THERMAL CONDUCTIVITY OF PYREX GLASS: SELECTED VALUES

by

LOIS C. K. CARWILE and HAROLD J. HOGE

March 1966

UNITED STATES ARMY
NATICK LABORATORIES
Natick, Massachusetts 01760

Pioneering Research
Division TC-1
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED.

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of trade names in this report does not constitute an official endorsement or approval of the use of such items.

Destroy this report when no longer needed. Do not return it to the originator.
TECHNICAL REPORT
66-14-PR

THERMAL CONDUCTIVITY OF PYREX GLASS:
SELECTED VALUES

by

Lois C. K. Carwile and Harold J. Hoge

Project reference: 1P014501B11A

Series: Thermal Conductivity-1

March 1966

Pioneering Research Division
U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760
FOREWORD

This report is the first of a series on the thermal conductivities of materials of scientific and engineering interest. The values selected are based on thorough study and critical evaluation of published investigations. In a critical survey such as this one, much depends on the judgment of the surveyors. The care that the authors of the present survey have exercised may be judged from the comments they have made on the individual papers examined. Their comments on the more important papers are in the text of the report. In addition, they have made many brief comments on less important papers; these comments are given as annotations, immediately following the listing of the paper in the references.

S. DAVID BAILEY
Director
Pioneering Research Division

APPROVED:

DALE H. SIELING
Scientific Director
U. S. Army Natick Laboratories

W. W. Vaughan
Brigadier General, USA
Commanding
CONTENTS

Introduction 1
Selection of Values 1
Reliability of the Tables 4
Data for Conversion of Units 6
References 7
ABSTRACT

The published literature on the thermal conductivity of Pyrex glass has been assembled and the results critically evaluated. Best values of thermal conductivity as a function of temperature have been selected. These are presented in both graphical and tabular form; they cover the range 50 to 850° K. An attempt was made to consult all work that could significantly affect the choice of best values. Published papers were located with the aid of Chemical Abstracts, Physics Abstracts, the Thermophysical Properties Retrieval Guide, and some other general sources. In addition, relevant references in the papers themselves were followed up until a substantially "closed system" had been generated, as shown by the fact that no new references were being turned up.
Introduction

Pyrex glass has sometimes been used as a standard material for the calibration or checking of thermal-conductivity apparatuses, and a knowledge of its conductivity is often required for the making of corrections. Pyrex is a trade-mark name of the Corning Glass Works, and is not necessarily limited to glass of a single composition. However, there is strong indication that "Pyrex chemical resistant glass, Code No. 774" is the glass that has been used by many investigators. In recent years "Code No. 7740" has been adopted as the preferred designation for the same glass.

The British glass sold under the trade-mark name "Phoenix" is stated by the manufacturer (24) to be near in composition to Pyrex. Thermal conductivities of Phoenix glass have been included in the survey and in the graphs, because of the lack of data on Pyrex at low temperatures. All data referring to Phoenix glass are so identified.

Morey (25) gives for the composition of Code No. 774, in weight percent: SiO₂, 80.5; B₂O₃, 12.9; Na₂O, 3.8; K₂O, 0.4; Al₂O₃, 2.2. Other investigators give compositions that do not differ greatly from this composition. For example, the B₂O₃ content quoted by 5 different investigators ranged from 11.50 to 12.9. Small differences in composition are not expected to affect the thermal conductivity appreciably, except possibly when an impurity is present that affects the transmission of radiant energy.

For the density of Pyrex, the value found by Stephens (4) is probably as reliable as any. He found by direct measurement, \( \rho = 2.233 \text{ g cm}^{-3} \) at 21° C. Five other values from the references quoted in this report range from 2.22 to 2.24.

Selection of the Values

The data were evaluated by graphical methods. Deviation plots were used, in which an equation represents the data approximately and departures from the equation are plotted; it was ultimately decided that the scattering of the data was so great that deviation plots were unnecessary, and simple graphs of thermal conductivity versus temperature were used. The original data of some investigators were given only in graphical form. In such cases the abscissa and ordinate of
each plotted point were read from the graph and recorded for subsequent use.

The selected relation between thermal conductivity and temperature is shown by the master curve in Fig. 1. Table 1.1 represents this master curve; it was obtained by reading values at uniform intervals from a large-scale version of the figure. The values were differenced and when necessary smoothed, but the table and the curve were kept consistent. The data from references (1) to (10) are shown in Fig. 1. These are considered the more important papers. References (11) to (19) contain data not plotted in the figure; often they contained only a single \( k \)-value. In one case the data had not been released for publication.

The greatest weight has been given to the data in the first three references listed. Birch and Clark (1) made absolute measurements with a guarded hot-plate. Lucks, et al. (2) made measurements relative to an Armco-iron standard, with the same heat flow in both the standard and the Pyrex. Challoner, Gundry, and Powell (3) made absolute measurements with radial heat flow in a sample in the form of a tube.

The data of Stephens (4) appear to be low, but their precision is high and they bridge the gap between about \( 90^\circ \text{K} \) and room temperature. The value of \( k \) at \( 25^\circ \text{C} \) accepted by Stephens appears to contain a transposition. We have corrected this by using the value 0.00253 instead of the published value 0.00235. This makes the data of Stephens self-consistent. A further increase in this reference value would raise all of Stephens' values proportionally. Plummer, Campbell, and Comstock (6) measured thermal diffusivities, and used accepted values of specific heat and density to calculate thermal conductivity.

Their values are the lowest reported in the major investigations.

The only values below \( 90^\circ \text{K} \) are those of Berman (7) and of Wilkinson and Wilks (8). In both investigations the glass was Phoenix rather than Pyrex. The data of Knapp (9), and of Smoke, Wisely, Ruh, Illyn, and Eichbaum (10) are high. Knapp (26) states that later work has indicated that his results are in error.

Table 1.2 is identical with Table 1.1 and with the master curve in Fig. 1 except for the change in units. Linear interpolation in a table will introduce no appreciable error when the second differences
Fig. 1. Experimental data on therm of data, (7) and (8), refer similar to Pyrex. The smx selected values. Low-temp the large-scale inset graph.
do not exceed 4. When second differences exceed 4, higher-order interpolation may be desirable to preserve the internal consistency of values taken from the tables. The error introduced by linear interpolation in Tables 1.1 and 1.2 will always be small compared to the uncertainty already present in the values themselves. When values outside the range of the tables are desired, they should be read directly from the master curves.

Reliability of the Tables

The master curve and the corresponding tabulated values of k are believed to be correct within ± 7 percent near room temperature. Where the data are more scarce or the measurements are more difficult, the uncertainty is greater; it may reach 15 percent at the upper limit of the data.

There is some evidence that radiative heat transfer becomes significant in Pyrex at temperatures above about 700°C (1260°F). Birch and Clark concluded that radiation would be negligible below 573 K. An upper limit for the error in k that would be caused by radiative heat transfer may be obtained by assuming the Pyrex to be perfectly transparent and the hot and cold plates to radiate and absorb as black bodies. Then, for a sample 1 cm thick, the apparent conductivity at 300°C would be 6 percent greater than the true conductivity. At 500°C the difference would be 23 percent; and at 700°C, 53 percent. These are upper limits, and the actual errors caused by lumping radiative heat transfer with conduction are probably much less. In a very thick sample the effect of radiative transfer could of course exceed the limits given above, because the difference between the apparent and the true conductivity is proportional to the thickness of the sample.

The estimated uncertainty of ± 7 percent near room temperature could be reduced to ± 4 or ± 5 percent except for the possibility that Pyrex glass may vary from sample to sample in a way not fully understood. Lucks (13) has recently measured a different sample of Pyrex in the same apparatus that was used in reference (2). The thermal conductivities found in the recent measurements, which extended from 325°C to 425°C, are about 6 percent lower than those plotted in Fig. 1, which are taken from reference (2). The transmittances of the two samples were measured, and found to be different in the wavelength
Table 1. Thermal conductivity of Pyrex glass

(Values below 100°K are based almost entirely on data for Phoenix glass.)

Table 1.1

<table>
<thead>
<tr>
<th>T (°K)</th>
<th>k (cal cm/°K cm² sec)</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.00059</td>
<td>75</td>
</tr>
<tr>
<td>100</td>
<td>0.00134</td>
<td>51</td>
</tr>
<tr>
<td>150</td>
<td>0.00185</td>
<td>39</td>
</tr>
<tr>
<td>200</td>
<td>0.00224</td>
<td>30</td>
</tr>
<tr>
<td>250</td>
<td>0.00254</td>
<td>22</td>
</tr>
<tr>
<td>300</td>
<td>0.00276</td>
<td>17</td>
</tr>
<tr>
<td>350</td>
<td>0.00293</td>
<td>15</td>
</tr>
<tr>
<td>400</td>
<td>0.00308</td>
<td>13</td>
</tr>
<tr>
<td>450</td>
<td>0.00321</td>
<td>12</td>
</tr>
<tr>
<td>500</td>
<td>0.00333</td>
<td>11</td>
</tr>
<tr>
<td>550</td>
<td>0.00344</td>
<td>12</td>
</tr>
<tr>
<td>600</td>
<td>0.00356</td>
<td>13</td>
</tr>
<tr>
<td>650</td>
<td>0.00369</td>
<td>15</td>
</tr>
<tr>
<td>700</td>
<td>0.00384</td>
<td>18</td>
</tr>
<tr>
<td>750</td>
<td>0.00402</td>
<td>21</td>
</tr>
<tr>
<td>800</td>
<td>0.00423</td>
<td>28</td>
</tr>
<tr>
<td>850</td>
<td>0.00451</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 1.2

<table>
<thead>
<tr>
<th>T (°R)</th>
<th>k (Btu in./°R ft² hr)</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.92</td>
<td>235</td>
</tr>
<tr>
<td>200</td>
<td>4.27</td>
<td>151</td>
</tr>
<tr>
<td>300</td>
<td>5.78</td>
<td>114</td>
</tr>
<tr>
<td>400</td>
<td>6.92</td>
<td>83</td>
</tr>
<tr>
<td>500</td>
<td>7.75</td>
<td>60</td>
</tr>
<tr>
<td>600</td>
<td>8.35</td>
<td>50</td>
</tr>
<tr>
<td>700</td>
<td>8.85</td>
<td>43</td>
</tr>
<tr>
<td>800</td>
<td>9.28</td>
<td>39</td>
</tr>
<tr>
<td>900</td>
<td>9.67</td>
<td>33</td>
</tr>
<tr>
<td>1000</td>
<td>10.0</td>
<td>4</td>
</tr>
<tr>
<td>1100</td>
<td>10.4</td>
<td>4</td>
</tr>
<tr>
<td>1200</td>
<td>10.8</td>
<td>6</td>
</tr>
<tr>
<td>1300</td>
<td>11.4</td>
<td>6</td>
</tr>
<tr>
<td>1400</td>
<td>12.0</td>
<td>8</td>
</tr>
<tr>
<td>1500</td>
<td>12.8</td>
<td>-</td>
</tr>
</tbody>
</table>
region of 3 microns. The difference was of the proper sign to account for the difference in k, but the observed discrepancy of 6 percent seems rather large to be accounted for by any difference in transmittance.

In contrast to the experience of Lucks is that of Bullard and Niblett (11), who sent one of their measured samples of Pyrex to Birch. They report that Birch found "no perceptible difference" between the thermal conductivity of this sample and that of his own sample of Pyrex.

Data for Conversion of Units

\[ T(*)_R = T(*)_K \times 1.8 \]
\[ T(*)_K = t(*_C) + 273.15 \]
\[ T(*)_R = t(*_F) + 459.67 \]

\[ \frac{\text{watt cm}}{\text{K cm}^2} = \frac{\text{cal cm}}{\text{K cm}^2 \text{ sec}} \times 4.1840 \]

\[ \frac{\text{Btu in.}}{\text{R ft}^2 \text{ hr}} = \frac{\text{cal cm}}{\text{K cm}^2 \text{ sec}} \times 2902.9 \]

\[ \frac{\text{Btu ft}}{\text{R ft}^2 \text{ hr}} = \frac{\text{cal cm}}{\text{K cm}^2 \text{ sec}} \times 241.91 \]
References

Containing data plotted in Fig. 1.


Containing data not plotted in Fig. 1; the less important, incidental, or unpublished values.


12. E. R. Ratcliffe, "Preliminary measurements to determine the effect of composition on the thermal conductivity of glass," Phys. Chem. Glasses 1, 103-4 (1960). One thermal-conductivity datum is quoted from Chaloner, Gundry, and Powell (3); also, the composition of the glass designated "A" establishes it as Pyrex, or something very similar to Pyrex.


17. P. W. Bridgman, "The thermal conductivity and compressibility of several rocks under high pressures," Am. J. Sci. 7, 81-102 (1924). Gives k of Pyrex as a function of pressure to 12,000 kg cm⁻².


Containing no thermal conductivity data on Pyrex.


The published literature on the thermal conductivity of Pyrex glass has been assembled and the results critically evaluated. Best values of thermal conductivity as a function of temperature have been selected. These are presented in both graphical and tabular form; they cover the range 50 to 350 K. An attempt was made to consult all work that could significantly affect the choice of best values. Published papers were located with the aid of Chemical Abstracts, Physics Abstracts, the Thermophysical Properties Retrieval Guide, and some other general sources. In addition, relevant references in the papers themselves were followed up until a substantially "closed system" had been generated, as shown by the fact that no new references were being turned up.
<table>
<thead>
<tr>
<th>KEY WORDS</th>
<th>LINK A</th>
<th>LINK B</th>
<th>LINK C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Heat transfer</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat resistant glass</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Pyrex glass</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transport properties</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Thermophysical properties</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrections</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization (corporate author) issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b. & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system number, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers (either by the originator or by the sponsor), also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

   (1) "Qualified requesters may obtain copies of this report from DDC."

   (2) "Foreign announcement and dissemination of this report by DDC is not authorized."

   (3) "U.S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through DDC."

   (4) "U.S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through DDC."

   (5) "All distribution of this report is controlled. Qualified DDC users shall request through DDC."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring (paying for) the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached. It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as (TS), (S), (C), or (U).

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.