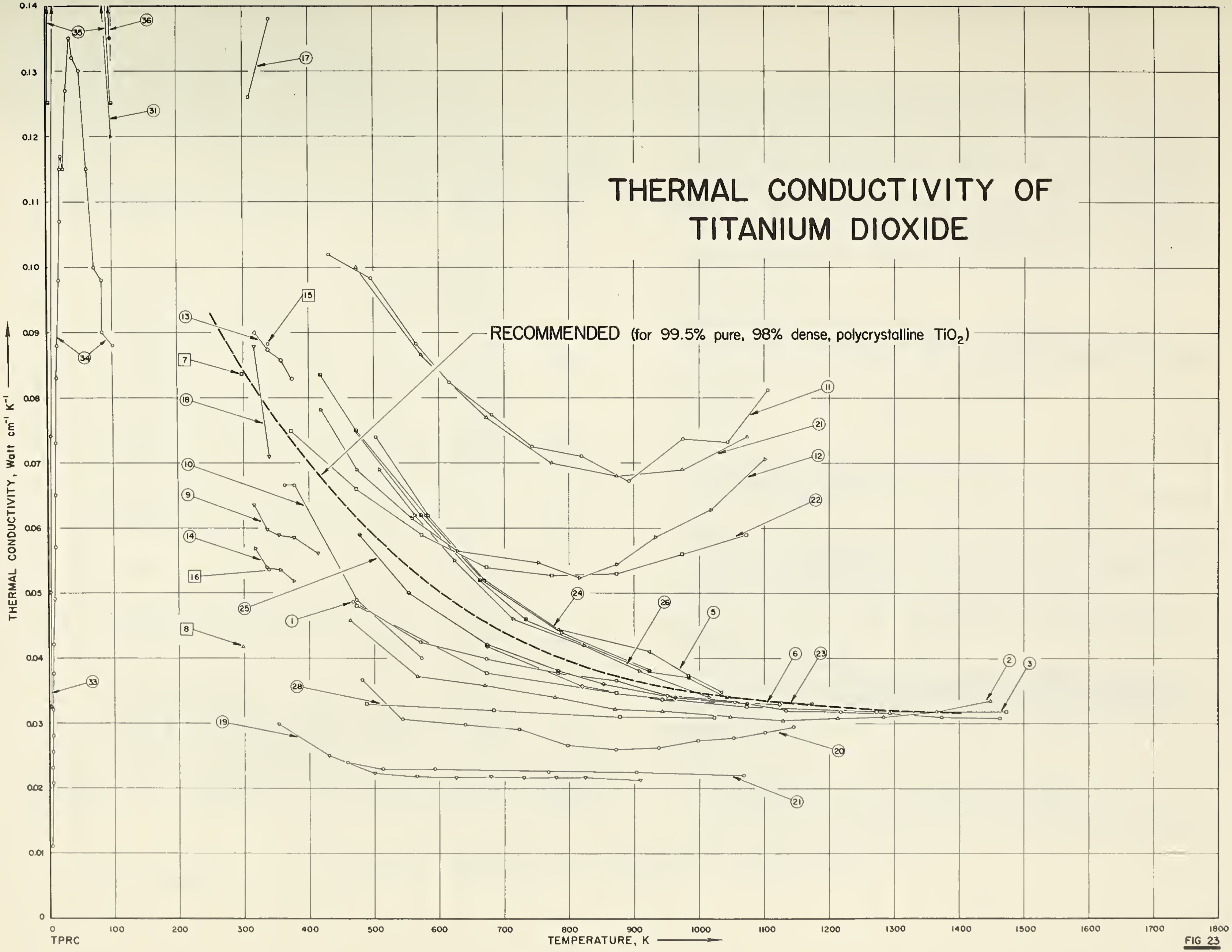# THERMAL CONDUCTIVITY OF TITANIUM DIOXIDE

FIG 23

TABLE 23. SPECIFICATIONS OF THE SPECIMENS OF TITANIUM DIOXIDE

Cur. No.	Ref.* No.	Author(s)	Year	Met'd. Used	Temp. Range (K)	Name and Specimen Designation	Composition (weight percent), Specifications, and Remarks
1	10	Norton, F.H., Kingery, W.D., et al.	1952	R	468-1463		Bulk density 4.11 g cm^{-3}.
2	10	Norton, F.H., Kingery, W.D., et al.	1952	R	463-1448		Same as above sample.
3	6	Kingery, W D., Francl. J., Coble, R. L., and Vasilos, T.	1954	C	473-1473		Polycrystal; prepared by calcining commercially pure TiO_2 at 1000 C, grinding for 12 hrs in a steel mill, acid leaching, slip-casting at pH of 3.5 with specific gravity 3.5, and then fired at 1700 C in an oxidizing atmosphere; bulk density 4.11 g cm^{-3}; porosity 3.5%.
4	28	Berman, R., Foster, E. L., and Ziman, J. M.	1956	L	2.2-88	Rutile	Single crystal.
5	146	Kingery, W. D. and Norton, F. H.	1955		473-1035	I	Polycrystal with crystal size 15 microns; pressed hydrostatically and sintered for 2 hrs at 1250 C; porosity 2.1%.
6	146	Kingery, W. D. and Norton, F. H.	1955		674-1123	II	Polycrystal with crystal size 28 microns; pressed hydrostatically and sintered for 8 hrs at 1450 C; porosity 3.0%.
7	152	Bopp, C. D , Sisman, O., and Towns, R. L.	1955	L	298.2	$TiO_2$192	No details.
8	152	Bopp, C. D., Sisman, O , et al.	1955	L	298.2	$TiO_2$192	The above specimen exposed to 5×10^{19} epithermal neutrons per cm^2 for 480 megawatt day in the Material Testing Reactor.
9	68	Koenig, J. H.	1954	C	317-414	Rutile; 217C-1	Natural single crystal with tetragonal crystal system.
10	38	Yoshida, I.	1960		363-573	Rutile	
11	145	Kingery, J. H. and Norton, F. H.	1955		432-1105		Single crystal.
12	145	Kingery, J. H. and Norton, F H.	1955		419-1102		Single crystal.
13	42	Koenig, J. H.	1953	C	319-376	217 A-1	Clear single crystal; heat flow direction parallel to the c-axis.
14	42	Koenig, J. H.	1953	C	317-377	217 B-1	Clear single crystal; a-axis parallel to the axis of the cylindrical specimen within 11 degrees; 0.250 ± 0.001 in. in dia and 0.250 ± 0.001 in. in length; positive optic sign and indices of refraction: e = 2.903 and w = 2.616.
15	42	Koenig, J. H.	1953	C	338.2		Same specimen as 217 A-1.
16	42	Koenig, J. H.	1953	C	338.2		Same specimen as 217 B-1.
17	71	McCarthy, D. A. and Ballard, S. S	1951	C	309, 341	Rutile	Single crystal; from Linde Air Products Co. of Tonawanda, N. Y.; measured with heat flow parallel to the optic axis; Pyrex glass used as standard.
18	71	McCarthy, D. A. and Ballard, S. S.	1951	C	317, 340	Rutile	Same as above; heat flow perpendicular to the optic axis.
19	332, 282	Buessem, W R. and Bush, E. A. Thielke, N. R.	1955	R	353-908	Porous	Composed of a mixture of 70% Titanox TG and 30% RA10MO with the former being previously calcined at 1550 C for one hr and ground to -100 mesh in a micropulverizer; the batch mixed in a porcelain mill using distilled water and flint pebbles; pressed by using 7% binder (composition: 500 g carbowax, 10 g methocel and 1000 cc water) at a pressure of approximately 4,400 psi and fired in a Pereny globar kiln at a rate of 120 C per hr and held at 1375 C for 30 min; 3.31 sp gr; 11,900 psi mod rupture; 17.1% apparent porosity; 5.6 shrinkage; specimen size: 5.40 cm o.d., 2.8 cm i.d. and 0.5 in. thickness; eleven rings stacked to form a cylinder of 5.5 in. high but measurements only made over the centrally-placed rings.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 23. SPECIFICATIONS OF THE SPECIMENS OF TITANIUM DIOXIDE (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	332, 282	Buessem, W.R. and Bush, E.A. Thielke, N.R.	1955	R	483-998	Dense titania	Pressed from Titanium Alloy Manufacturing Co. heavy grade titania with 7% binder (same composition as the above); set on c.p. zirconia powder, heated at a rate of 60 C per hr, and held for 20 min at a peak temperature of 1390 C; 3.95 sp. gr.; 16,600 psi mod rupture; 0.1% apparent porosity; 14.0% shrinkage; specimen size: 4.92 cm o.d., 2.61 cm i.d., and 0.5 in. thickness; same specimen assembly as the above specimen.
21	293	Charvat, F.R. and Kingery, W.D.	1957	C	473-1073		Single crystal; 99.5$^+$ pure; from Linde Co.; heat flow parallel to c-axis.
22	293	Charvat, F.R. and Kingery, W.D.	1957	C	373-1073		Single crystal; 99.5$^+$ pure; from Linde Co.; heat flow perpendicular to c-axis.
23	293	Charvat, F.R. and Kingery, W.D.	1957	C	423-1173		Polycrystalline; 99.5$^+$ pure; data corrected to zero porosity.
24	293	Charvat, F.R. and Kingery, W.D.	1957	C	503-923	No. 1	Polycrystalline; 99.5$^+$ pure; gravimetric porosity 2.1%, microscopic porosity 2.5%; average grain size 15 μ.
25	293	Charvat, F.R. and Kingery, W.D.	1957	C	478-1073	No. 2	Polycrystalline; 99.5$^+$ pure; gravimetric porosity 3.0%, microscopic porosity 3%; average grain size 28 μ; measured before reheating.
26	293	Charvat, F.R. and Kingery, W.D.	1957	C	508-1015	No. 2	The above specimen measured after reheating.
27	293	Charvat, F.R. and Kingery, W.D.	1957	C	458-1068	No. 3	Polycrystalline; 99.5$^+$ pure; gravimetric porosity 5.7%, microscopic porosity 8%; grain size not determined; measured before reheating.
28	293	Charvat, F.R. and Kingery, W.D.	1957	C	488-1023	No. 3	The above specimen measured after reheating; gravimetric porosity 3.9%, microscopic porosity 5%.
29	310	Thurber, W.R. and Mante, A.J.H.	1965	L	2.3-98	1cO	0.0001 ~ 0.001 each Ba, Cu, and Si, and perhaps smaller quantities of Al, Ca, and Fe; impurity concentration $10^{17} \sim 10^{18}$ atoms cm^{-3}; single crystal cut from a boule grown by the Verneuil method and supplied by National Lead Co.; specimen axis parallel to the c-axis of the crystal with heat flow in the c direction; oxidized in air for 2 days at 700 C; specimen surfaces roughened with silicon carbide paper with No. 600 used for the final finish; dimensions 1 by 4 by 24 mm.
30	310	Thurber, W.R. and Mante, A.J.H.	1965	L	2.7-98	1aO	Cut from the same boule as the above specimen 1cO and with the same impurities, the same heat and mechanical treatments; specimen axis parallel to the a-axis of the crystal; dimensions 1 by 4 by 19 mm.
31	310	Thurber, W.R. and Mante, A.J.H.	1965	L	2.3-100	1aOVR	The above specimen 1aO heated at 1175 C in vacuum of about 10^{-5} mm Hg for 27 hrs and then, while still in vacuum, cooled to near room temperature in 1 or 2 min by pouring water over the containing quartz tube after sliding the furnace away; defect concentration 1×10^{19} cm^{-3}; electrical resistivity 3.5 ohm cm at 300 K.
32	310	Thurber, W.R. and Mante, A.J.H.	1965	L	3.8-33	1aOVRO	The above specimen 1aOVR reoxidized at 600 C in flowing oxygen for 2 days.
33	310	Thurber, W.R. and Mante, A.J.H.	1965	L	1.4-33	1aOVROO	The above specimen 1aOVRO reoxidized at 700 C for 7 days and at 800 C for 10 days in flowing oxygen.
34	310	Thurber, W.R and Mante, A.J.H.	1965	L	2.5-100	2aOHR	Cut from the same boule as the above specimen 1cO; specimen axis parallel to the a-axis of the crystal; dimensions 1 by 4 by 19 mm; heated at 900 C in flowing hydrogen for 2 hrs, then the hydrogen was flushed out with argon and the furnace cooled to near room temperature in 2 or 3 hrs; defect concentration 1×10^{20} cm^{-3}; electrical resistivity 0.35 ohm cm at 300 K.

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*See TPRC Data Book Vol. 3, Chapter 1, References

TABLE 23. SPECIFICATIONS OF THE SPECIMENS OF TITANIUM DIOXIDE (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	310	Thurber, W. R. and Mante, A. J. H.	1965	L	2. 0-98	2aOHRO	The above specimen 2aOHR oxidized at 700 C in flowing oxygen for 10 days.
36	310	Thurber, W. R. and Mante, A. J. H.	1965	L	2. 0-98	3aNb	0. 1 Nb_2O_5; cut from a boule grown from rutile powder which contained 0. 1% Nb_2O_5 and supplied by the National Lead Co. ; niobium concentration 1.6×10^{19} atoms cm^{-3}; electrical resistivity 3. 1 ohm cm at 300 K; specimen dimensions 1 x 3. 5 x 14 mm.

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*See TPRC Data Book Vol. 3, Chapter 1, References

C. References

1. Touloukian, Y.S., Thermophysical Properties Research Center Data Book, Volume III. Nonmetallic Elements, Compounds and Mixtures (in Solid State at Normal Temperature and Pressure), Chapter 1. Thermal Conductivity. Data sheets updated twice a year; 390 pages in Chapter 1 as of June 1965, 11 in. x 17 in.
2. Euler, F., "Simple Geometric Model for the Effect of Porosity on Material Constants", J. Appl. Phys., 28 (11), 1342-5, 1957.
3. Maxwell, J.C., "A Treatise on Electricity and Magnetism", Dover Edition (republication of the third edition of 1891), Vol. 1, 1954, 440-1.
4. Loeb, A.L., "Thermal Conductivity: VIII, A Theory of Thermal Conductivity of Porous Materials", J. Am. Ceram. Soc., 37 (2), Part II, 96-9, 1954.
5. Charvat, F.R. and Kingery, W.D., "Thermal Conductivity: XIII, Effect of Microstructure on Conductivity of Single-Phase Ceramics", J. Am. Ceram. Soc., 40 (9), 306-15, 1957.
6. Powell, R.W., "The Thermal Conductivity of Beryllia", Trans. Brit. Ceram. Soc., 53 (7), 389-97, 1954.
7. Taylor, R.E. "Thermal Conductivity and Thermal Expansion of BeO at Elevated Temperatures", USAEC Rept. NAA-SR-4905, 1-19, 1960.
8. Birch, F. and Clark, H., "The Thermal Conductivity of Rocks and its Dependence upon Temperature and Composition", Am. J. Sci., 238, 529-58, 1940.
9. Robertson, R., Fox, J.G., and Martin, A.E., "Two Types of Diamond", Phil. Trans. Roy. Soc., A232, 463-536, 1934.
10. Champion, F.C., "Some Physical Properties of Diamonds", Advances in Phys., 5 (20), 383-411, 1956.
11. 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.
12. 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.
13. Robinson, H.E. and Flynn, D.R., National Bureau of Standards, Washington, D.C., private communication.
14. Flieger, H.W., Jr., National Bureau of Standards, Washington, D.C., unpublished data.
15. Moser, H., "Measurement of True Specific Heat of Silver, Nickel, β-Brass, Quartz and Vitreous Silica between 50 and 700 C by a Refined Method", Physik. Z., 37, 737-53, 1936.
16. Mosesman, M.A. and Pitzer, K.S., "Thermodynamic Properties of the Crystalline Forms of Silica", J. Am. Chem. Soc., 63, 2348-56, 1941.
17. Sinel'nikov, N.N., "A Vacuum Adiabatic Calorimeter and Some New Data on the α-β Transition for Quartz", Doklady Akad. Nauk SSSR, 92, 369-72, 1953.
18. Rosenholtz, J.L. and Smith, D.T., "Linear Thermal Expansion and Inversions of Quartz, Various Rock Crystal", Am. Mineralogist, 26, 103-9, 1941.
19. Thurber, W.R. and Mante, A.J.H., "Thermal Conductivity and Thermoelectric Power of Rutile (TiO_2)", Phys. Rev., 139 (5A), A1655-65, 1965.

PART III

THERMAL CONDUCTIVITY OF LIQUIDS

PART III - THERMAL CONDUCTIVITY OF LIQUIDS

A. Introduction

Nine liquids were selected for examination. Four of these liquids have previously been analyzed by Makita and constitute part of TPRC Data Book Volume, II, Chapter 1. The results of his analysis have been compared with further work in the present study and are discussed below.

B. Thermal Conductivity of a Group of Selected Liquids

Argon.-Three experimental works are available on the thermal conductivity of liquid argon. Keyes [192*] made measurements in a coaxial-cylinder apparatus near saturation conditions at three temperatures from 86. 9 K to 111.9 K. The extensive measurements of Uhlir [353] were made in a coaxial-cylinder apparatus using the gas thermometer, covering temperatures from 86 to 150 K and pressures up to 96 atm. The uncertainty in the measurements was 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 [57,413], over the temperature range from 93 up to 150.7 K for the liquid phase under various pressures up to 120 atm. From the standpoint of the experimental method and procedure, all the above measurements are considered to be reliable.

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

$$10^6 k \text{ (cgsu)} = 516.609 - 2.32178\ T - 0.00255768\ T^2 \text{ (T in K)}.^{\dagger}$$

In arriving at this formula, the values at the critical point are excluded because the uncertainty in the measurements and the graphical extrapolation would increase. Therefore, the above equation should be valid in the temperature range from 80 to 148 K. This equation is found to fit the above enumerated values with a mean deviation of 0.61 percent and a maximum of 1.9 percent. The recommended values (Table 24) are generated from the above formula, and the values at all temperatures should be correct within two percent.

In the departure plot (Figure 24), the departures of the data near the critical point of curves 1 and 2 are calculated beyond the limit of the above equation.

Carbon Tetrachloride.-Makita considered 20 experimental measurements in the literature on the thermal conductivity of liquid carbon tetrachloride. The extensive measurements of Challoner-Powell [434], Filippov [442], Mason [475], Riedel [279,486], Schmidt - Leidenfrost [492] were considered to be reliable from the standpoint of their experimental methods and procedures, and were given weight in this analysis. Furthermore, the single point values of Frontas'ev-Gusakov [447,448], Riedel [483,484] and Van de Held-Van Drunen [507] were also considered reliable and were used for the estimation of the most probable correlation. Although there were several other extensive measurements [427-29, 437, 517], these were considered to be less reliable, and therefore, were given no weight in his analysis.

The correlation formula obtained was

$$10^6 k \text{ (cgsu)} = 384.690 - 0.457184\ T \quad \text{(T in K)}.$$

This equation was found to fit the above enumerated measurements with a mean deviation of 1.4 percent and a maximum of 4.9 percent.

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[*] Reference numbers used in the text, tables and figures of Parts III and IV of this report refer to the section of References in Volume II, Chapter I of TPRC Data Book.

[†] No attempt has been made to round-off computer results for equation coefficients, which are given to more places then are physically significant. They have been left in the original form to eliminate error generated by using an equation with rounded coefficients for interpolation.

The recommended values were calculated from the above equation and were considered to be substantially correct in the range from 255 K to 378 K.

Subsequently, some further sources of values have been compared with Makita's correlation. The result of this comparison (shown in Figure 25) is to indicate agreement to within four percent in the worst case and to about two percent as an average. As some measurements disagreed with the original correlation to as much as twelve percent, it can be concluded that the further sources are in satisfactory agreement with Makita's correlation and that the latter can be considered as a satisfactory basis for generating the recommended values.

The recommended values were therefore generated from Makita's correlation equation above and then converted into the tabulated units (watts $cm^{-1} K^{-1}$) using the appropriate conversion factor. The values so obtained are given in Table 24, while Figure 25 is a departure plot of the references which were compared. As stated above, a probable error of two percent appears realistic.

Diphenyl. - Three sets of experimental data are available for the thermal conductivity of liquid Diphenyl. Analysis of these data showed that, to within the experimental uncertainty, it was possible to represent these as a linear function of temperature. The recommended values were read from a large scale plot and checked by differencing. They should be accurate to two percent for the entire range of the tabulation (330-600 K). The values are given in Table 24 while Figure 26 is the departure plot for this substance.

Helium. - A number of experimental works has 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 2.17 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.

The thermal conductivity of liquid helium-I was first measured by Keesom - Keesom [547], and it was found that the value is of the same order of magnitude as that of gases at ordinary temperatures. Grenier [133, 545, 546] made measurements in a parallel-plate apparatus within the uncertainty of 10 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 [48, 49] 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 - Lee [544] 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

$$10^6 k \text{ (cgsu)} = 99.5614 - 43.8934\, T + 8.94877\, T^2 \qquad (T \text{ in K}).$$

This equation should be valid at temperature above 2.2 K. The above equation is found to fit the data of Fairbank - Lee with a mean deviation of 1.7 percent and a maximum of 3.7 percent. The recommended values of Table 24 are generated from this equation, and the values should be substantially correct within two percent. Figure 27 is a departure plot for this substance.

On the other hand, of all the physical properties of helium-II, the most remarkable is the extraordinarily high transport of heat. Preliminary measurements by Keesom - Keesom [547] at 1.4 and 1.75 K gave values of the thermal conductivity of about 190 cal $cm^{-1} sec^{-1} K^{-1}$. It may be noted that this value is about 200 times that of copper at ordinary temperatures. In their further measurements [548, 560, 561], it was found that the thermal conductivity as a function of temperature has a very pronounced maximum near 1.92 K, and under some condition, a thermal conductivity as high as 810 $cal^{-1} cm^{-1} sec^{-1} K^{-1}$ was observed. Hence, liquid helium-II is by far the best heat conducting substance known. A number of investigations have been carried out on the super-heat-conduction of liquid helium-II [198, 231, 548--567]. The mechanism of heat transport in liquid helium-II is quite different from that in helium-I or other liquids due to its extreme fluidity and the associated transport of energy by virtue of convective currents. Under these circumstances it is not possible to observe a "true" thermal conductivity as a transport property. Therefore, observed thermal conductivity values are found to depend markedly on the conditions of measurement, that is, the heat current density, the temperature gradient, and the dimensions of the test cell used. It is considered to be impossible to treat the heat conduction in helium-II in the same way as in other liquids. Therefore, no correlation is attempted in this analysis.

Nitrogen. - There exist eight available experimental works on the thermal conductivity of liquid nitrogen. The extensive measurements of both Uhlir [353] and Ziebland - Burton [57, 413] are considered to be the most reliable from the standpoint of the experimental method and procedure. As they did not give the values for the saturated liquid, a graphical extrapolation is 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. [276, 531] is also partly used in this analysis. On the other hand, two sets of data reported by Borovik [42, 46] deviate considerably, and the values of Hammann [139] and Prosad [535] are too high. Therefore, no weight is given to these sets of data.

The correlation formula is determined from the reliable values described above, excluding those at the critical point because the values near the critical point are considered to be less reliable. The correlation formula is given by

$$10^6 k \text{ (cgsu)} = 695.957 - 5.15493\, T + 0.00504635\, T^2 \qquad (T \text{ in K}).$$

This equation should be valid between 60 and 123 K. It is 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 recommended values of Table 24 are calculated from the above equation and the data above -320 F should be substantially correct within two percent.

In the departure plot (Figure 28), the values near the critical point of curve 1, 6, and 8 are plotted beyond the limit of validity of the above formula. A single point value which was obtained at 33 atm by Ziebland - Burton [412] is plotted without any extrapolation to the saturated liquid. Furthermore, only a part of the results of Hamman (curve 3) is plotted for the sake of clarity in this figure.

m-Terphenyl. - Only two sets of experimental values were available for the thermal conductivity of liquid m-Terphenyl, the results of Horrocks and McLaughlin [637] from 355 to 407 K and of Reiter [639] from 373 to 623 K. Graphical plotting of these data revealed a difference in the two sets of about three percent. There was also a difference in the temperature derivative of thermal conductivity.

In preparing the recommended values, a smooth curve was drawn through the higher temperature Reiter data and midway between the two sets of data for the lower temperatures. Values, read off this curve and checked by differencing for even increments of temperature, are given in Table 24. Figure 29 is the departure plot for this substance. The reliability of the recommended values can be assessed as about two percent.

p-Terphenyl. - Experimental measurements of the thermal conductivity of p-Terphenyl have been reported by Horrocks and McLaughlin [637] and Reiter [639], for temperature ranges of 488-520 and 523-623 K, respectively. these data appear to be in reasonably good concordance. The recommended values of Table 24 were obtained from a smooth curve drawn through the experimental data and should be accurate to within one-half percent between 490 and 620 K and one percent for all other temperatures tabulated. Figure 30 is the departure plot for this substance.

Toluene. - Makita analyzed twenty-four experimental works on the thermal conductivity of liquid toluene. The discrepancy between the reported values of different investigators was found to be extremely large. The results of several extensive measurements fall into two groups, one group being about twelve percent to eighteen percent higher than the other. The results of Abas-Zade [1, 2], who used the hot-wire method, and those of Bridgman [431], Markwood-Benning [238], and Smith [500], who used the coaxial-cylinder method, all fall in the higher set. On the other hand, recent results of Calloner-Powell [434], Filippov [100, 441], McCready [471], Os' minin [478], Riedel [486], Schmidt-Leidenfrost [492], Vargaftik [508] and Ziebland [519] fall within the lower group. From the standpoint of the experimental method and procedure, the latter set of data were felt to be more reliable. Therefore, the eight sets of extensive data mentioned above were given equal weight in his analysis, and the single point values of Frontas' ev-Gusakov [447, 448] and Riedel [483, 484] were also included in the estimation of the post probable values.

The correlation formula obtained was

$$10^6 k\ (\text{cgsu}) = 502.540 - 0.607275\ T \qquad (T \text{ in K}).$$

This equation was found to fit the experimental values of the above-enumerated investigators with a mean deviation of 1.2 percent and a maximum of 3.9 percent.

The above equation was used for the calculation of the recommended values. The values should be correct in the temperature range between 189 K and 389 K.

Although Abas-Zade [2] made measurements up to the critical point and Filippov [100, 441] also measured up to 511 K under saturation pressures, no correlation was attempted in the region where the vapor pressure is higher than one atmosphere.

It can be concluded that Makita' s recommended values were accurate to about four percent.

In the present work, experimental measurements made subsequent to Makita's correlation and other measurements not utilized by him have been compared with his correlated values. The results of both comparisons are given in the departure plot of Figure 31. From this, it might be deduced that the correlation is satisfactory at 265 K and high by one or two percent at about 375 K. As the uncertainty in these figures is less than the uncertainty in the bulk of the newer data (of about three percent) and in the data compared by Makita (of about four percent), the original Makita correlation is felt to be satisfactory and there is felt to be no rational basis for a change in the correlation at this time. The recommended values of Table 24 were obtained by interpolation of the Makita tabulation. They should be accurate to four percent.

Water. - More than sixty experimental works are available on the thermal conductivity of liquid water. With two exceptions [217, 488], experimental results show that the thermal conductivity of water increases with increasing temperature from the normal melting point to the normal boiling point and reaches a maximum near 400 K. Beyond this temperature the thermal conductivity first decreases gradually and at a faster rate near the critical point. The extensive results of Timrot - Vargaftik [339] and Schmidt - Sellschopp [494] have long been considered to be most reliable and were cited in review papers [258, 465, 498, 520] and many handbooks. Subsequently, more careful measurements were reported by Powell-Challoner [434, 480], Riedel [279, 485, 486, 487], Schmidt-Leidenfrost [301, 492, 493], Vargaftik-Oleshchuk [509, 510], Wright [518], and some other investigators. Furthermore, Powell [479] made a study and recommended the most probable values.

This analysis is divided into the following three parts:

(a) The supercooled state -- below the normal melting point.

There is only one set of data reported by Riedel [485], who extrapolated the values of various salt solutions to zero concentration, and covered temperatures down to 233.16 K. The reported values are exactly linear with temperature. However, his value at the normal melting point is about one percent higher than the most probable value of the normal state at the same temperature. Therefore, Riedel' s data were adjusted by a parallel displacement and the final correlation formula is

$$10^6 k\ (\text{cgsu}) = 273.778 + 3.90000\ T \qquad (T \text{ in K}).$$

This equation should be valid in the temperature range from 233.16 to 273.16 K, and should be accurate within one percent. The recommended values from 250 to 265 K were calculated from this equation.

(b) The normal liquid state -- from the normal melting point to the thermal conductivity maxima.

Seven sets of data [279, 479, 480, 487, 493, 510, 518] were selected as the most reliable and were given equal weight. The correlation formula obtained is

$$10^6 k \text{ (cgsu)} = -1390.53 + 15.1937\ T - 0.0190398\ T^2 \text{ (T in K)}.$$

This equation should be valid between 273.16 and 413.16 K. It is found that this equation fits the above-mentioned data with a mean deviation of 0.24 percent and a maximum of 0.82 percent. This equation was used to generate the recommended values from 265 to 410 K.

(c) The higher vapor pressure state -- from near the thermal conductivity maxima up to the critical point.

The values of Vargaftik - Oleshchuk [509, 510] are considered to be more reliable than the older data of Timrot - Vargaftik [339]. Therefore, the weight given in this analysis is two to the former and one to the latter. The correlation formula obtained is

$$10^6 k \text{ (cgsu)} = -339.838 + 9.86669\ T - 0.0123045\ T^2 \qquad \text{(T in K)}.$$

This equation should be valid in the temperature range from 413.16 to 613.16 K, and is found to fit the experimental data of Vargaftik - Oleshchuk with a mean deviation of 0.39 percent and a maximum of 1.4 percent. No further extrapolation is recommended since the deviation becomes extremely large beyond 613.16 K. The tabulated values from 420 to 610 K are calculated from this formula.

For the sake of clarity, the departure curves are presented on three plots (Figure 32). The first plot consists of 16 sets of data up to 380 K. The second plot represents 26 other works in the same temperature range. The third plot depicts three sets of data at vapor pressures higher than one atm.

Seven sets of data [217, 450, 461, 471, 472, 473, 488] which yield departures greater than 10 percent, and older data [429, 430, 453, 454, 455, 456, 511, 512, 513, 514, 516] which were published in the 19th century, are not shown at all. The recommended values appear in Table 24.

TABLE 24. THERMAL CONDUCTIVITY OF A GROUP OF SELECTED LIQUIDS
(mw. $cm^{-1}K^{-1}$)

T (K)	Helium	Nitrogen	Argon	Carbon tetra-chloride	Diphenyl	m-Terphenyl	Toluene	Water
2.4	0.192							
2.6	0.193							
2.8	0.197							
3.0	0.204							
3.2	0.214							
3.4	0.227							
3.6	0.241							
3.8	0.260							
4.0	0.282							
4.2	0.307							
4.4	(0.335)‡							
4.6	(0.366)‡							
4.8	(0.400)‡							
5.0	(0.437)‡							
5.2	(0.477)‡							
60		1.692†						
65		1.598						
70		1.504						
75		1.411						
80		1.320‡	1.315†					
85		1.229‡	1.258					
90		1.140‡	1.200‡					
95		1.051‡	1.141‡					
100		0.965‡	1.082‡					
105		0.879‡	1.023‡					
110		0.794‡	0.963‡					
115		0.710‡	0.903‡					
120		0.627‡	0.842‡					
125		0.544‡	0.780‡					
130			0.717‡					
135			0.654‡					
140			0.591‡					
145			0.527‡					
150			0.463‡				(1.719)†	
160							(1.694)†	
170							(1.669)†	
180							1.644	
190							1.619	
200							1.594	
210							1.569	
220							1.543	
230				(1.169)†			1.518	
240				(1.150)†			1.492	
250				1.131			1.467	5.22†
260				1.112			1.442	5.39†
270				1.093			1.416	5.55†
280				1.074			1.391	5.74
290				1.055			1.365	5.92
300				1.036			1.340	6.09
310				1.017			1.315	6.23
320				0.997			1.289	6.37
330				0.978	(1.402)†		1.264	6.48
340				0.959	(1.387)†		1.238	6.59
350				0.940	1.373	(1.361)†	1.213	6.68
360				(0.921)	1.359	(1.356)†	1.188	6.75
370				(0.902)	1.345	1.351	1.162	6.80
380				(0.882)	1.331	1.346	1.137	6.84‡
390				(0.863)	1.316	1.341	(1.112)‡	6.86‡

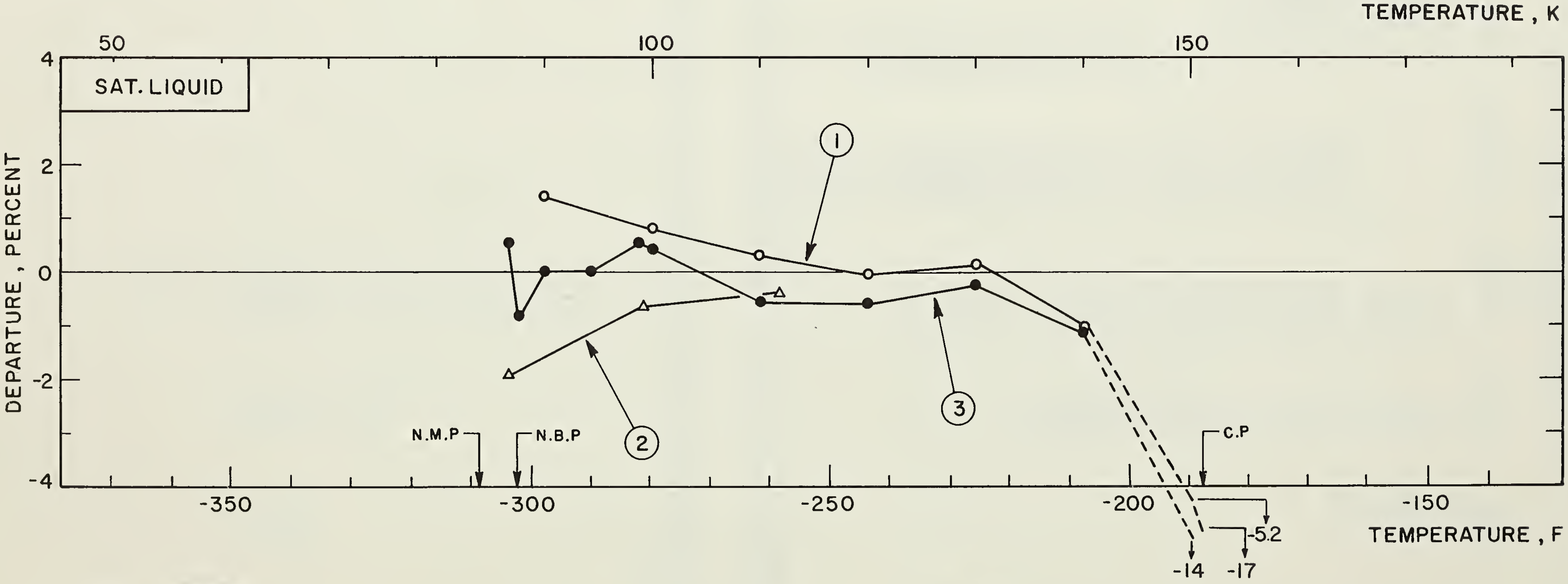
TABLE 24. THERMAL CONDUCTIVITY OF A GROUP OF SELECTED LIQUIDS (mw. cm^{-1}K^{-1}) (continued)

T (K)	Carbon tetra-chloride	Diphenyl	m-Terphenyl	p-Terphenyl	Toluene	Water
400	(0.844)	1.302	1.335		(1.086)[‡]	6.86[‡]
410	(0.825)	1.288	1.329		(1.061)[‡]	6.86[‡]
420	(0.806)	1.274	1.323		(1.036)[‡]	6.84[‡]
430	(0.787)	1.259	1.317		(1.013)[‡]	6.81[‡]
440	(0.768)	1.245	1.310		(0.985)[‡]	6.78[‡]
450	(0.749)	1.231	1.304	1.320[†]	(0.959)[‡]	6.73[‡]
460		1.217	1.297	1.310[†]	(0.933)[‡]	6.67[‡]
470		1.202	1.290	1.300[†]	(0.908)[‡]	6.61[‡]
480		1.188	1.283	1.289[†]	(0.885)[‡]	6.53[‡]
490		1.174	1.276	1.278	(0.862)[‡]	6.45[‡]
500		1.160	1.268	1.267	(0.839)[‡]	6.35[‡]
510		1.146	1.261	1.256		6.24[‡]
520		1.131	1.254	1.244		6.12[‡]
530		1.117[‡]	1.246	1.232		5.99[‡]
540		1.103[‡]	1.238	1.220		5.86[‡]
550		1.089[‡]	1.230	1.208		5.71[‡]
560		1.074[‡]	1.222	1.196		5.55[‡]
570		1.060[‡]	1.213	1.184		5.39[‡]
580		1.046[‡]	1.205	1.172		5.20[‡]
590		1.032[‡]	1.197	1.159		5.01[‡]
600		1.018[‡]	1.188	1.143		4.81[‡]
610			1.180	1.129		4.60[‡]
620			1.172	1.113		4.40[‡]
630			1.163	1.097		(4.20)[‡]
640			1.155[‡]	1.079		(4.01)[‡]
650			1.146[‡]	1.062		

[†] Extrapolated for the supercooled liquid. [Approximate n. m. p. in K: N_2, 63; A, 84; CCl_4, 250; $C_{12}H_{10}$, 342; m-$C_{18}H_{14}$, 361; p-$C_{18}H_{14}$, 486; C_7H_{10}, 178; H_2O, 273.1].

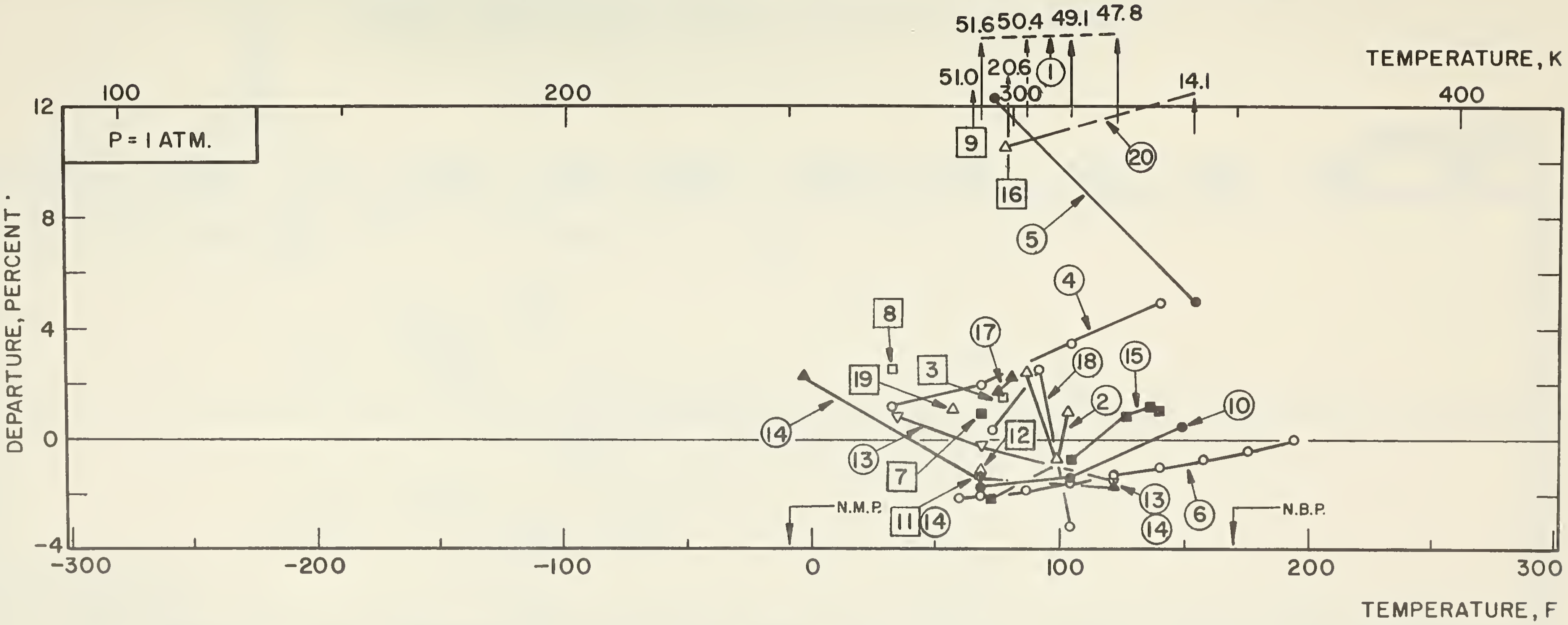
[‡] Under saturation vapor pressure [Approximate n.b.p. in K: He, 4.3; N_2, 77; A, 88; CCl_4, 350; $C_{12}H_{10}$, 528; m-$C_{18}H_{14}$, 637; p-$C_{18}H_{14}$, 658; C_7H_{10}, 384; H_2O, 373].

FIGURE 24. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID ARGON



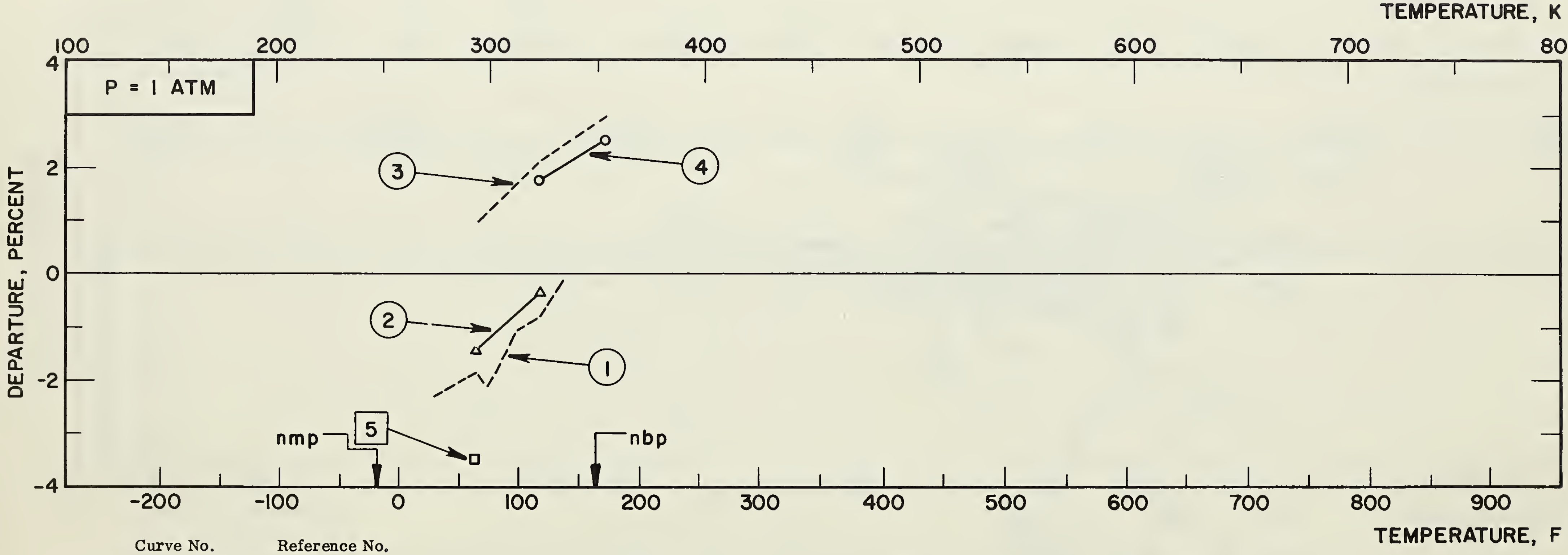
Curve	Reference
1	57, 413
2	192
3	353

FIGURE 25. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID CARBON TETRACHLORIDE



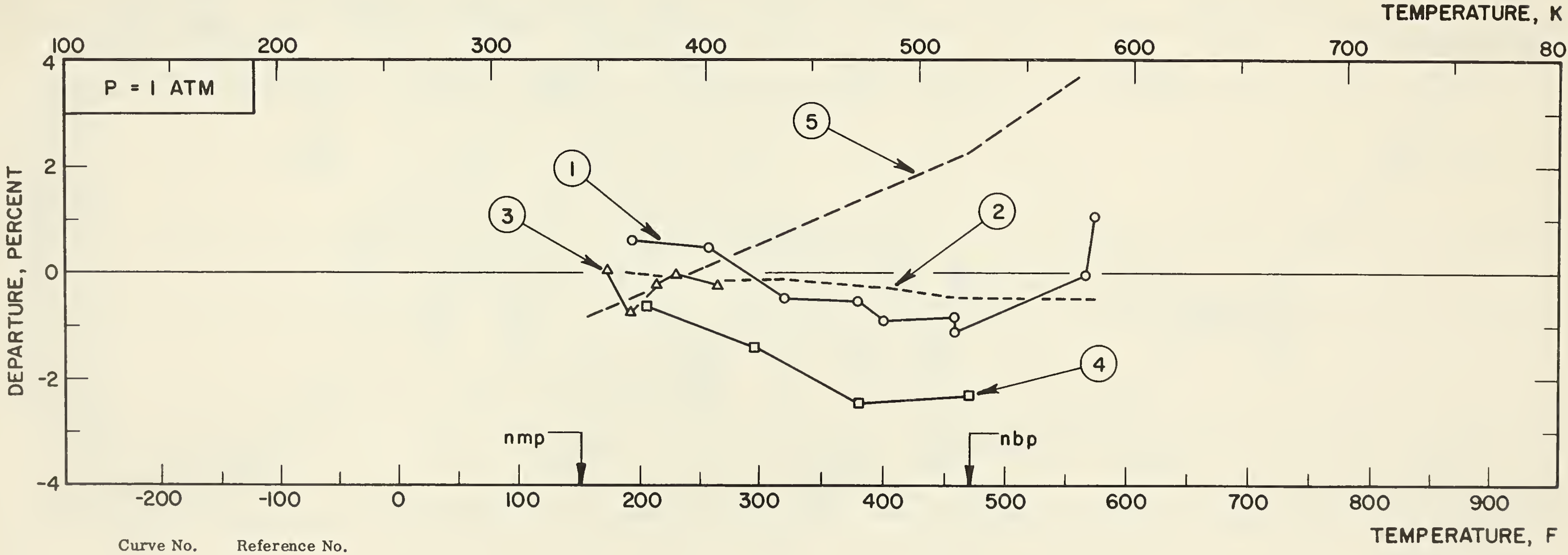
Curve	Reference	Curve	Reference
1	427	11	483
2	29	12	484
3	433	13	279
4	434	14	486
5	437	15	492
6	442	16	497
7	447, 448	17	503
8	450	18	504, 505
9	458	19	507
10	475	20	517

FIGURE 25. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID CARBON TETRACHLORIDE (continued)



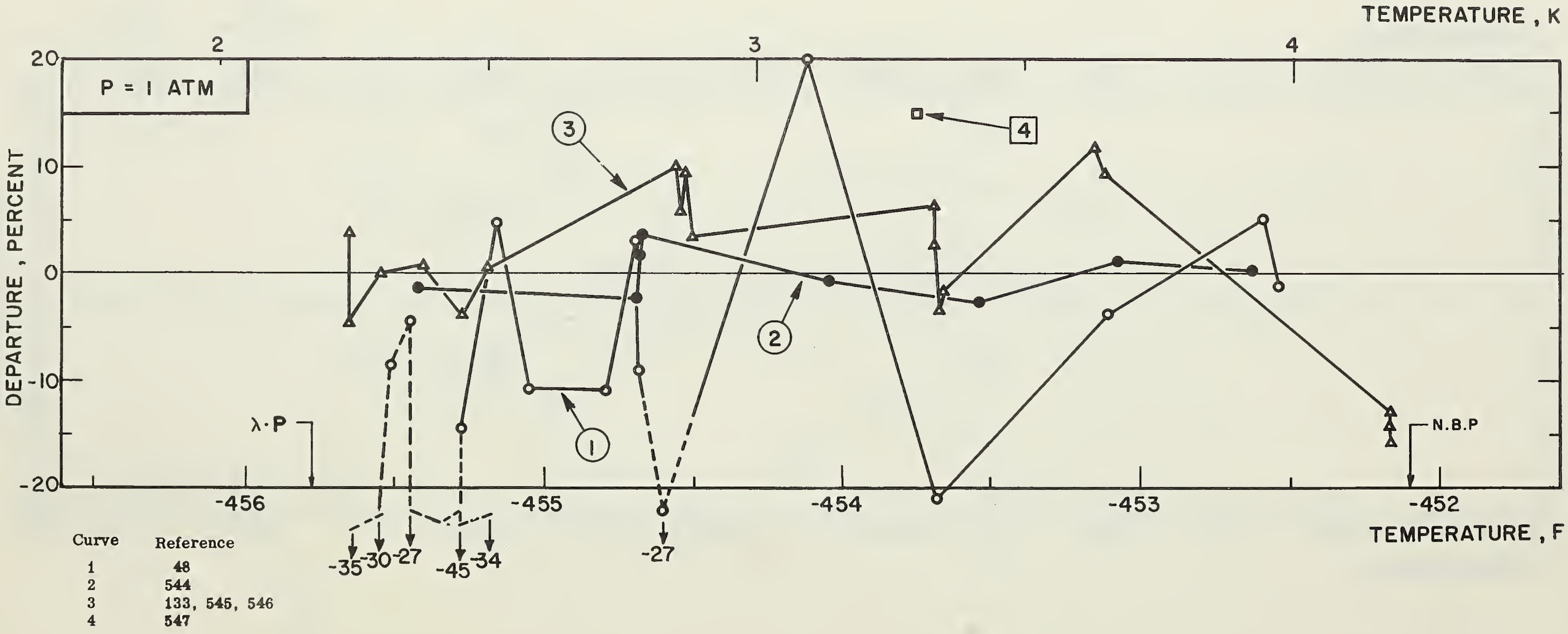
Curve No.	Reference No.
1	632
2	633
3	634
4	634
5	635

FIGURE 26. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID DIPHENYL



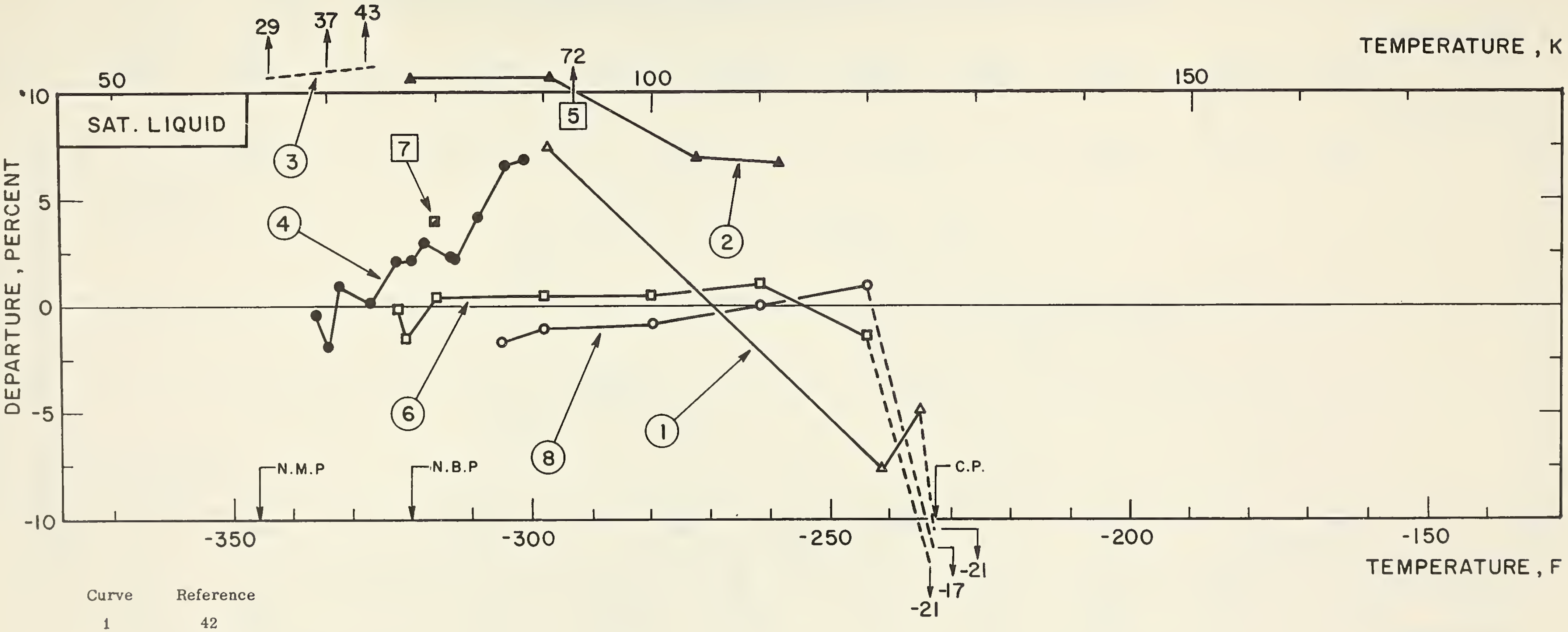
Curve No.	Reference No.
1	638
2	636, 638
3	637
4	639
5	640

FIGURE 27. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID HELIUM



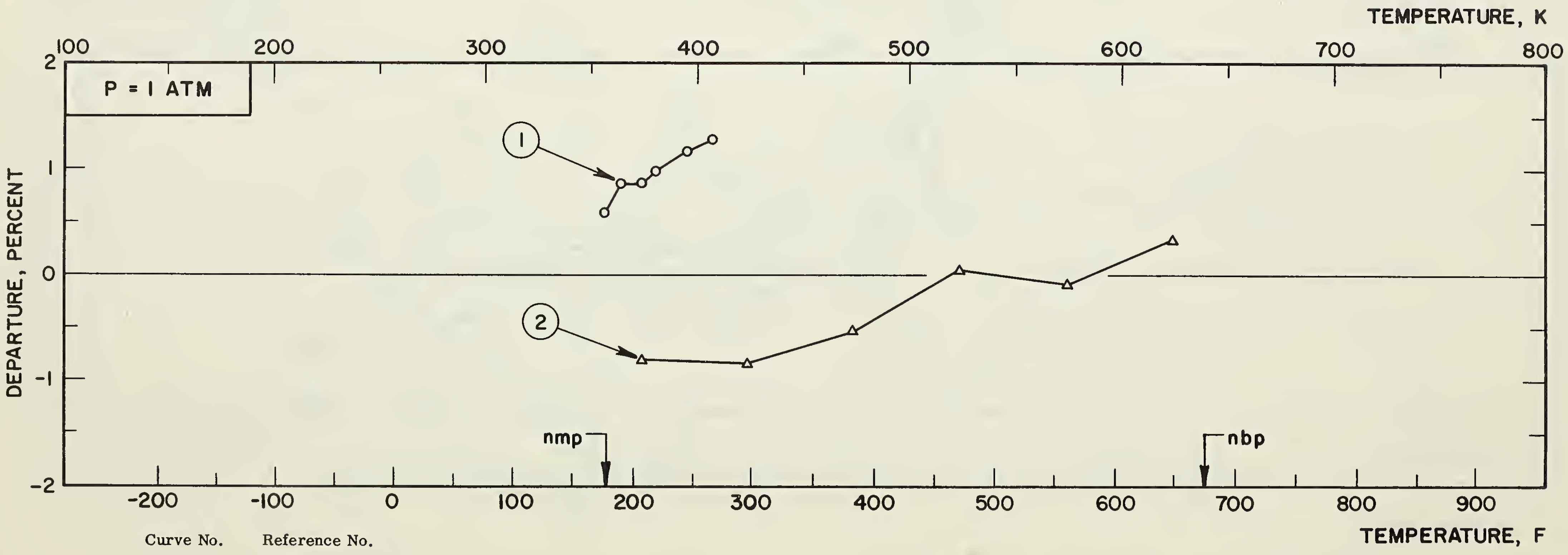
Curve	Reference
1	48
2	544
3	133, 545, 546
4	547

FIGURE 28. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID NITROGEN



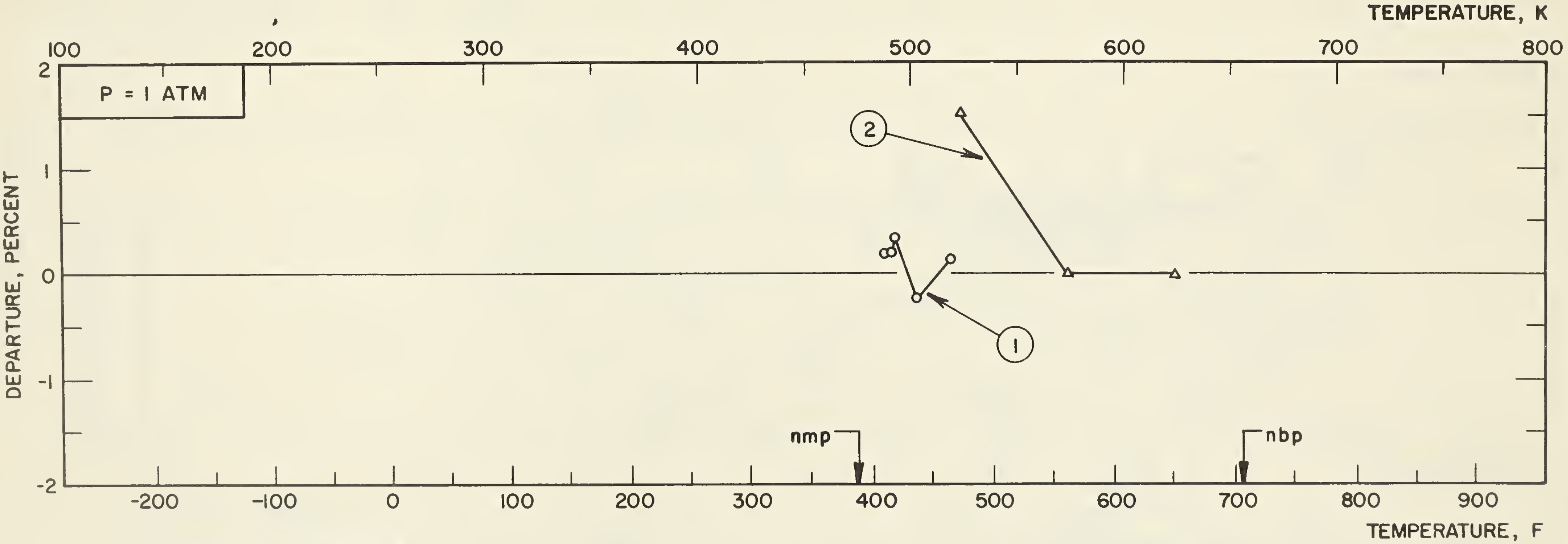
Curve	Reference
1	42
2	46
3	139
4	276, 531
5	535
6	353
7	412
8	57, 413

FIGURE 29. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID m-TERPHENYL



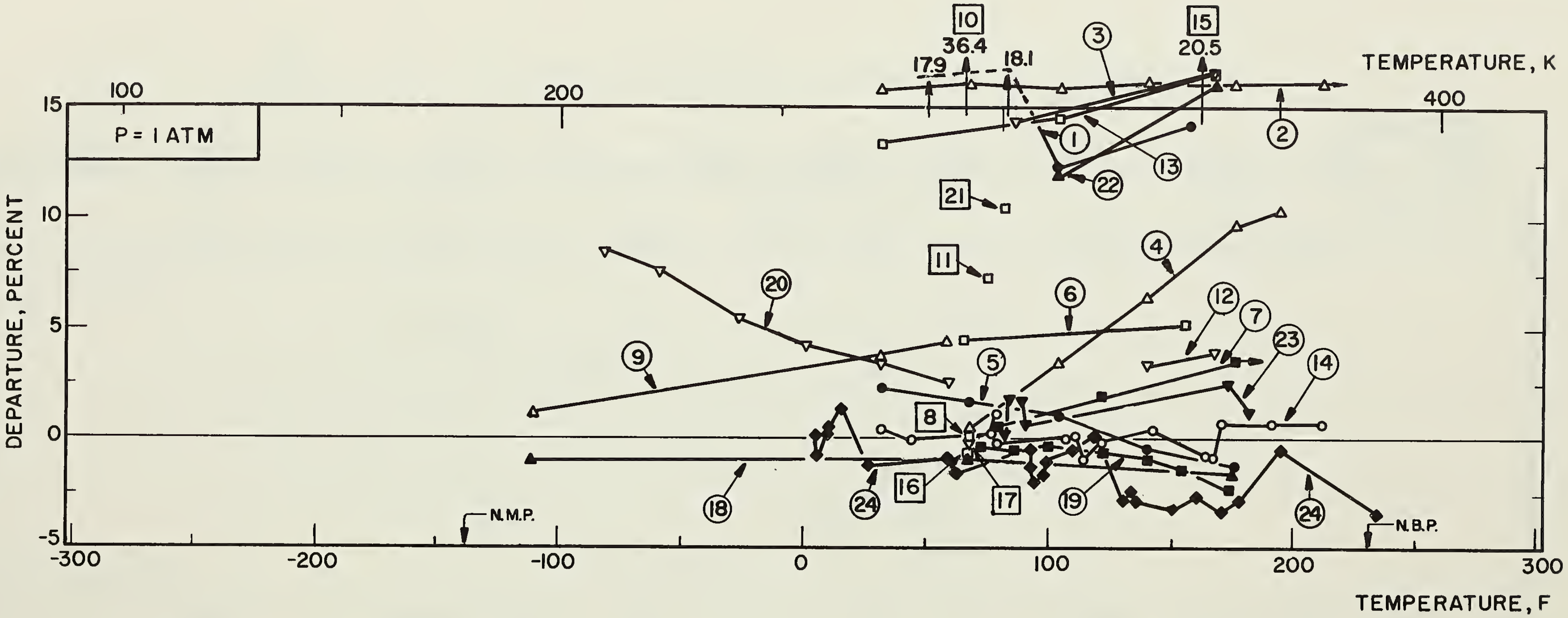
Curve No.	Reference No.
1	637
2	639

FIGURE 30. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID p-TERPHENYL



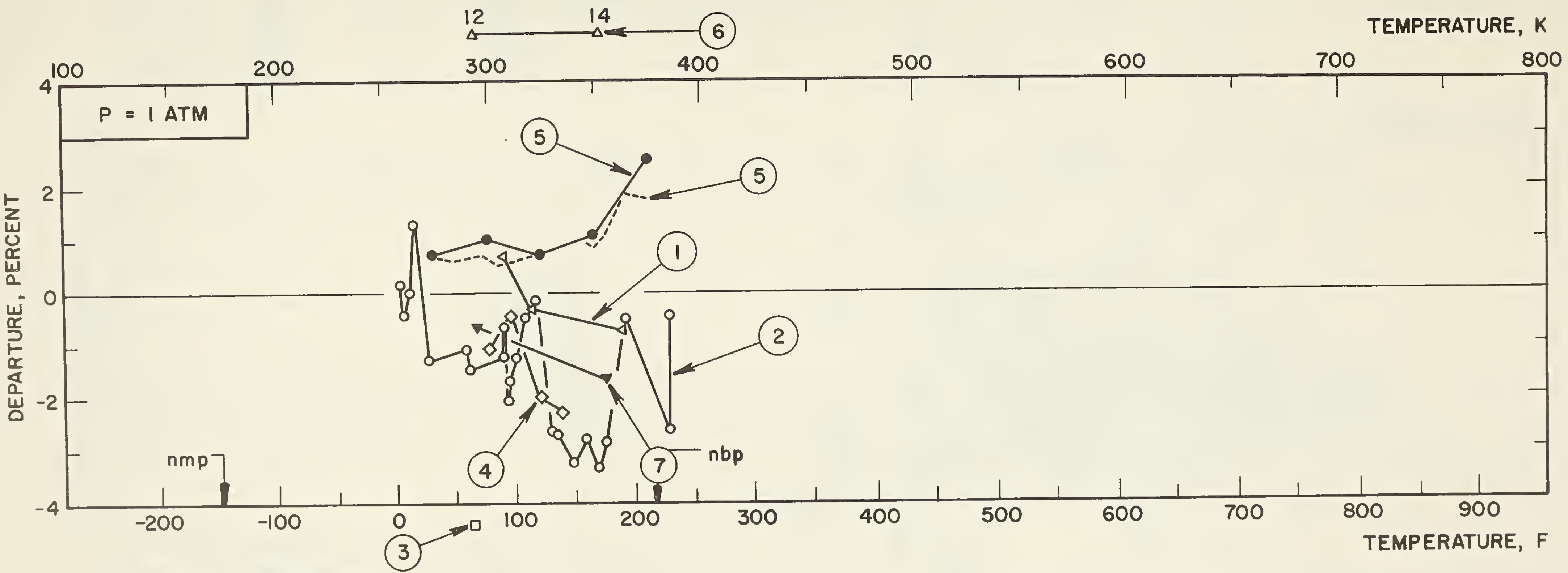
Curve No.	Reference No.
1	637
2	639

FIGURE 31. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID TOLUENE



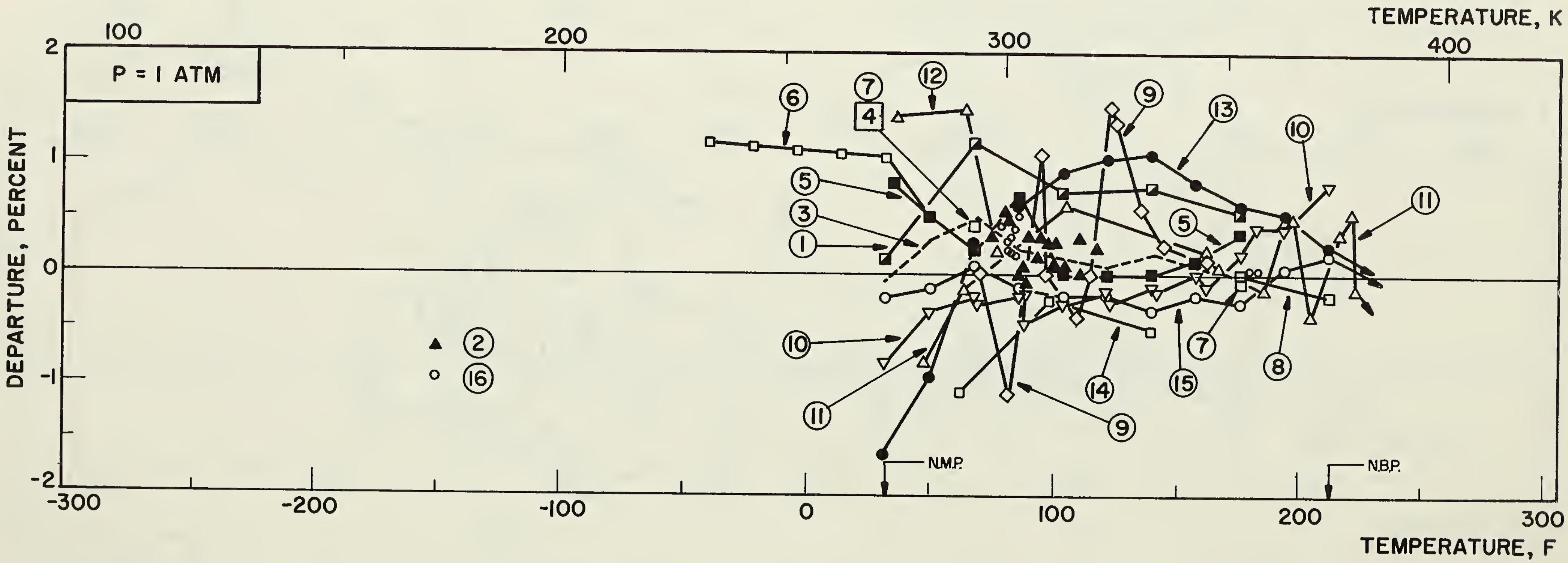
Curve	Reference	Curve	Reference
1	1	13	238
2	2	14	478
3	431	15	482
4	432	16	483
5	434	17	484
6	437	18	486
7	100, 441	19	492
8	447, 448	20	495
9	450	21	497
10	460	22	500
11	462, 463	23	508
12	471	24	519

FIGURE 31. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID TOLUENE (continued)



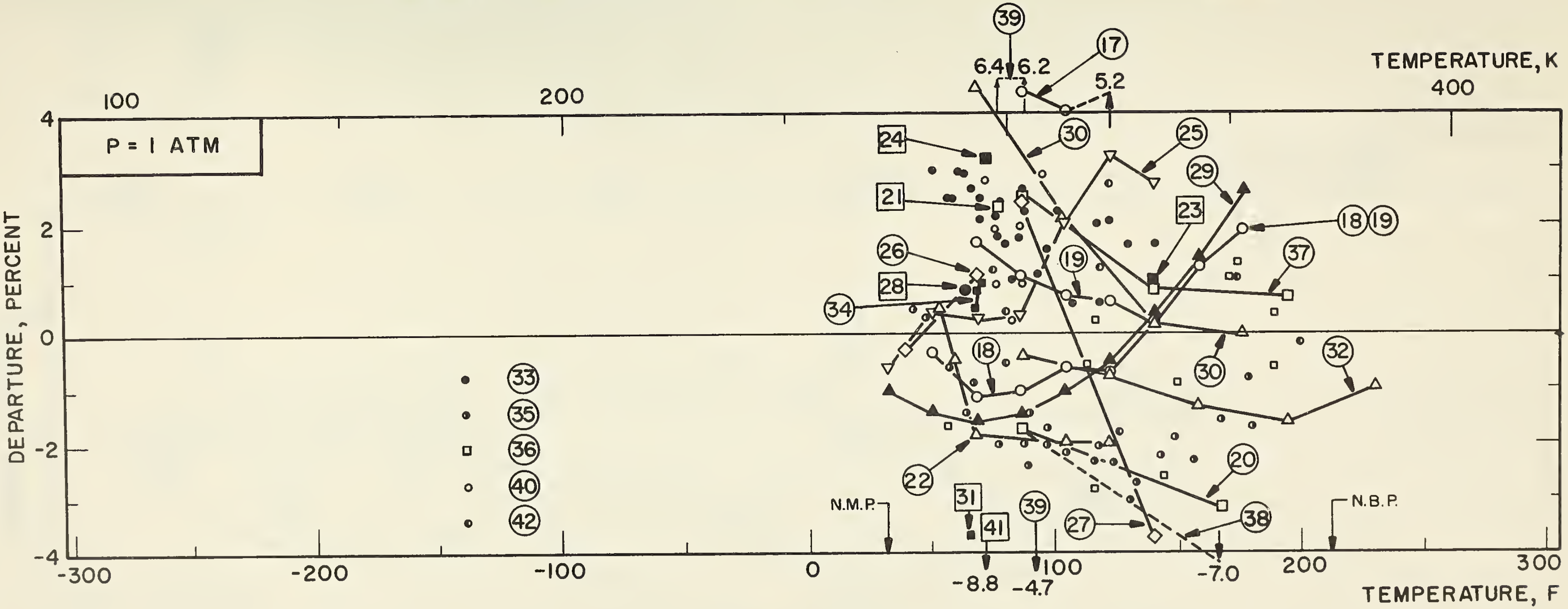
Curve No.	Reference No.
1	638
2	641
3	643
4	637
5	632
6	633
7	642

FIGURE 32. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID WATER (A)



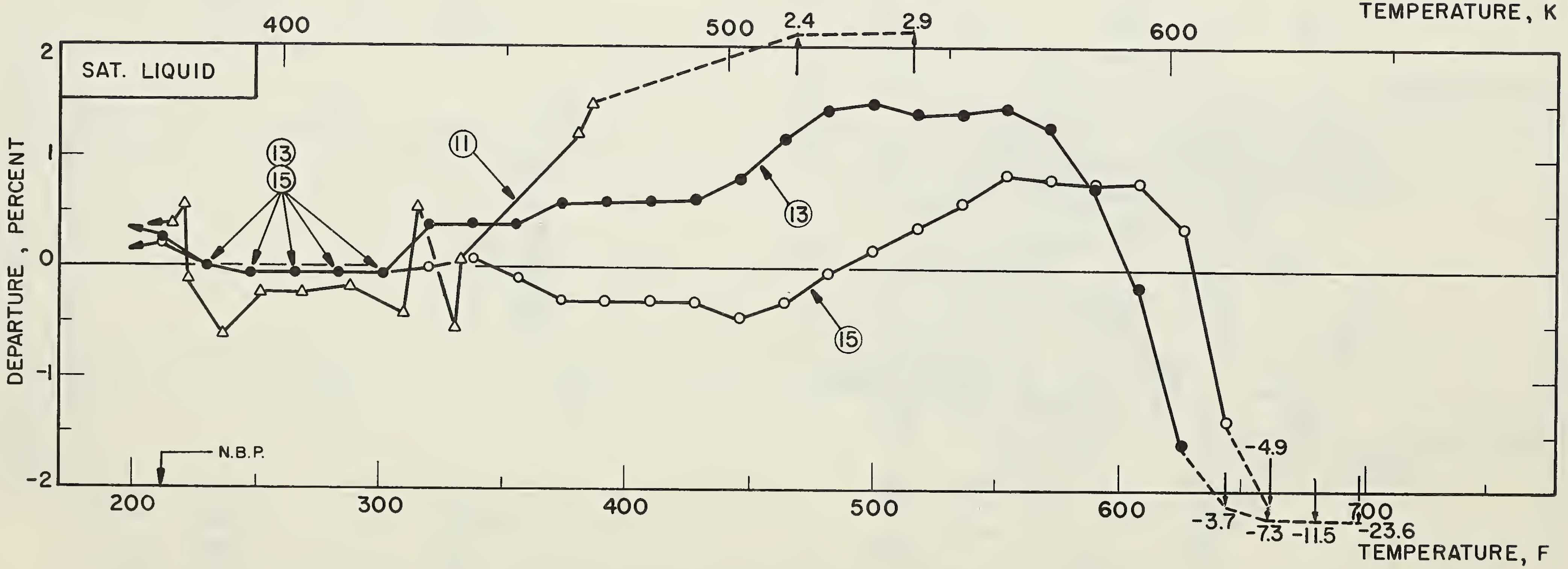
Curve	Reference	Curve	Reference
1	434	9	301, 492
2	480	10	493
3	479	11	494
4	483	12	495
5	279	13	339
6	485	14	507
7	486	15	509, 510
8	487	16	518

FIGURE 32. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID WATER (B) (continued)



Curve	Reference	Curve	Reference
17	424	30	464
18	425, 426	31	469
19	428	32	470
20	431	33	474
21	433	34	476
22	438	35	477
23	439	36	478
24	443	37	499
25	444, 445, 446	38	500
26	449	39	502
27	457	40	503
28	458	41	515
29	459, 460	42	517

FIGURE 32. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF LIQUID WATER (C) (continued)



Curve	Reference
11	494
13	339
15	509, 510

PART IV

THERMAL CONDUCTIVITY OF GASES

PART IV - THERMAL CONDUCTIVITY OF GASES

A. Introduction

Recent developments have resulted in more accurate experimental and theoretical methods of determining the conductivity of gases at high temperatures. Despite such developments, the reliability of the data is still, in some cases, doubtful. In the analyses which follow, preference has been given to experimental data over theoretical or, where only theoretical values exist, to those which are derived from the most reliable basis.

B. Thermal Conductivity of a Group of Selected Gases

Argon

Experimental measurements have been reported for the thermal conductivity of gaseous argon for temperatures between about 90 and 1373 K and many correlations and calculations have appeared, the more recent extending to temperatures will above 15, 000 K. At atmospheric pressure, the ionization is of the order of one, five and ten percent at temperatures of 9400, 10, 900 and 11, 750 K, respectively. Hence, the tabulation of recommended values only extends to 10, 000 K so that these values may, without serious error, be said to refer to neutral argon.

As shown by the departure plots (Figure 33)*, most experimental, correlated and calculated values are in reasonable accord and the accuracy of the recommended values of Table 25, 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 between 1500 and 10, 000 K.

Carbon Tetrachloride

Surprisingly few experimental measurements of the thermal conductivity of gaseous carbon tetrachloride appear to have been made. The most recent data are those of Masia and co-workers [571, 578] and earlier measurements were made by Eucken [97] and Moser [51, 254, 416]. Two correlations have appeared by Lenoir [223] and Vargaftik [601, 602] in addition to several nomograms which were not considered in this analysis.

As will be noted from the departure plot (Figure 34) a five percent difference exists between the Masia and Moser values. The Lenoir correlation, given without source references, was evidently based on the Moser data while that of Vargaftik evidently considered only the Eucken and Moser data. The recommended values here presented in Table 26 were based on the Eucken and Masia data for temperatures from 273 to 373 K and the trend for higher temperatures was adjusted to approach the Vargaftik value at about 573 K.

In view of the disagreement between the Masia and Moser data, the tabulation of recommended values only extends from 250 to 500 K and the values must be regarded as only being accurate to five percent. If further experimentation shows the Masia data to be accurate, this error estimate can be reduced to one or two percent.

Diphenyl

The only information available to TPRC concerning the thermal conductivity of gaseous diphenyl is contained in an AEC Report by Ellard et al. [644]. These workers tabulate values from 340 to 820 K without information as to the source. The values of Table 27 are the result of smoothing the above table. No departure plot is given due to the complete absence of other source information and the values must be considered definitely provisional until such time when experimental data becomes known.

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* Reference numbers used in Parts III and IV of this report refer to the section of References in Volume II, Chapter 1 of TPRC Data Book.

Helium

Helium is one of the few gases where quantum effects become significant at low temperatures. In addition to the experimental data of Ubbink and deHaas [251] calculated values have been made for very low temperatures and the recommended values for such temperatures were deduced from a curve drawn through both calculated and experimental values. 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 the tabulation.

No experimental data were found below about 2 K and gaps exist between 4 to 14 K, 21 to 73 K and above 2000 K. Some discrepancies exist between the measurements of different workers. The trend of the Johnston and Grilly data [168] and some previous correlations [147, 187, 223, 521, 570, 630, 631] is to produce values lower than the Kannuluik and Carmen [173] data. The values were selected so as to agree with the higher temperature data of the latter workers. This selection agrees with the trend of the considerably higher temperature data of Blais and Mann [569] and of Petersen and Bonilla [628].

Certain conclusions can be reached concerning previous analyses. The calculated values of Amdur [10] and the recommended tables of Chelton and Mann [81] should be disregarded below 100 K. The tables of Lenoir [223] agree to within about one percent between 20 and 450 K while the NBS tables [147] only agree to the same accuracy between about 205 and 415 K.

Many correlations [147, 187, 223, 521, 630, 631] fail above about 600 K. Of the seventeen different values found in the literature for the thermal conductivity at the ice point (273. 15 K), thirteen agree to within two percent with the recommended value of this report. Further experimental measurements are desirable for temperatures below 100 K and above 600 K.

Below 100 K the recommended values of Table 28 should be accurate to within five percent, from 100 to 400 K the accuracy should be one percent, from 400 to 700 K five percent, from 700 to 2000 K ten percent and above 2000 K as much as twenty-five percent. The departure plots appear in Figure 35.

Nitrogen

Many experimental, theoretical and correlated sets of values are available for the thermal conductivity of gaseous nitrogen. In view of this fact, it is surprising that 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, for the Keyes [187] and NBS [146] correlations, 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 trend of the experimental and theoretical values differs. 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 for temperatures to 3500 K, at which temperature the reaction contribution of some two percent is less than the uncertainty in the recommended values. The recommended values can thus be considered as applying to both the equilibrium and the frozen gas.

The accuracy of the recommended values of Table 29 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. Further experiments are to be desired 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 about 4000 K and certainly for higher temperatures. The departure plots appear in Figure 36.

m-Terphenyl

No values have been found for the thermal conductivity of gaseous m-Terphenyl.

p-Terphenyl

No values have been found for the thermal conductivity of gaseous p-Terphenyl.

Toluene

Data on the thermal conductivity of gaseous toluene have been reported by Abas-Zade [2] for temperatures between 273 and 594 K. Examination of these data showed that between 373 and 573 K a linear variation of thermal conductivity with temperatures apparently occurs. The value quoted at the highest temperature appears anomalously high unless decomposition of the vapor occurred. In the preparation of the table of recommended values a smooth curve was drawn through the experimental points except for the value at 594 K. The recommended values of Table 30 were obtained from this curve which was assumed to be linear above 373 K. The trend of the data with temperature is in need of rechecking by new measurements. Provisionally, the accuracy can be assessed at two precent below 530 K and ten percent for the higher temperatures. The departure plot appears in Figure 37.

Water (Steam)

In preparing tables of recommended values for the thermal conductivity of water vapor a more complete collection of tabulations based upon correlating equations, etc., was made than usual. This was done because severe disagreement exists between different sets of data for this substance. Many users of tabulated values have been unaware of the primary data upon which their tables were based and of the fact that such primary data were subject to large errors. Recent measurements have shown that at least one set of primary data are in considerable error and hence also many tabulations.

Examination of the departure plots (Figure 38) reveals that there now exist a large number of experimental data which agree with the recommended values to within some three percent. In severe disagreement are the measurements of Keyes, reported by himself [187] and with Sandell [195]. These show a systematic trend with temperature in disagreement with others and also with more recent measurements and should be disregarded. A large number of tabulations have wholly or in part been based upon the Keyes data. Those of Lenoir [223], Keyes [187], Nusselt [263, see also 201], Keenan and Keyes [594], Jakob [593], van Iterson [592] and Grober and Erk [591], are unsatisfactory above about 373 K and only moderately accurate for the few cases [201, 223, 263, 594] where they extend to lower temperatures. In addition to the recommended values, the tabulations of Koch and Fritz [201], the recalulated values of Keyes and Sandell [360, 365, 366] and the Russian data cited by Keyes [596] are reasonably accurate for all temperatures as are those of Keyes and Vines [590] for temperatures above 420 K. Still in severe disagreement are the high temperature data of Geier and Schafer [587] and Vargaftik et al. [360, 365, 366]. For this reason, the tabulation of recommended values has been curtailed to 900 K.

The accuracy of the recommended values of Table 31 can be estimated as being within two percent from 320 to 700 K, and five percent from 250 to 310 K and 710 to 900 K. The uncertainty at the higher temperatures is produced by the problem of estimating the radiation error in the vapor. Due to the high boiling point of water as compared to most fluids, pressure effects are significant to higher temperatures than usual and hence influence the recommended values to about 600 K. More precise recommended values for temperatures below 600 K will require a detailed consideration to be made of the pressure effect and has thus limited the suggested accuracy to two percent rather than a closer tolerance. Further experimentation is to be desired for all temperatures and pressures so that the uncertainties due to pressure, radiation, and accomodation effects can be reduced.

TABLE 25. THERMAL CONDUCTIVITY OF GASEOUS ARGON (mw. cm^{-1} K^{-1})

T (K)	k	T (K)	k	T (K)	k
50	(0.0326)*	650	0.319	2500	0.815
60	(0.0392)*	660	0.322	2600	0.839
70	(0.0457)*	670	0.326	2700	0.864
80	(0.0522)*	680	0.329	2800	0.888
90	0.0587	690	0.333	2900	0.913
100	0.0652	700	0.336	3000	0.938
110	0.0716	710	0.339	3100	0.962
120	0.0779	720	0.343	3200	0.987
130	0.0839	730	0.346	3300	1.011
140	0.0898	740	0.349	3400	1.036
150	0.0957	750	0.353	3500	1.060
160	0.1016	760	0.356	3600	1.084
170	0.1074	770	0.359	3700	1.109
180	0.1131	780	0.362	3800	1.133
190	0.1188	790	0.366	3900	1.158
200	0.1244	800	0.369	4000	1.182
210	0.1300	810	0.372	4100	1.207
220	0.1355	820	0.375	4200	1.231
230	0.1409	830	0.378	4300	1.256
240	0.1462	840	0.381	4400	1.281
250	0.1515	850	0.384	4500	1.305
260	0.1567	860	0.387	4600	1.330
270	0.1619	870	0.390	4700	1.354
280	0.1671	880	0.393	4800	1.379
290	0.1722	890	0.396	4900	1.404
300	0.1772	900	0.398	5000	1.429
310	0.1822	910	0.401	5200	1.478
320	0.1871	920	0.404	5400	1.526
330	0.1919	930	0.407	5600	1.575
340	0.1966	940	0.410	5800	1.624
350	0.2013	950	0.413	6000	1.673
360	0.2059	960	0.416	6200	1.722
370	0.2103	970	0.418	6400	1.771
380	0.2147	980	0.421	6600	1.821
390	0.2190	990	0.424	6800	1.881
400	0.2233	1000	0.427	7000	1.950
410	0.2276	1050	0.441	7200	2.03
420	0.2318	1100	0.454	7400	2.12
430	0.2359	1150	0.468	7600	2.23
440	0.2400	1200	0.481	7800	2.35
450	0.2441	1250	0.495	8000	2.48
460	0.2481	1300	0.508	8200	2.63
470	0.2520	1350	0.521	8400	2.80
480	0.2559	1400	0.535	8600	2.99
490	0.2599	1450	0.548	8800	3.18
500	0.2638	1500	0.561	9000	3.39
510	0.268	1550	0.575	9200	3.61
520	0.272	1600	0.588	9400	3.83
530	0.276	1650	0.602	9600	4.07
540	0.280	1700	0.615	9800	4.31
550	0.283	1750	0.628	10000	4.56
560	0.287	1800	0.641		
570	0.290	1850	0.654		
580	0.294	1900	0.667		
590	0.297	1950	0.680		
600	0.301	2000	0.692		
610	0.305	2100	0.717		
620	0.308	2200	0.741		
630	0.311	2300	0.766		
640	0.315	2400	0.790		

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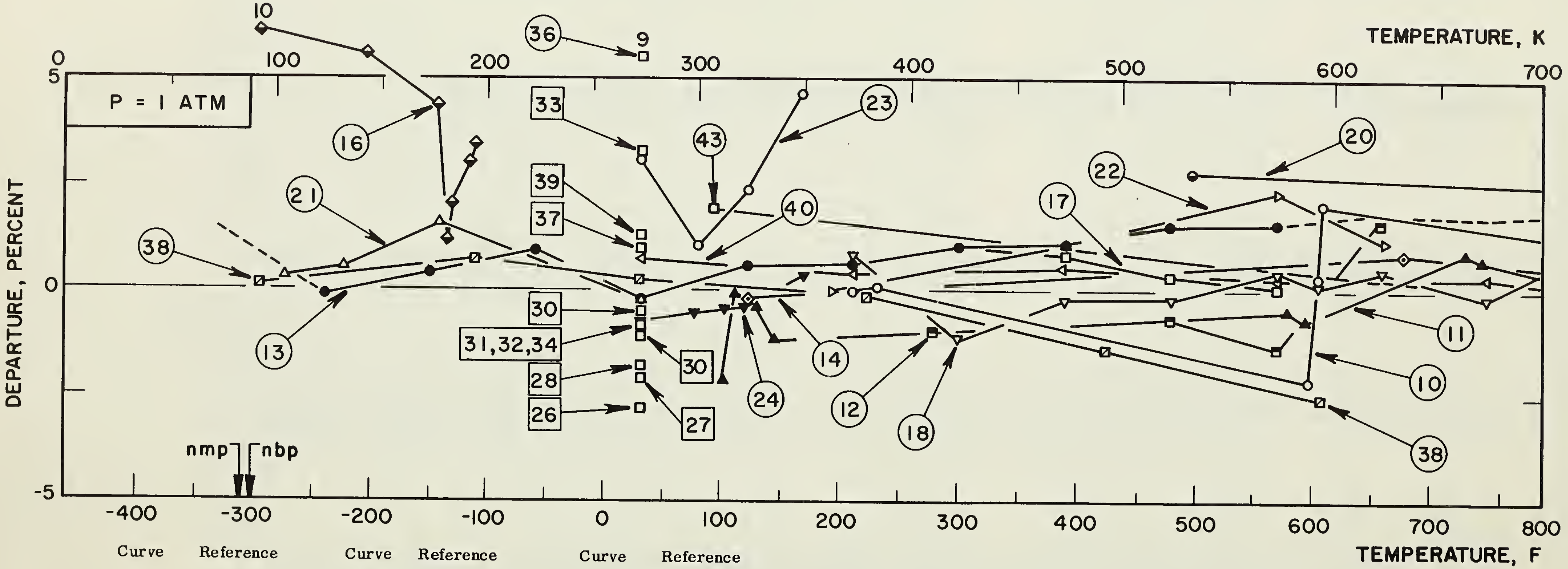
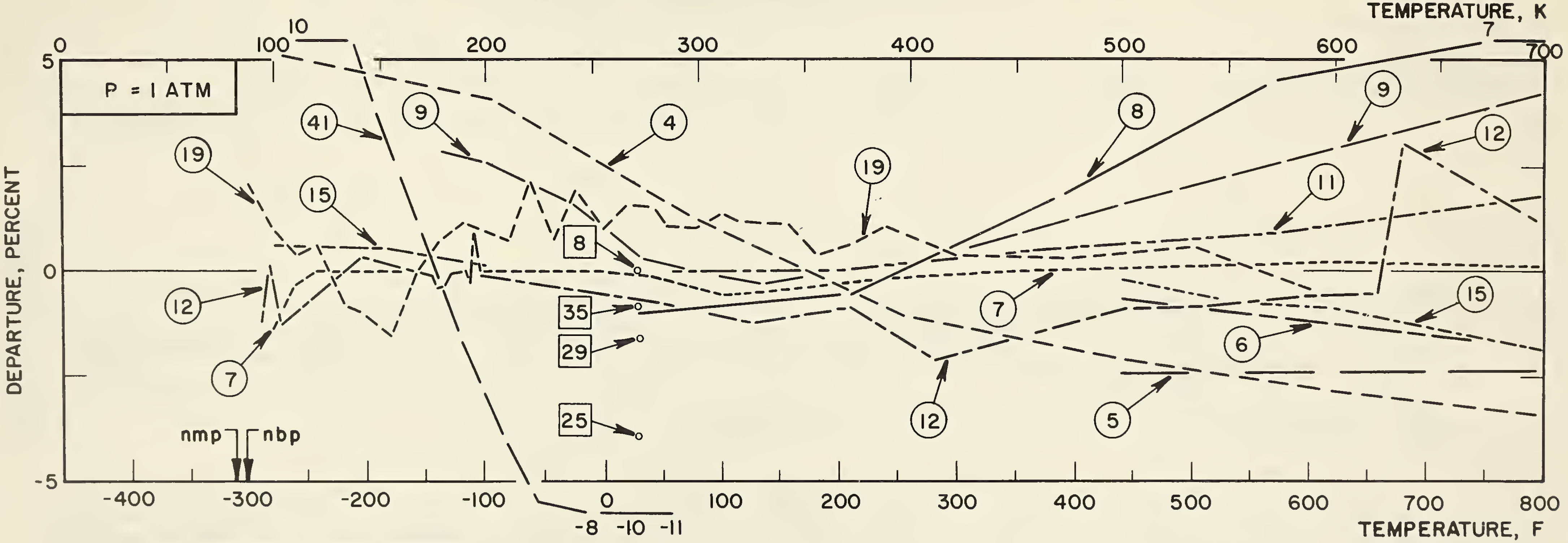
*Extrapolated

FIGURE 33 DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON



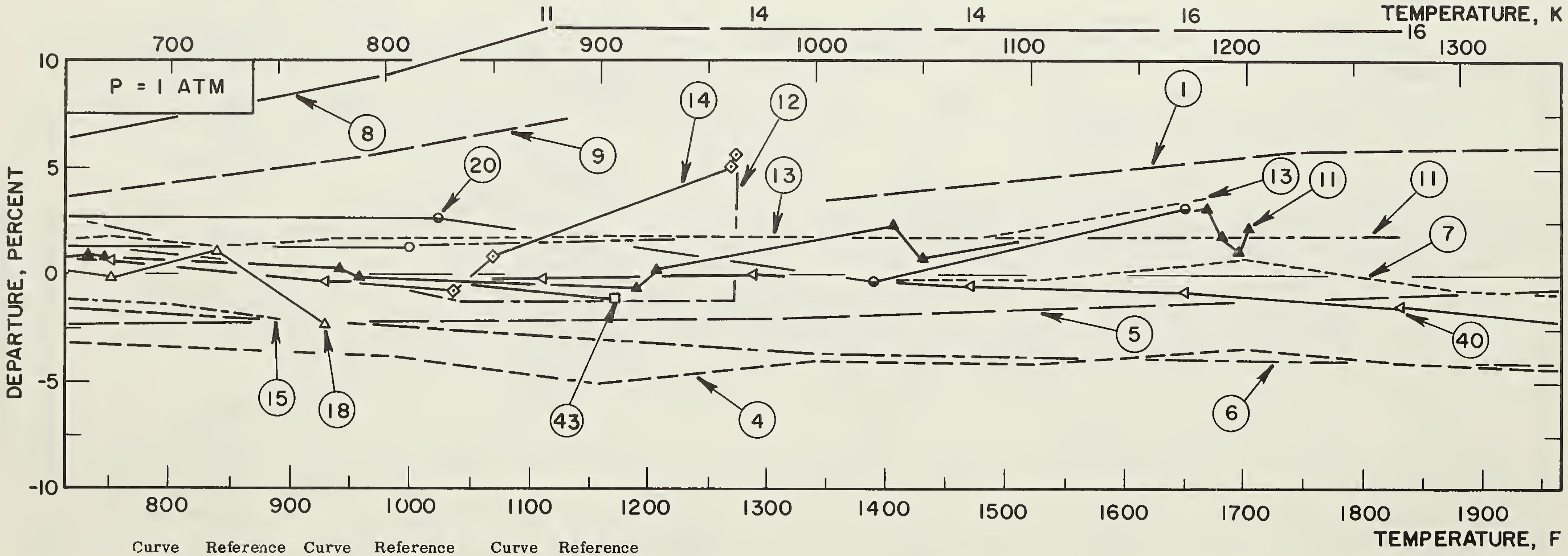
Curve	Reference	Curve	Reference	Curve	Reference
10	64, 65	21	192	32	96
11	617	22	191	33	81, 82
12	618	23	249	34	401
13	187	24	619	36	325
14	280, 281	26	177	37	174
16	412	27	379, 385	38	173
17	112	28	218	39	86
18	305	30	353	40	292, 293
20	369	31	156	43	628

FIGURE 33 DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



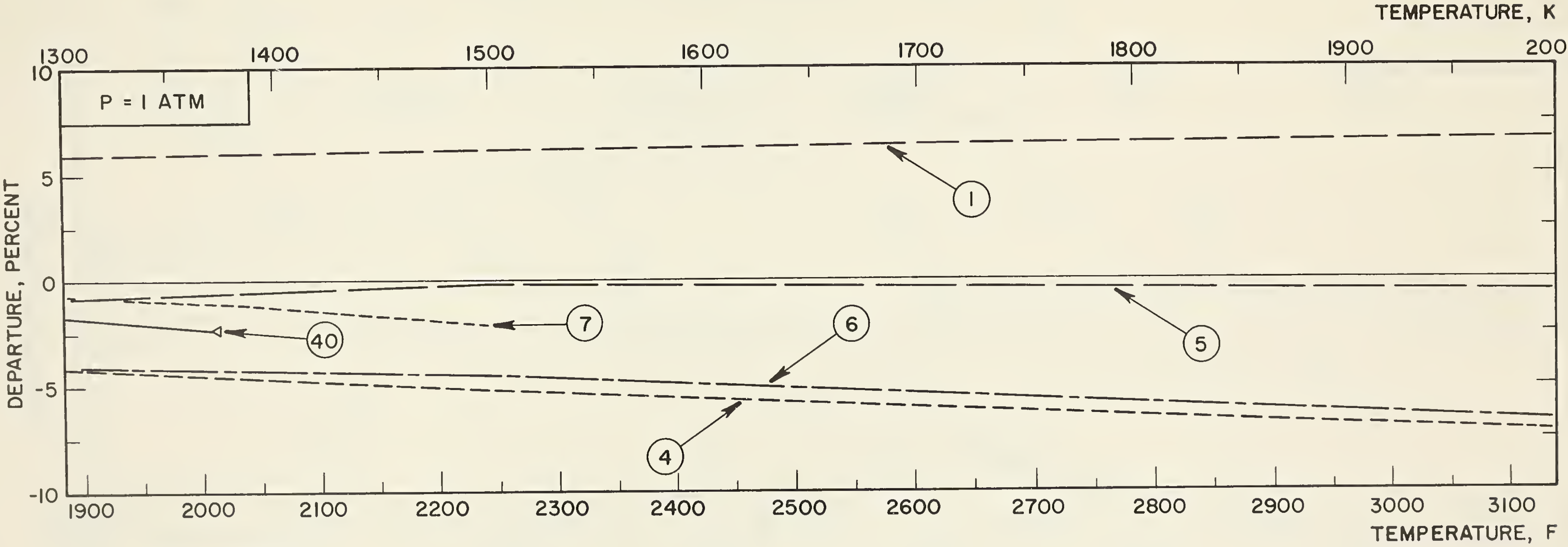
Curve	Reference	Curve	Reference
4	521	19	223
5	614	25	416
6	615	29	181
7	146, 147	35	97
8	616	41	11
9	603		
11	617		
12	618		
15	105		

FIGURE 33 DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



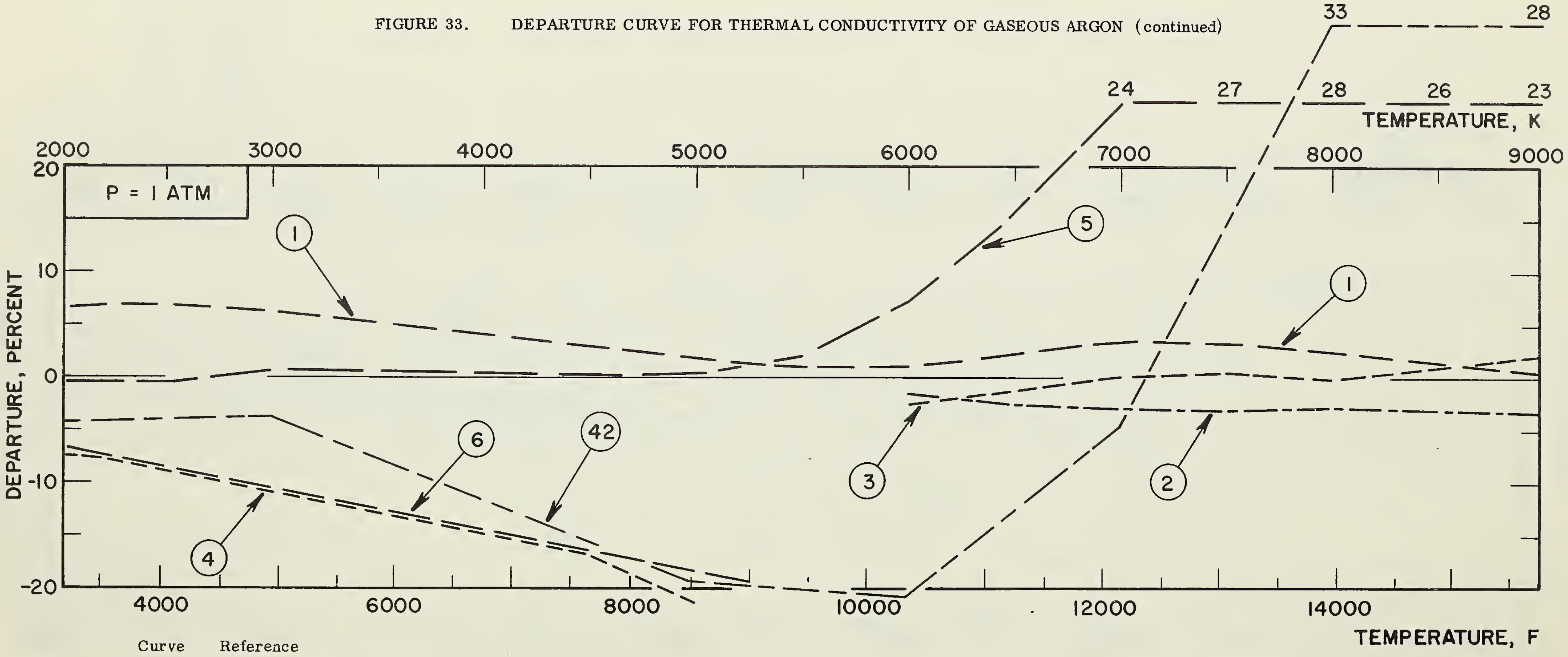
Curve	Reference	Curve	Reference	Curve	Reference
1	611	10	64, 65	40	292, 293
4	521	11	617	43	628
5	614	12	618		
5	615	13	187		
7	146	14	280, 281		
8	616	18	305		
9	603	20	369		

FIGURE 33. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



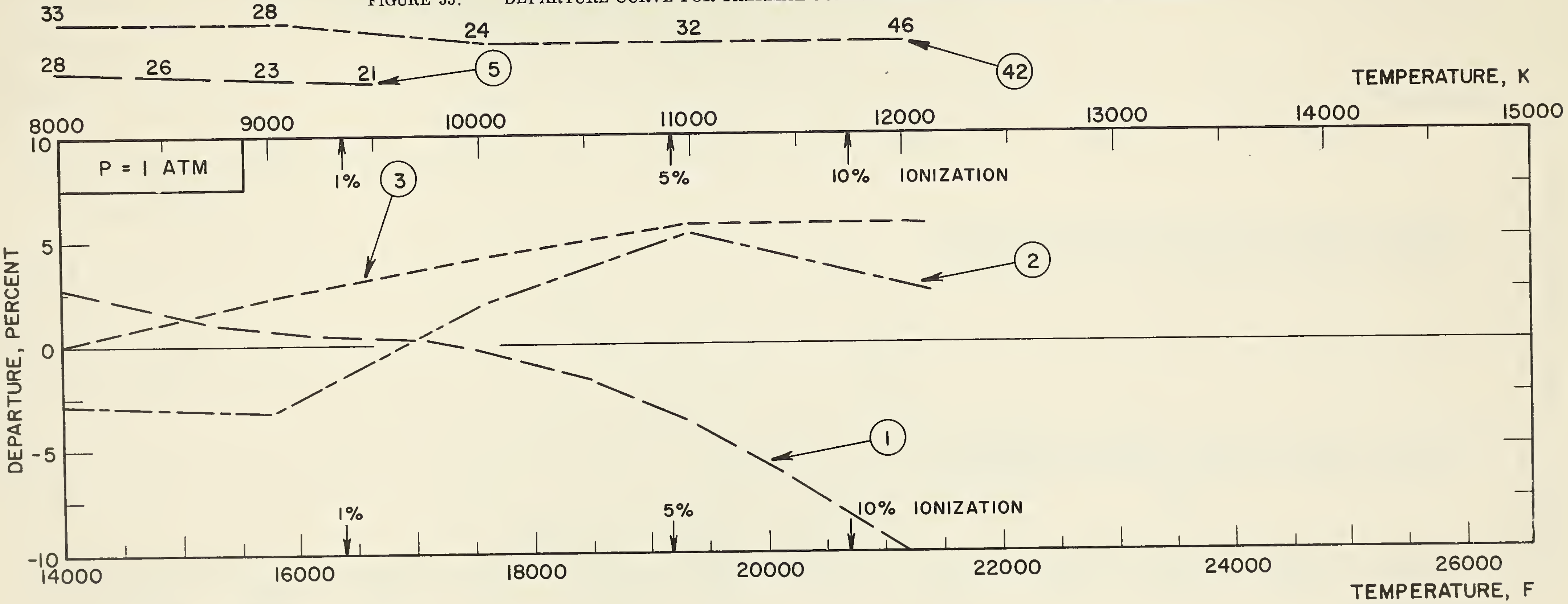
Curve	Reference
1	611
4	521
5	614
6	615
7	146
40	292, 293

FIGURE 33. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)



Curve	Reference
1	611
2	612
3	613
4	521
5	614
6	615
42	620

FIGURE 33. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS ARGON (continued)

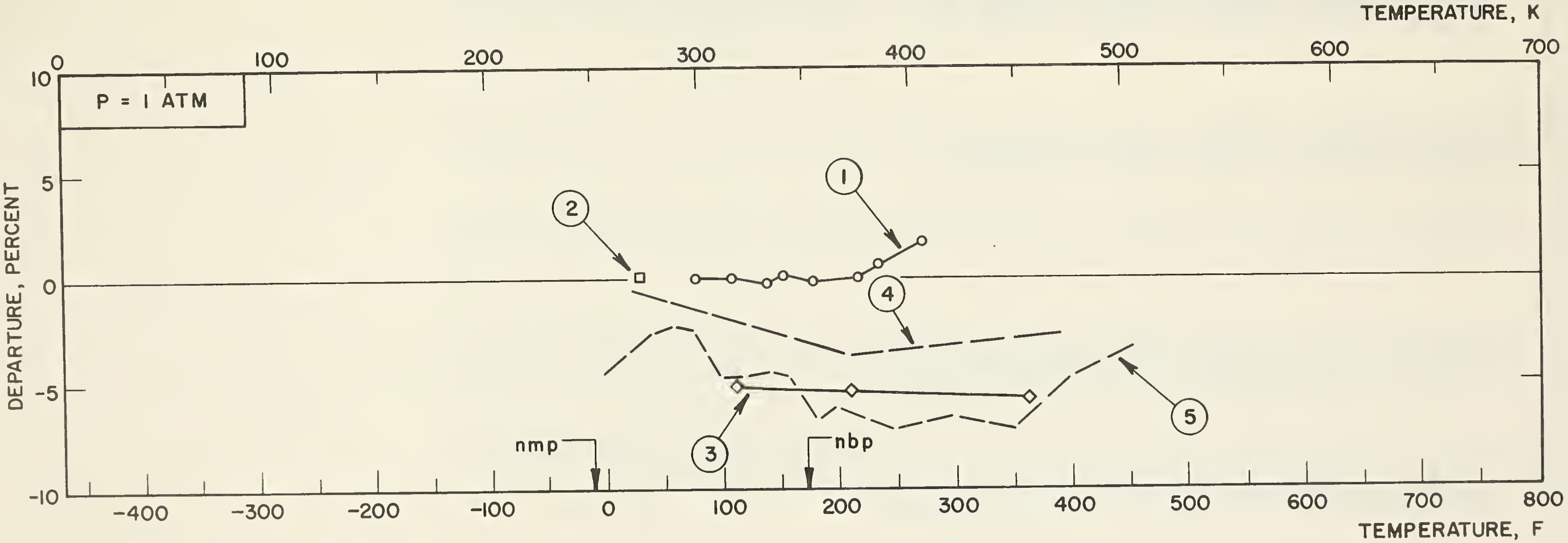


Curve	Reference
1	611
2	612
3	613
5	614
42	620

TABLE 26. THERMAL CONDUCTIVITY OF GASEOUS CARBON TETRACHLORIDE (mw. cm^{-1} K^{-1})

T (K)	k
250	0.0528
260	0.0555
270	0.0583
280	0.0612
290	0.0642
300	0.0673
310	0.0705
320	0.0738
330	0.0770
340	0.0803
350	0.0835
360	0.0866
370	0.0897
380	0.0928
390	0.0959
400	0.0989
410	0.1019
420	0.1049
430	0.1079
440	0.1108
450	0.1136
460	0.1163
470	0.1189
480	0.1214
490	0.1238
500	0.1261

FIGURE 34 DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS CARBON TETRACHLORIDE



Curve No.	Reference
1	571, 578
2	97
3	51, 254
4	601, 602
5	223

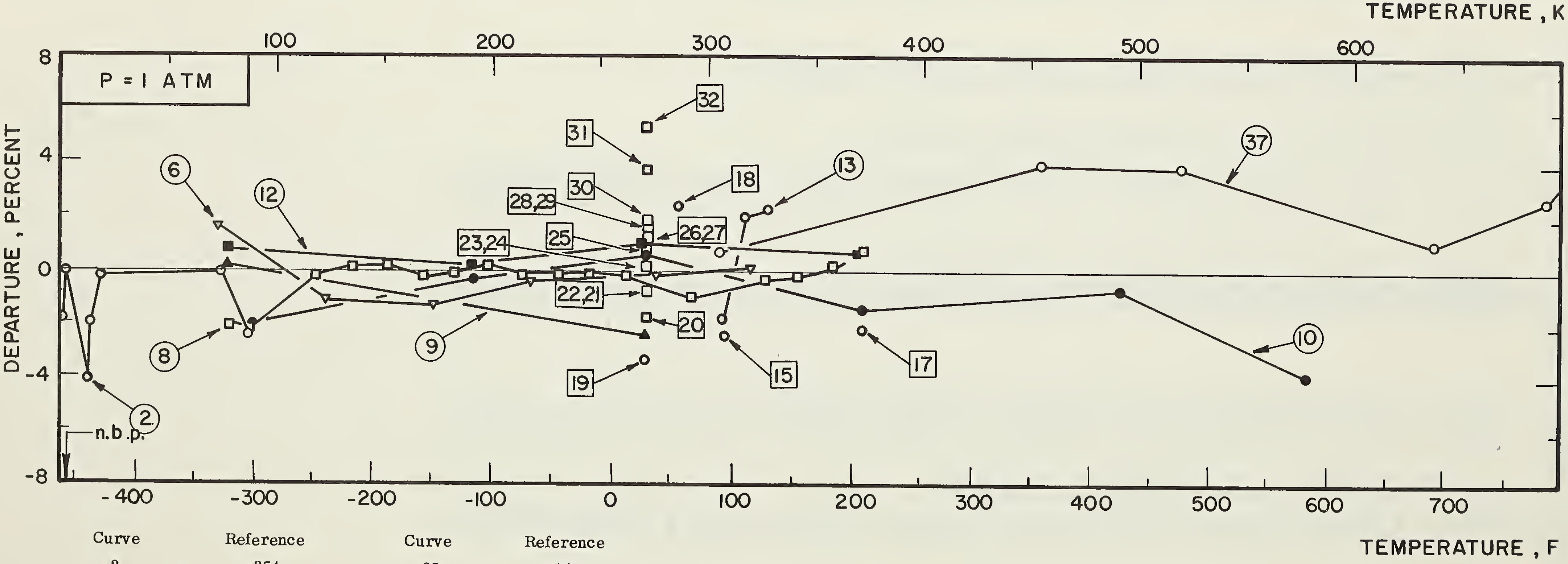
TABLE 27. THERMAL CONDUCTIVITY OF GASEOUS DIPHENYL (mw. cm^{-1} K^{-1})

T (K)	k	T (K)	k
300	0.075	600	0.304
310	0.082	610	0.312
320	0.089	620	0.321
330	0.095	630	0.330
340	0.102	640	0.338
350	0.109	650	0.347
360	0.116	660	0.356
370	0.123	670	0.364
380	0.130	680	0.373
390	0.137	690	0.382
400	0.144	700	0.391
410	0.151	710	0.400
420	0.159	720	0.408
430	0.166	730	0.418
440	0.173	740	0.426
450	0.181	750	0.436
460	0.188	760	0.445
470	0.196	770	0.454
480	0.203	780	0.463
490	0.211	790	0.472
500	0.220	800	0.481
510	0.228	810	0.490
520	0.236	820	0.499
530	0.244	830	0.508
540	0.253	840	0.518
550	0.261	850	0.527
560	0.269		
570	0.278		
580	0.287		
590	0.295		

TABLE 28. THERMAL CONDUCTIVITY OF GASEOUS HELIUM (mw. cm^{-1} K^{-1})

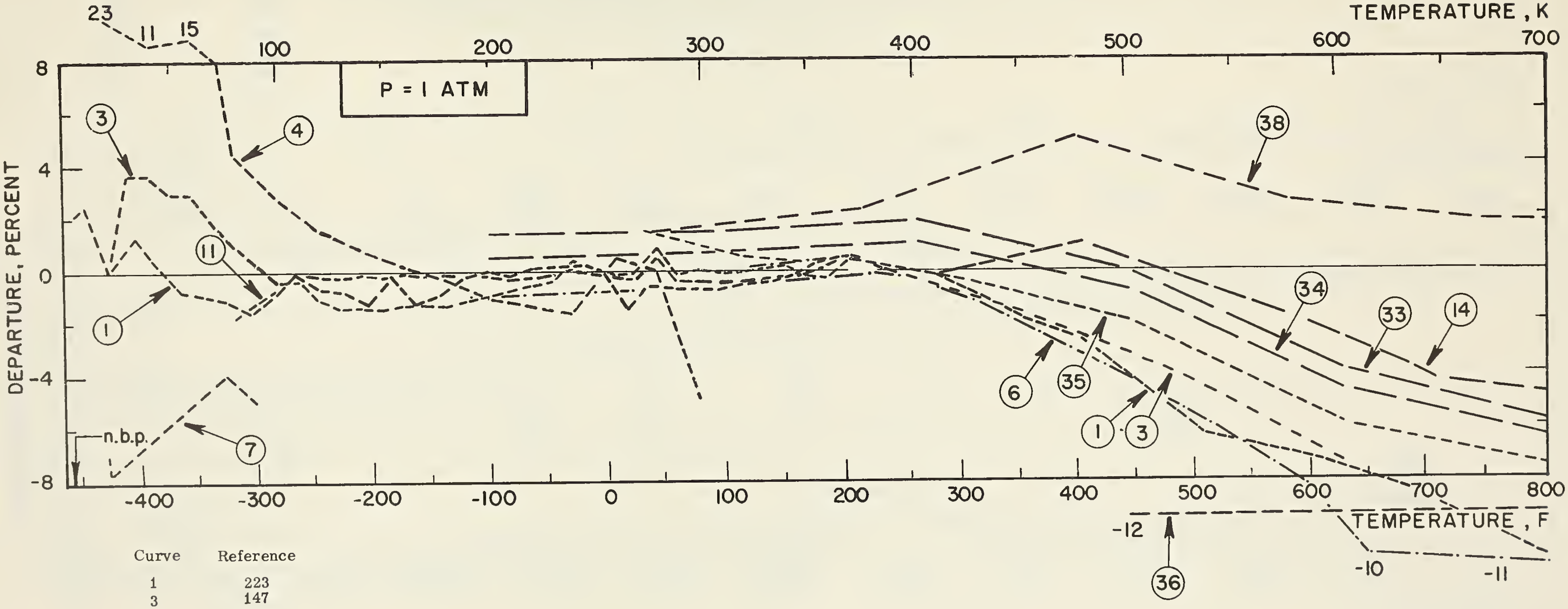
T (K)	k	T (K)	k	T (K)	k	T (K)	k
0.08	0.00044	150	0.950	650	2.64	1750	5.57
0.09	0.00053	160	0.992	660	2.67	1800	5.70
0.10	0.00064	170	1.033	670	2.69	1850	5.83
0.15	0.00130	180	1.072	680	2.72	1900	5.96
0.20	0.00231	190	1.112	690	2.75	1950	6.08
0.25	0.0039	200	1.151	700	2.78	2000	6.20
0.30	0.0062	210	1.190	710	2.81	2100	6.44
0.35	0.0089	220	1.228	720	2.84	2200	6.69
0.40	0.0120	230	1.266	730	2.87	2300	6.93
0.45	0.0154	240	1.304	740	2.90	2400	7.16
0.5	0.0187	250	1.338	750	2.92	2500	7.39
0.6	0.0231	260	1.372	760	2.95	2600	7.62
0.7	0.0252	270	1.405	770	2.98	2700	7.85
0.8	0.0262	280	1.437	780	3.01	2800	8.07
0.9	0.0266	290	1.468	790	3.04	2900	8.29
1.0	0.0269	300	1.499	800	3.07	3000	8.51
1.25	0.0281	310	1.530	810	3.09	3100	8.72
1.5	0.0306	320	1.560	820	3.12	3200	8.95
2.0	0.0393	330	1.590	830	3.15	3300	9.16
2.5	0.0502	340	1.619	840	3.18	3400	9.37
3.0	0.0607	350	1.649	850	3.21	3500	9.58
3.5	0.0732	360	1.678	860	3.23	3600	9.79
4.0	0.0803	370	1.708	870	3.26	3700	10.00
4.5	0.0879	380	1.737	880	3.29	3800	10.22
5.0	0.0962	390	1.766	890	3.32	3900	10.43
6	0.1113	400	1.795	900	3.35	4000	10.64
7	0.1247	410	1.824	910	3.37	4100	10.85
8	0.1393	420	1.853	920	3.40	4200	11.06
9	0.1523	430	1.882	930	3.43	4300	11.27
10	0.1640	440	1.914	940	3.46	4400	11.48
12	0.1866	450	1.947	950	3.49	4500	11.69
14	0.2067	460	1.980	960	3.52	4600	11.90
16	0.2259	470	2.013	970	3.54	4700	12.11
18	0.2435	480	2.046	980	3.57	4800	12.31
20	0.2582	490	2.080	990	3.60	4900	12.51
25	0.2962	500	2.114	1000	3.63	5000	12.71
30	0.3330	510	2.15	1050	3.76		
35	0.3669	520	2.18	1100	3.89		
40	0.4000	530	2.22	1150	4.03		
45	0.4314	540	2.25	1200	4.16		
50	0.4623	550	2.29	1250	4.29		
60	0.521	560	2.33	1300	4.43		
70	0.578	570	2.36	1350	4.55		
80	0.631	580	2.40	1400	4.69		
90	0.679	590	2.43	1450	4.82		
100	0.730	600	2.47	1500	4.94		
110	0.776	610	2.51	1550	5.07		
120	0.819	620	2.54	1600	5.21		
130	0.863	630	2.58	1650	5.33		
140	0.907	640	2.61	1700	5.45		

FIGURE 35. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM



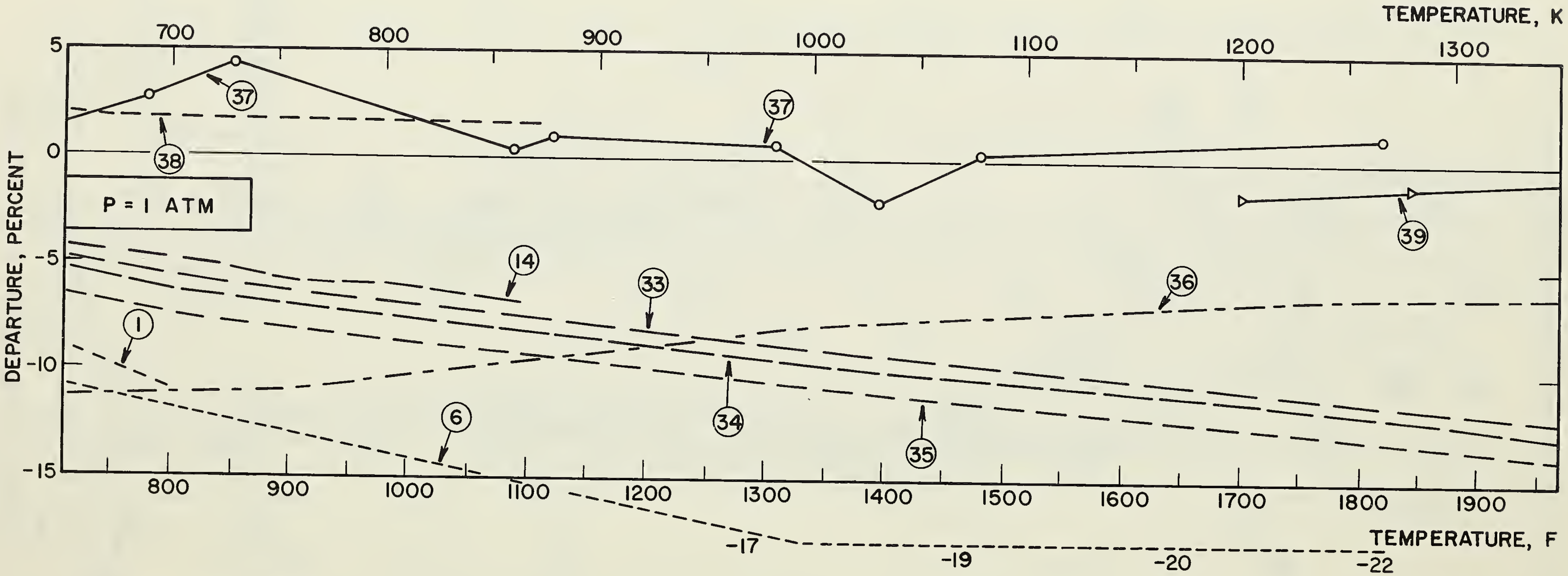
Curve	Reference	Curve	Reference
2	351	25	14
6	187	26	97
8	168	27	95
9	96	28	177
10	74	29	378
12	95	30	166
13	336	31	86
15	288, 289	32	43
17	64, 65	37	628
18	107		
19	143		
20	83		
21	95, 160		
22	81, 82		
23	147, 188		
24	372		

FIGURE 35. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (Continued)



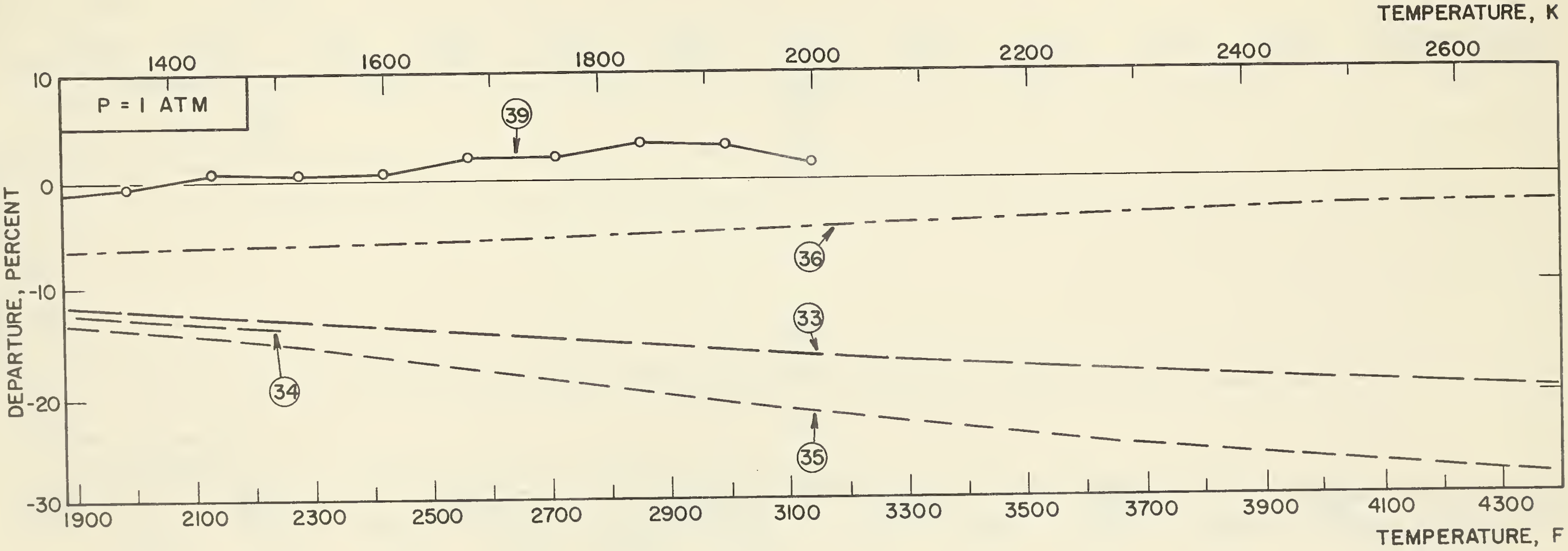
Curve	Reference
1	223
3	147
4	523
6	187
7	10
11	168
14	258
33	521
34	630
35	631
36	611
38	616

FIGURE 35. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



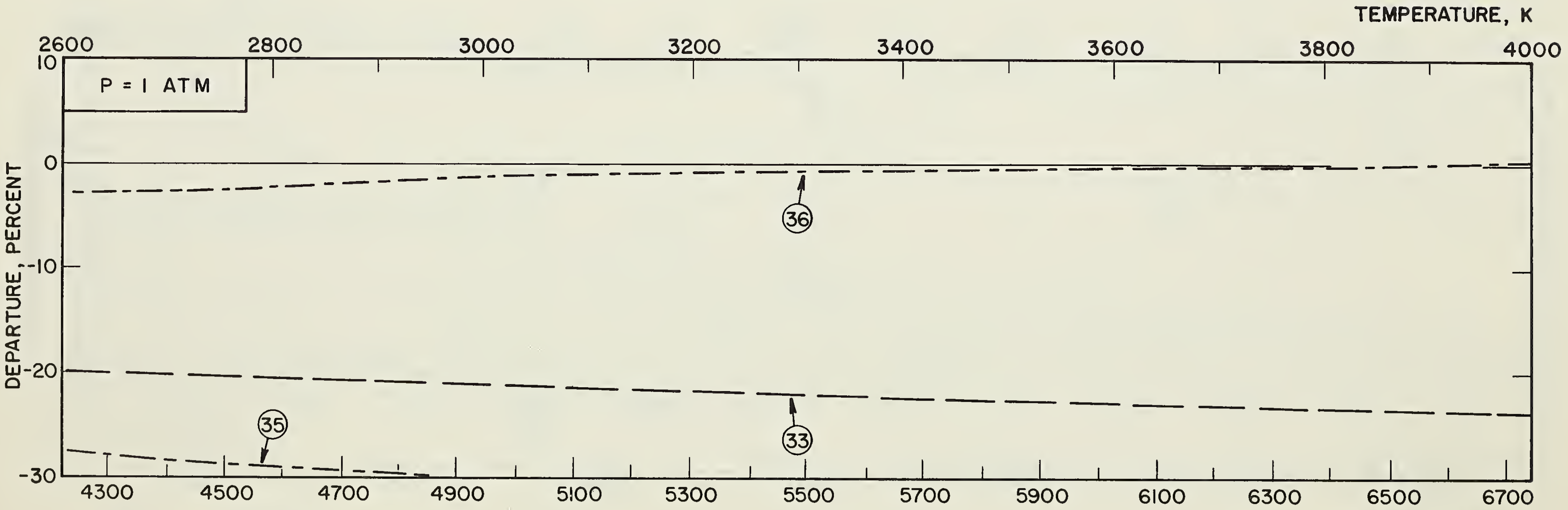
Curve	Reference
1	223
6	187
14	258
33	521
34	630
35	631
36	611
37	628
38	616
39	569

FIGURE 35. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



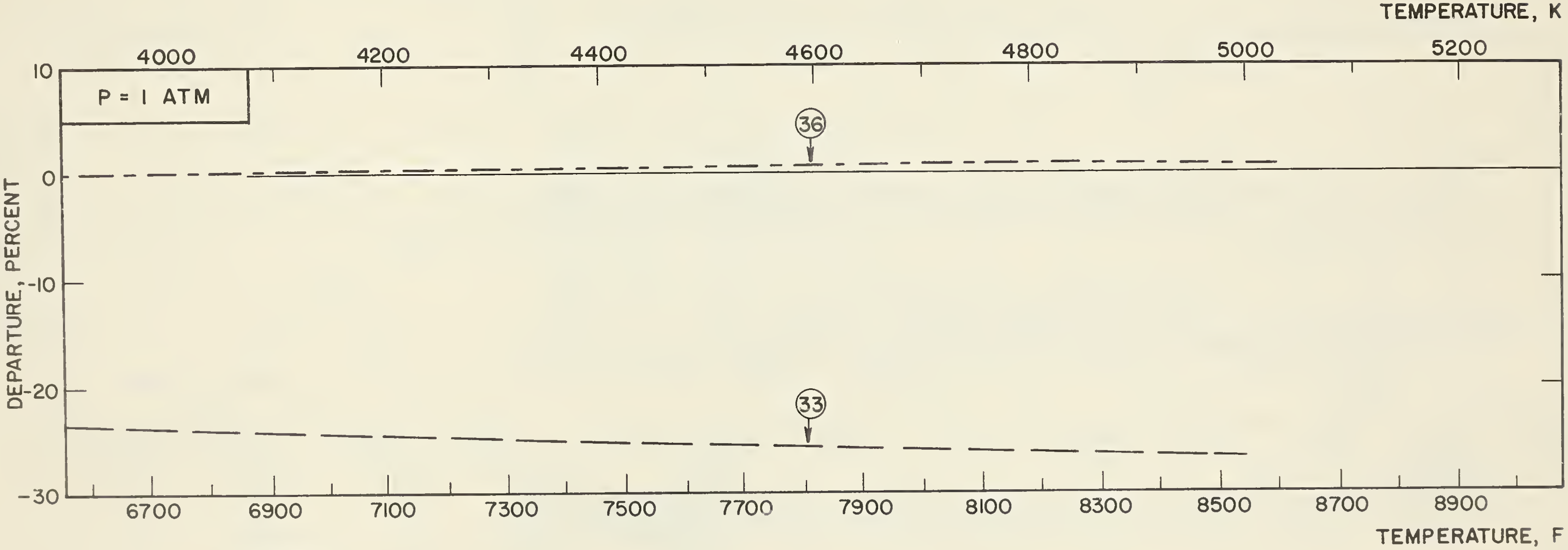
Curve	Reference
33	521
34	630
35	631
36	611
39	569

FIGURE 35 DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



Curve	Reference
33	521
35	631
36	611

FIGURE 35. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS HELIUM (continued)



Curve	Reference
33	521
36	611

TABLE 29. THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (mw. cm^{-1} K^{-1})

T (K)	k	T (K)	k	T (K)	k
50	(0.0485)*	500	0.3864	950	0.609
60	(0.0578)*	510	0.392	960	0.613
70	(0.0670)*	520	0.398	970	0.618
80	0.0762	530	0.403	980	0.622
90	0.0852	540	0.408	990	0.626
100	0.0941	550	0.414	1000	0.631
110	0.1030	560	0.420	1050	0.651
120	0.1119	570	0.425	1100	0.672
130	0.1208	580	0.431	1150	0.693
140	0.1296	590	0.436	1200	0.713
150	0.1385	600	0.441	1250	0.733
160	0.1474	610	0.446	1300	0.754
170	0.1562	620	0.452	1350	0.775
180	0.1651	630	0.457	1400	0.797
190	0.1739	640	0.462	1450	0.819
200	0.1826	650	0.467	1500	0.842
210	0.1908	660	0.472	1550	0.867
220	0.1989	670	0.478	1600	0.893
230	0.2067	680	0.483	1650	0.921
240	0.2145	690	0.488	1700	0.950
250	0.2222	700	0.493	1750	0.981
260	0.2298	710	0.498	1800	1.013
270	0.2374	720	0.503	1850	1.046
280	0.2449	730	0.508	1900	1.080
290	0.2524	740	0.513	1950	1.113
300	0.2598	750	0.517	2000	1.146
310	0.2671	760	0.522	2100	1.207
320	0.2741	770	0.526	2200	1.263
330	0.2808	780	0.531	2300	1.314
340	0.2874	790	0.536	2400	1.361
350	0.2939	800	0.541	2500	1.406
360	0.3002	810	0.546	2600	1.449
370	0.3065	820	0.551	2700	1.494
380	0.3127	830	0.555	2800	1.542
390	0.3189	840	0.559	2900	1.590
400	0.3252	850	0.564	3000	1.640
410	0.3314	860	0.569	3100	1.691
420	0.3376	870	0.574	3200	1.743
430	0.3438	880	0.578	3300	1.795
440	0.3501	890	0.583	3400	1.853
450	0.3564	900	0.587	3500	1.915
460	0.3626	910	0.592		
470	0.3688	920	0.596		
480	0.3749	930	0.600		
490	0.3808	940	0.605		

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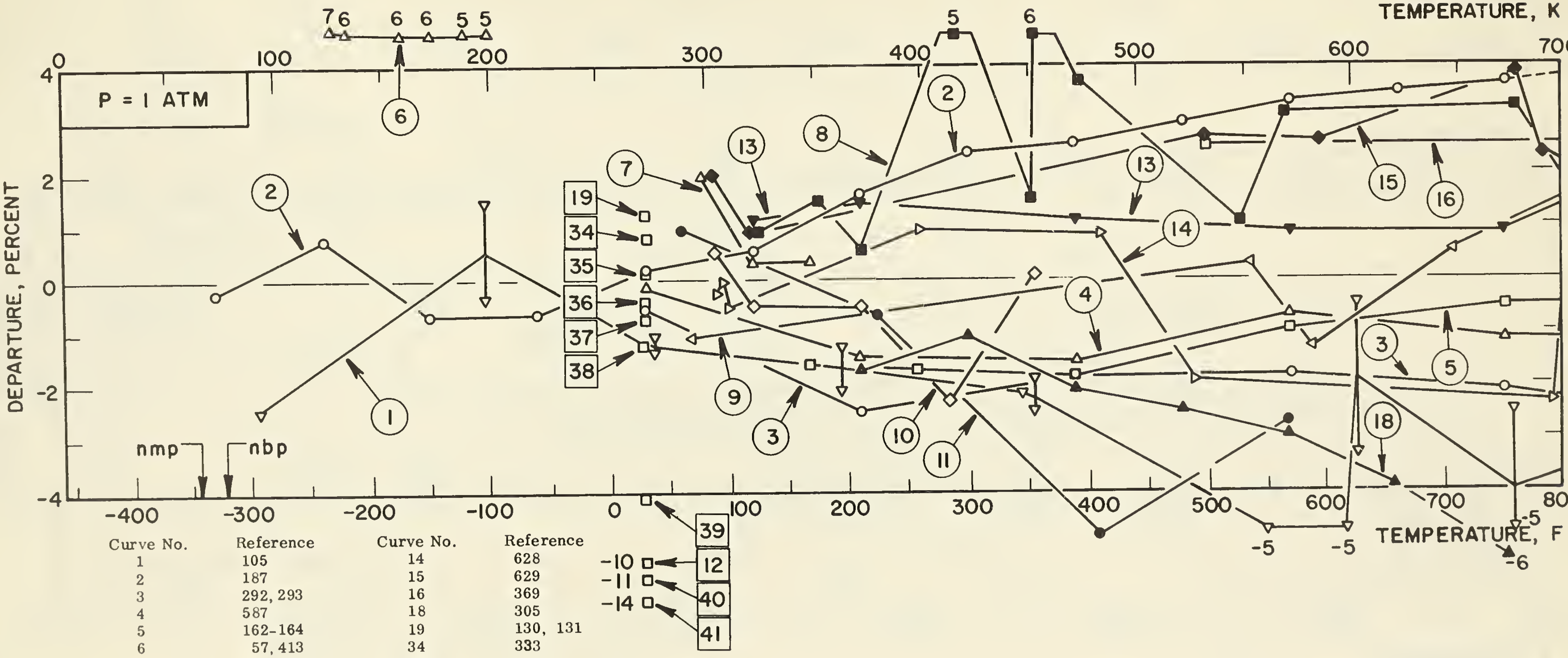
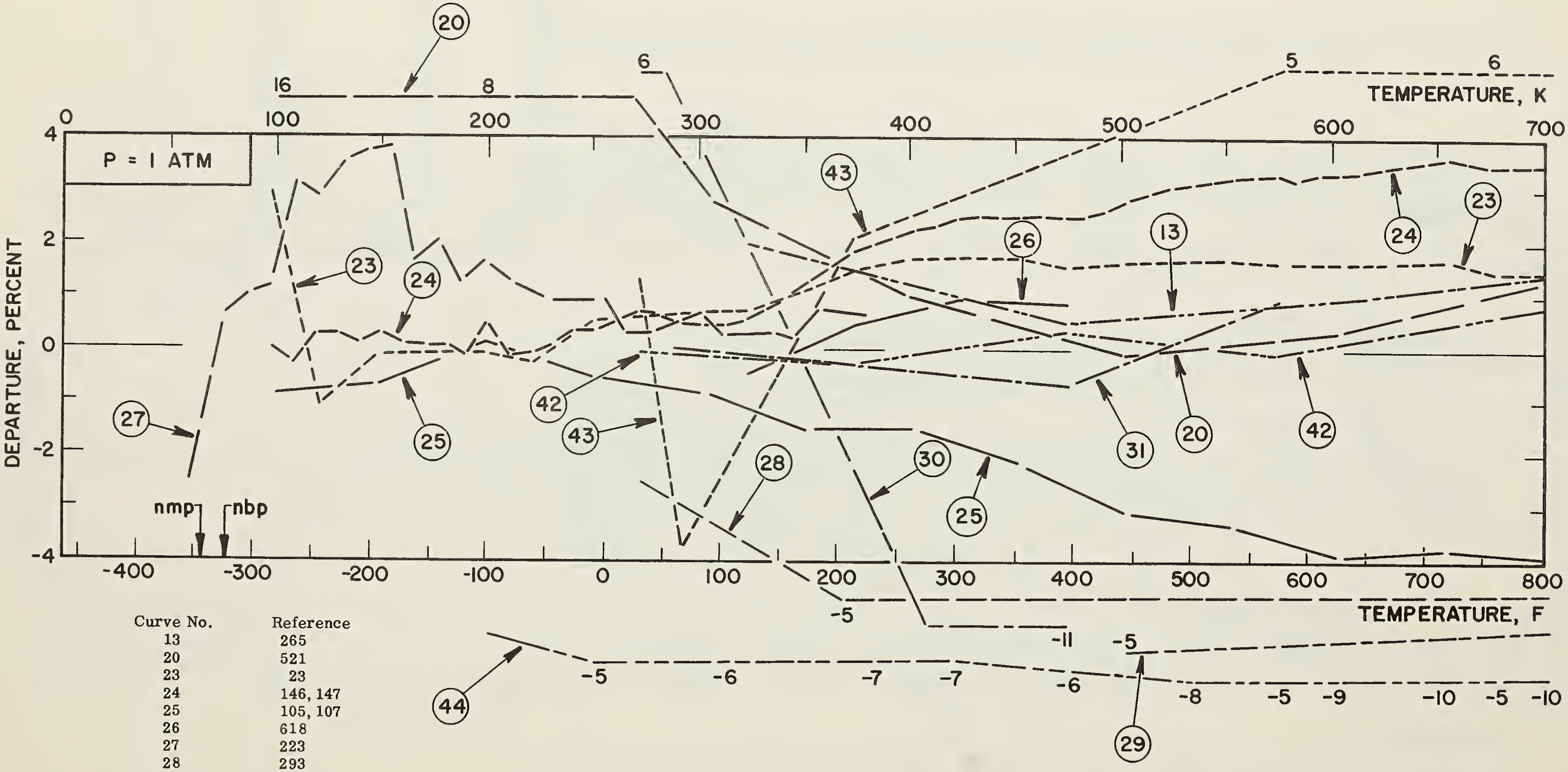
* Extrapolated

FIGURE 36 DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN



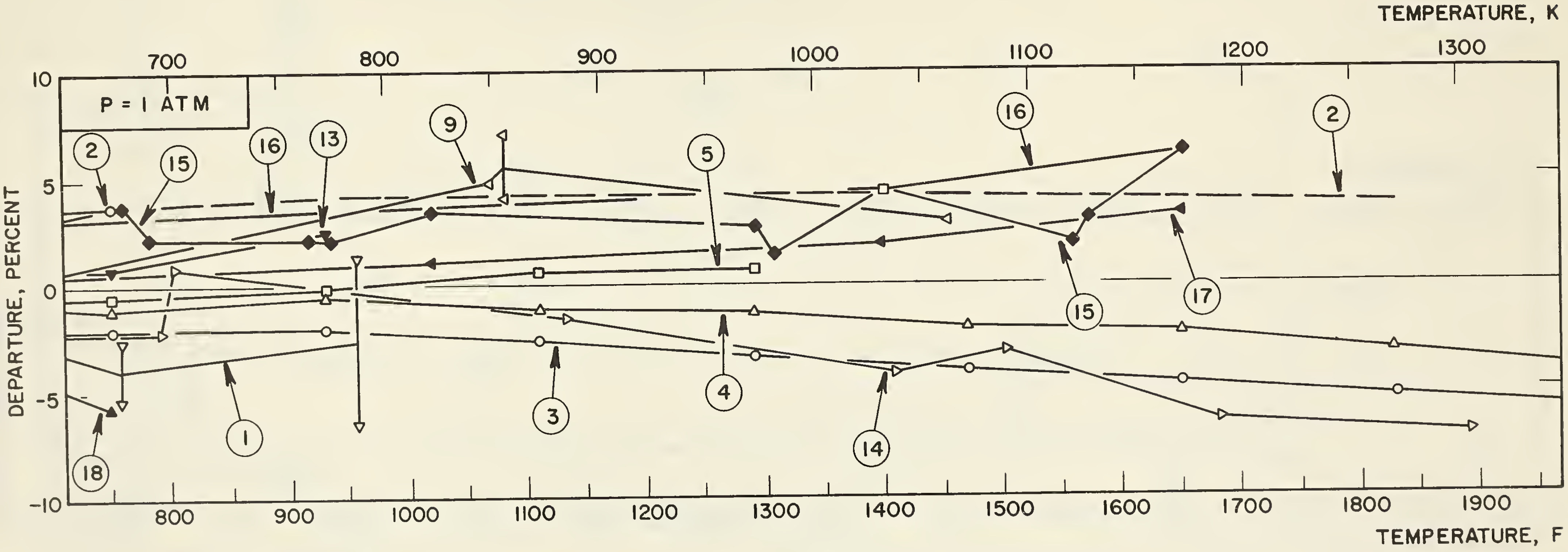
Curve No.	Reference	Curve No.	Reference
1	105	14	628
2	187	15	629
3	292, 293	16	369
4	587	18	305
5	162-164	19	130, 131
6	57, 413	34	333
7	247	35	97
8	365, 366	36	401
9	626	37	137
10	627	38	96, 385
11	331	39	156
12	143	40	396, 399
13	265	41	340

FIGURE 36 DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



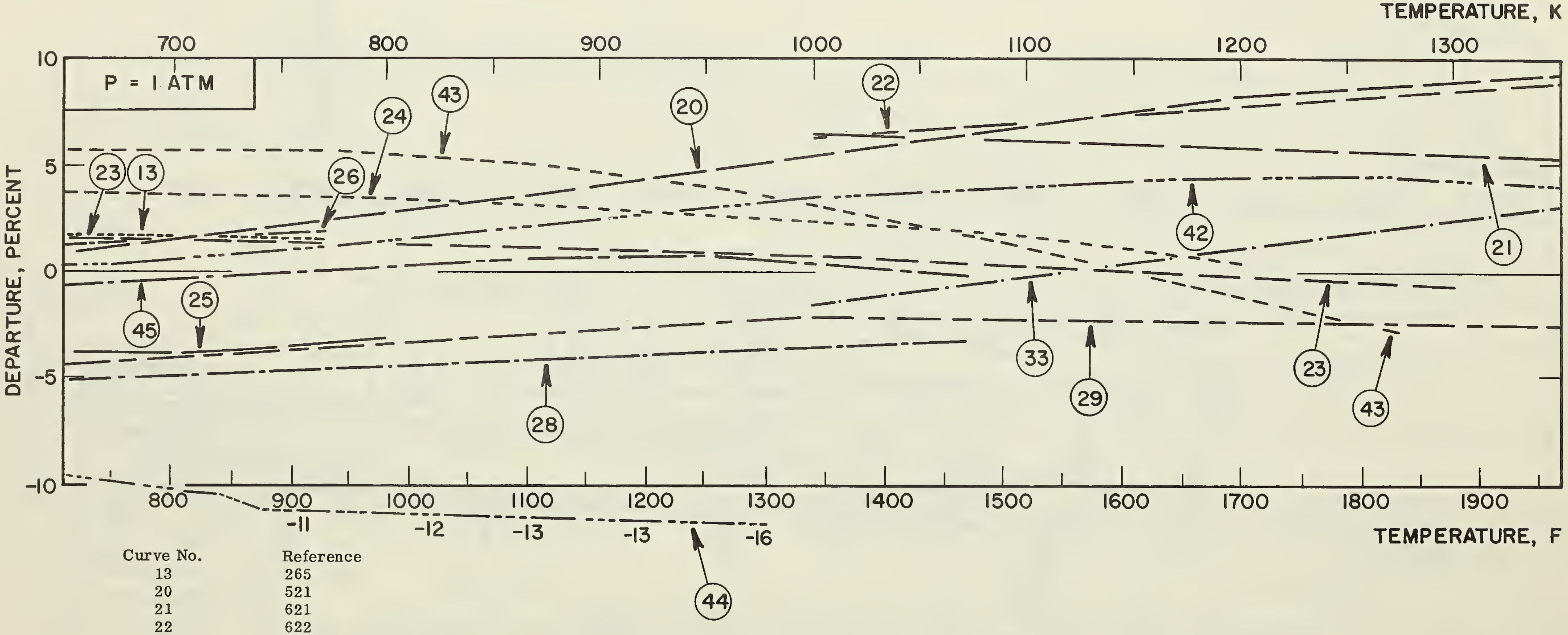
Curve No.	Reference
13	265
20	521
23	23
24	146, 147
25	105, 107
26	618
27	223
28	293
29	623
30	600
31	331, 332
42	629
43	601-3, 616
44	257

FIGURE 36. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



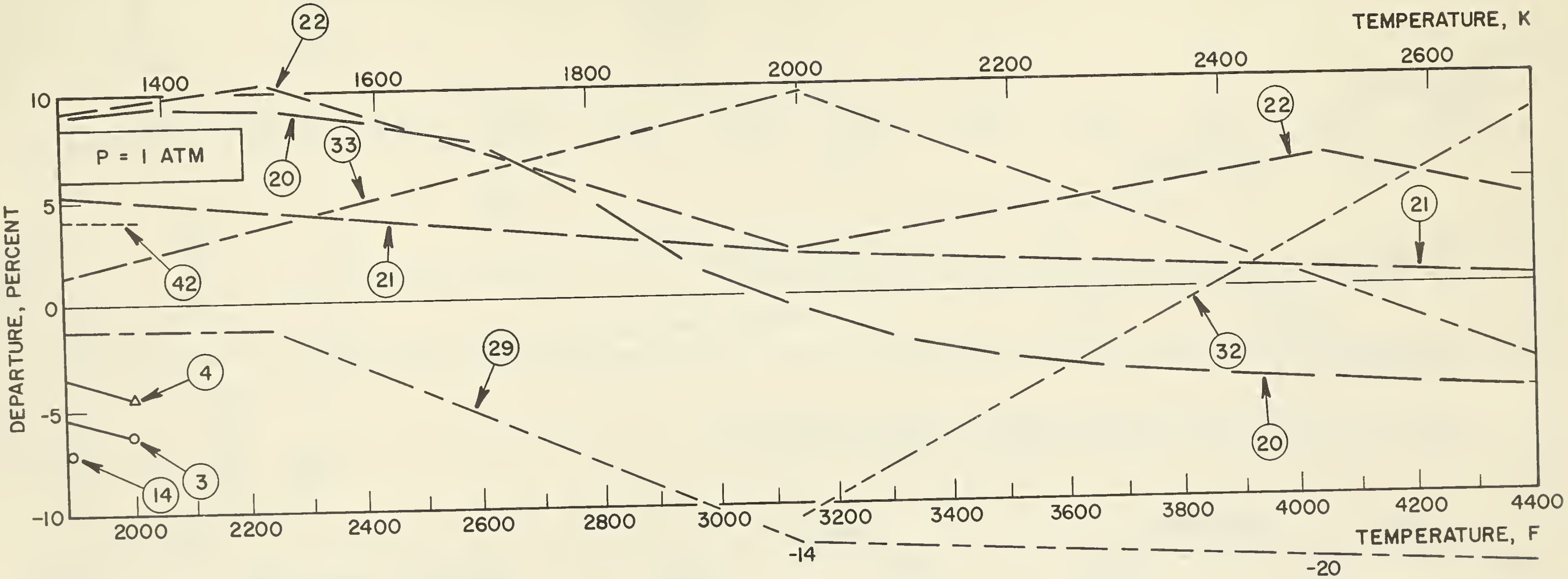
Curve No.	Reference
1	105
2	187
3	292, 293
4	587
5	162-4
9	626
13	265
14	628
15	629
16	369
17	369, 618
18	305

FIGURE 36. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



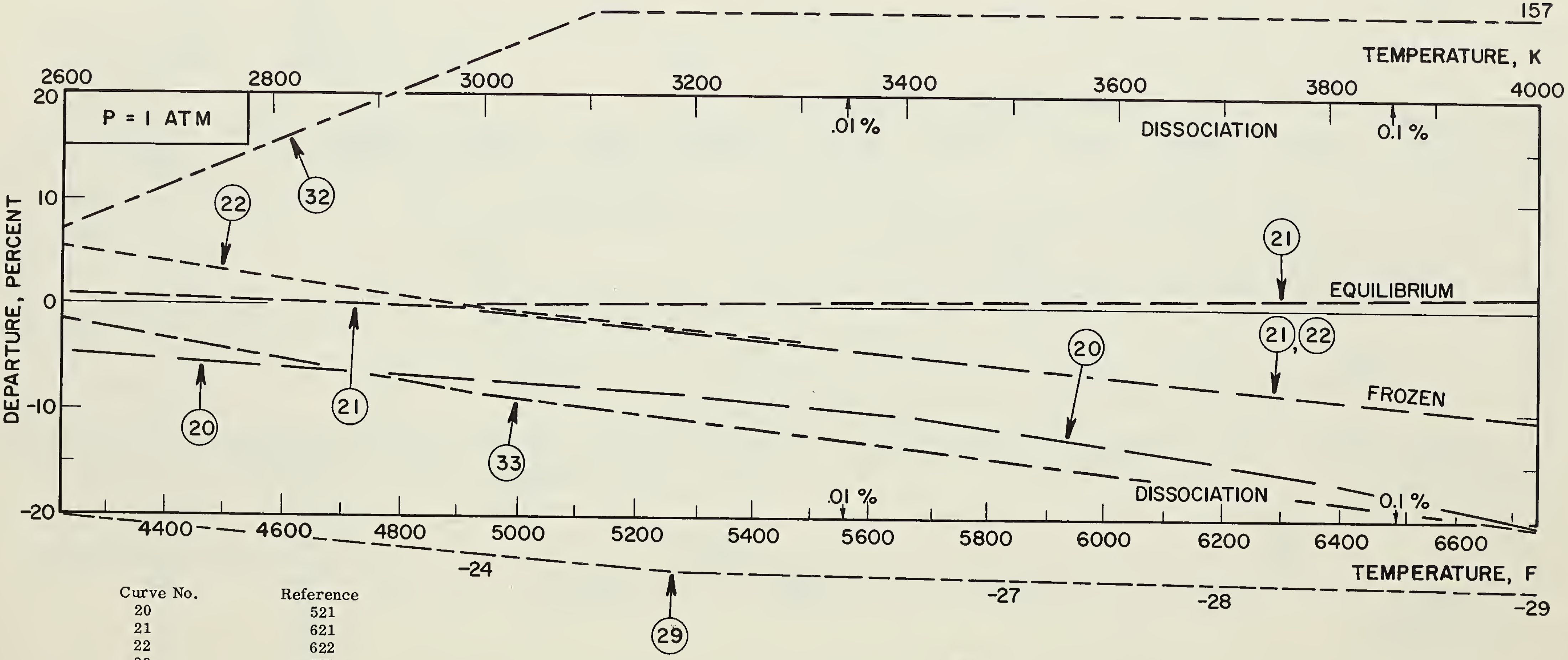
Curve No.	Reference
13	265
20	521
21	621
22	622
23	23
24	146, 147
25	105, 107
26	618
28	293
29	623
33	625
42	629
43	601-3, 616
44	257
45	281

FIGURE 36. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)



Curve No.	Reference
3	292, 293
4	587
14	628
20	521
21	621
22	622
29	623
32	624
33	625
42	629

FIGURE 36. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS NITROGEN (continued)

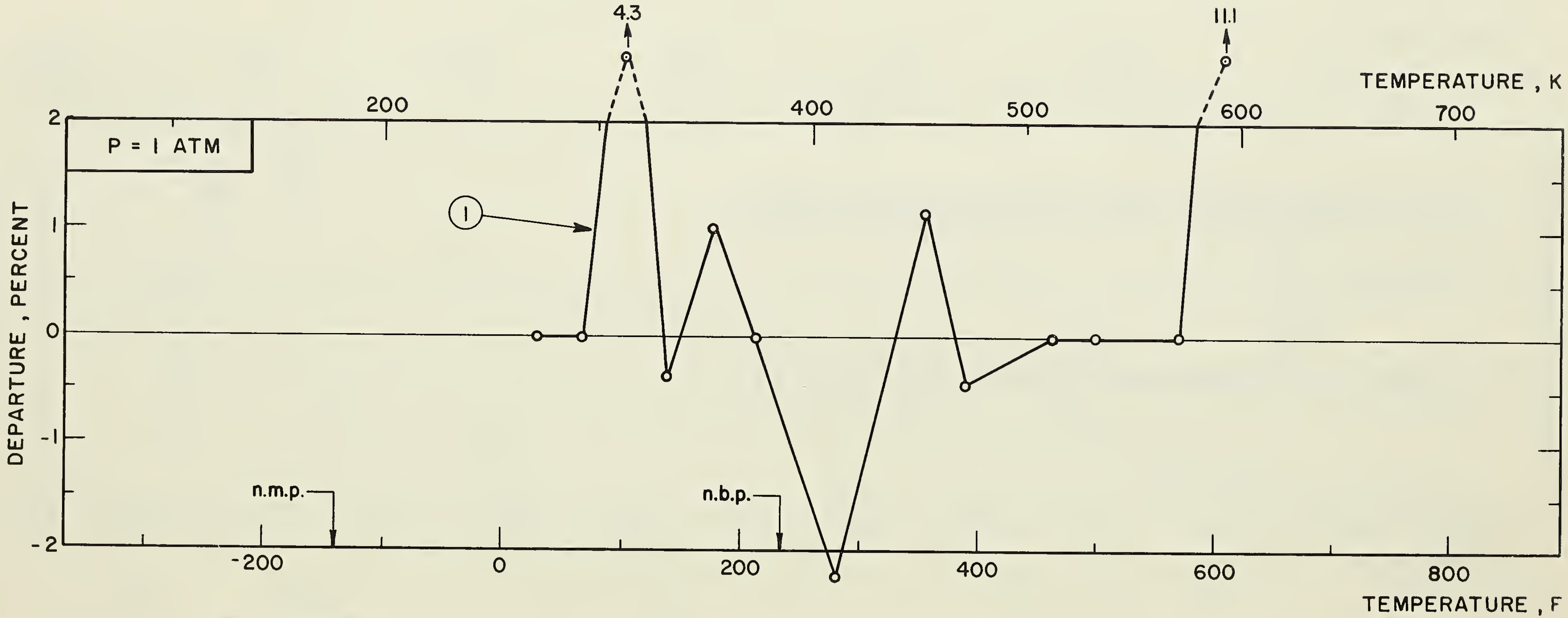


Curve No.	Reference
20	521
21	621
22	622
29	623
32	624
33	625

TABLE 30. THERMAL CONDUCTIVITY OF GASEOUS TOLUENE (mw. cm^{-1} K^{-1})

T (K)	k
250	0.116
260	0.121
270	0.126
280	0.133
290	0.139
300	0.146
310	0.154
320	0.162
330	0.170
340	0.180
350	0.189
360	0.198
370	0.208
380	0.219
390	0.230
400	0.240
410	0.251
420	0.262
430	0.273
440	0.284
450	0.295
460	0.305
470	0.316
480	0.327
490	0.338
500	0.349
510	0.360
520	0.371
530	0.382
540	0.393
550	0.405
560	0.416
570	0.427
580	0.439
590	0.450
600	0.461

FIGURE 37. DEPARTURE PLOT FOR THERMAL CONDUCTIVITY OF GASEOUS TOLUENE



Curve	Reference
1	2

TABLE 31. THERMAL CONDUCTIVITY OF GASEOUS WATER (STEAM) (mw. cm^{-1} K^{-1})

T (K)	k
250	(0.140)*
260	(0.148)*
270	(0.156)*
280	0.164
290	0.172
300	0.181
310	0.189
320	0.197
330	0.205
340	0.214
350	0.222
360	0.231
370	0.239
380	0.248
390	0.256
400	0.264
410	0.273
420	0.282
430	0.291
440	0.300
450	0.307
460	0.317
470	0.327
480	0.337
490	0.347
500	0.357
510	0.368
520	0.378
530	0.389
540	0.400
550	0.411
560	0.422
570	0.432
580	0.443
590	0.454
600	0.464
610	0.475
620	0.486
630	0.497
640	0.508
650	0.518
660	0.529
670	0.540
680	0.551
690	0.562
700	0.572
710	0.58
720	0.59
730	0.60
740	0.62
750	0.63
760	0.64
770	0.65
780	0.66
790	0.67
800	0.68
810	0.69
820	0.70
830	0.71
840	0.72
850	0.73
860	0.74
870	0.75
880	0.76
890	0.77
900	0.78

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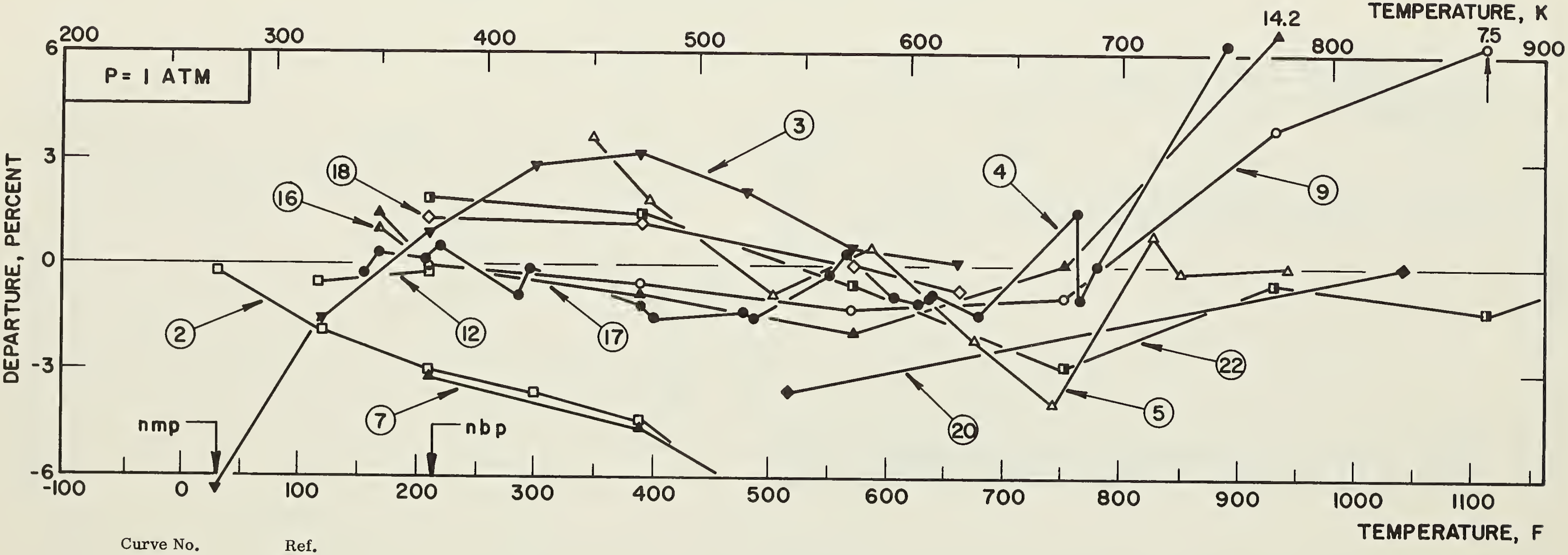
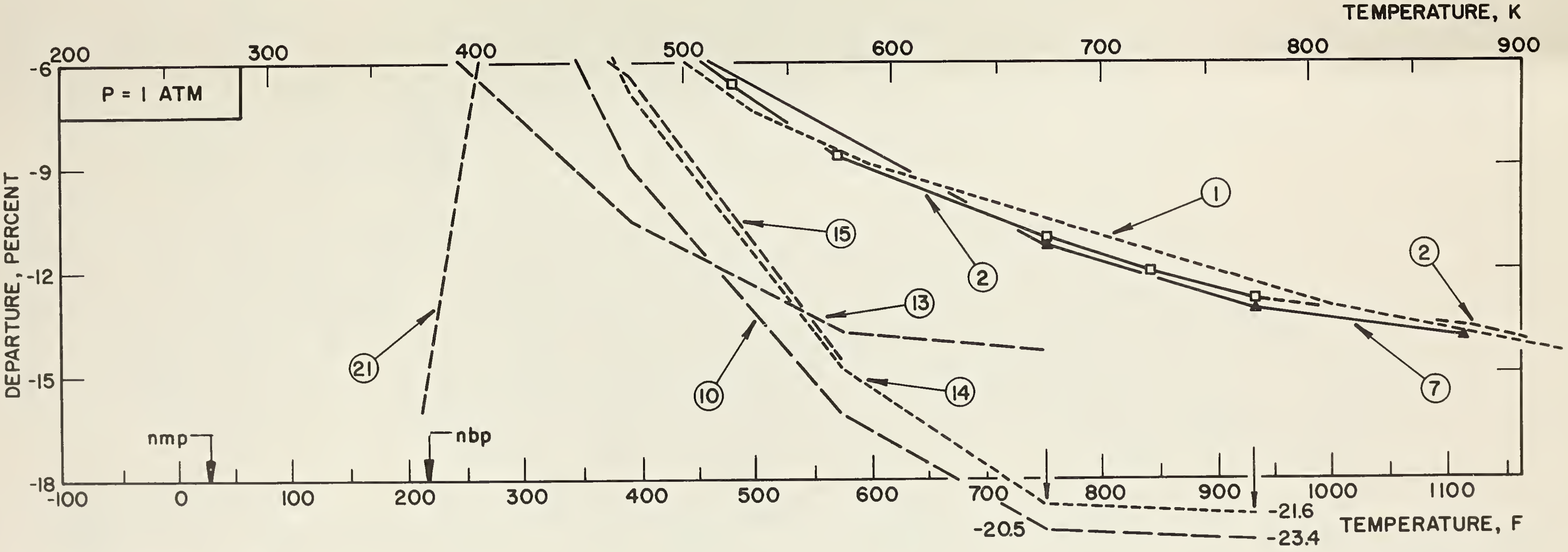
* Extrapolated

FIGURE 38. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS WATER (STEAM)



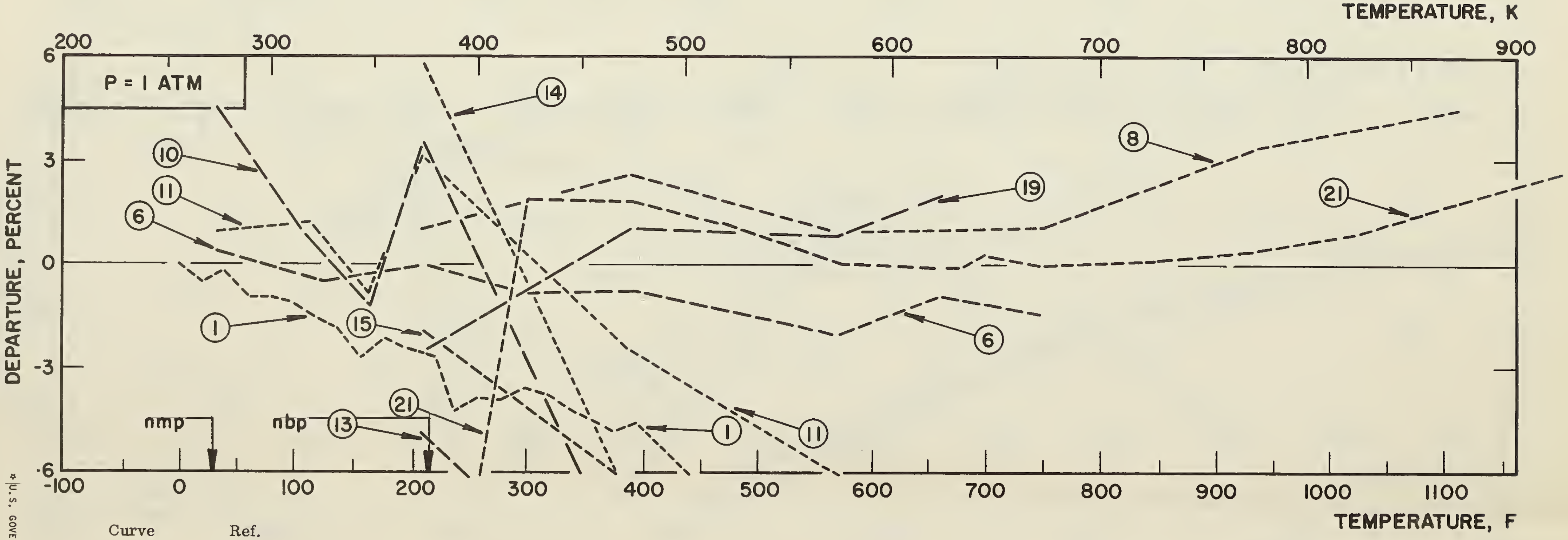
Curve No.	Ref.
2	187
3	358
4	356
5	360, 365, 366
7	195
9	360, 365, 366
12	254
16	252
17	597
18	596
20	369
22	587

FIGURE 38. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS WATER (STEAM) (continued)



Curve No.	Ref.
1	223
2	187
7	195
10	263, 201
13	593
14	592
15	591
21	590

FIGURE 38. DEPARTURE CURVE FOR THERMAL CONDUCTIVITY OF GASEOUS WATER (STEAM) (continued)



Curve	Ref.
1	223
6	201
8	360, 365, 366
10	263, 201
11	594
13	593
14	592
15	591
19	596
21	590

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