THERMOPHYSICAL PROPERTIES DATA BASE ACTIVITIES AT OWENS-CORNING FIBERGLAS

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ABSTRACT

The success of any modeling effort depends upon the material property data used as input. To provide a firm foundation for our modeling efforts an activity was started at the Owens-Corning Fiberglas Technical Center for development of a data base of thermophysical properties of building materials. The purpose of this paper is to review the rationale for and the activities in this effort. Deficiencies in existing compilations of property data and the need for an expanded data base are discussed. Sources of literature data and the steps taken to collect and archive original references are described. A description is given of the steps taken to utilize the literature data. Included are details of the tabulations of property data, statistical analyses of data, and the generation of recommended sets of property values. Examples are given of the information contained in a data book being prepared, including tablular and graphical displays of data, and recommended equations.

INTRODUCTION

As the energy crisis has intensified, an increasing amount of activity has been aimed at modeling the thermal performance of buildings. The success of any such modeling activity, no matter how sophisticated, ultimately depends upon the material property data used as input. To provide a firm foundation for our modeling activities, an effort was started for development of a data base of thermophysical properties of building materials, with emphasis on thermal conductivity and specific heat.

Although several compilations of property data are available, each of them has certain limitations. The ASHRAE Handbook of Fundamentals[1] is usually considered to be the authoritative source of data for building materials. However, with a few exceptions, these data are limited to a mean temperature near 297 K and to materials in a dry condition. The values given are intended to be used for design purposes and are not completely adequate for detailed modeling. Another source of information is the series of books compiled by the Thermophysical Properties Research Center at Purdue University[2]. While these books contain data on building materials, the main emphasis on data analysis has been placed on simpler materials, such as the pure elements and compounds. Many handbooks and textbooks contain tables of property data. These usually consist of a selection of data which are borrowed from one book to another to such an extent that the original sources of the data are practically forgotten.

With these limitations of existing compilations in mind, an effort was started to collect and analyze the available thermophysical property data on a wide

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variety of building materials. In this paper, a description of this activity and some of its results will be given. Numerical data will be presented for two materials, wood and glass fiber insulation; similar data are being prepared for other materials and will be presented at a later time. These materials include wood products, gypsum wallboard, various insulation materials, masonry materials, and soils.

COLLECTION AND TABULATION OF LITERATURE DATA

The first step was to identify and obtain copies of the most pertinent papers and reports. Copies of all the pertinent papers referenced in the ASHRAE Handbook were obtained. Additional sources of references were the Thermophysical Properties of Matter series[2], the Thermophysical Properties Research Literature Retrieval Guides[3,4], and a bibliographical search performed by the Thermophysical Properties Research Center. In-house capabilities were also used to perform searches of computerized literature data bases. As references were identified, copies were obtained of the most accessible papers and reports. As with any literature search, this one remains an on-going project. New references are continually being found and documents being obtained. However, for the most important building materials, the major sources of data are felt to have been covered. As documents are being obtained, they are archived in our laboratory and information sheets are filled out containing bibliographic information, abstracts, and key words. The information sheets are then stored in the computer in such a way that a computerized search for references can be made. This in-house computerized data bank includes similar information for documents we have collected dealing with many other aspects of energy conservation in buildings.

As the documents were collected, they were studied and applicable data were extracted and tabulated. Applicable data are defined as those from original sources rather than secondary sources. Data are also considered to be applicable only if they were measured in air (rather than in a vacuum or some other gas) and if the temperatures and temperature differentials were close to the normal building conditions (i.e., data at cryogenic or very high temperatures were excluded). Separate data tabulations were organized by material and by property categories. Some material categories included are wood, wood fiberboards, plywood, gypsum wallboard, glass fiber insulation, rock wool insulation, cellulose insulation, foam insulations, perlite, vermiculite, bricks, concrete, concrete masonry units, and soils. Property categories were initially limited to thermal conductivity (or conductance) and specific heat, although some documents were also obtained that deal with thermal expansion and thermal radiative properties.

These data tabulations are organized in loose-leaf notebook form and will ultimately be made available to the public. An example of a page from this tabulation is shown in Figure 1. In order to avoid becoming outdated, entries in these tables are made in SI units. In principle, these tables follow the format used by the Thermophysical Properties Research Center. However, a few columns have been added that seem appropriate for this particular collection of data. The first column in the data table is a data set number. This number is merely for identification purposes and is not intended to be any sort of ranking. The data tables are open-ended, so that as new data becomes available it may be added to the end of the table and the data set numbers are merely continued. The next item is a number which refers to the original source of the data; a complete list of references would be appended to the data tables. Next is the year in which the reference was published. This item is useful in that materials or accepted experimental procedures or both may have changed since the publication date. Since the mean temperature is usually the major independent variable, it is listed in the next column. For consistency, data within a given set are usually listed in order of increasing temperature. Exceptions to this might occur when it is useful to list data in the order measured, for example, when cycling a specimen between low and high temperatures. The next column contains the reported property data. Following this are columns that contain the density of the specimen at test conditions and the moisture content, expressed as a percentage of dry weight. These two quantities are broken out into separate columns since they are the major factors that characterize a specimen of a building material. The final column contains further characterization information on the specimen and details of the experiment. The entries in this column will vary depending upon the amount of information given in the original source, but will usually include some of the following: specimen material, size, and orientation, chemical composition and source of material, measurement technique, and measured temperature differential.

DATA ANALYSIS FOR WOOD

After tabulating the available data for a particular material, the data were analyzed to obtain equations which could be used to relate the property to temperature, density, moisture content, and orientation. Usually, individual data points were given equal weighting; however, in some cases data points judged to be questionable were deleted from the curve fits. Since a very large quantity of data was available for wood, the steps used for analysis of this data will be described in detail.

First, consider the thermal conductivity. A large amount of data was found in the literature for the thermal conductivity of wood[5-12]. The data cover a wide range of densities and moisture contents, but pertain mostly to mean temperatures near ambient. In addition, only a few data are available which give information on anisotropy with respect to heat flow orientation relative to grain direction.

Since the largest block of data was that near room temperature with heat flow across the grain, it was analyzed first.* Some anistropy exists between the radial and tangential directions. However this anisotropy is substantially smaller than that between either of these directions and the parallel-to-grain direction. In building envelopes, heat rarely flows along purely radial or tangential directions, and therefore the only two directions considered here are the cross-grain and parallel-to-grain directions. Previous research has shown the thermal conductivity of wood to depend upon density and moisture content, but to be otherwise essentially independent of species. Thus, an equation was desired that related conductivity to these two quantities. Rather than using complicated theoretical relations, a simpler empirical approach was used. This simple empirical equation has built into it the physical constraint that as the density approaches zero, the conductivity approaches that of air. In addition, it involves the simplest assumption that the conductivity varies linearly with both the mass of the wood and the mass of contained water. It should be noted that the equations derived here would not be expected to hold when moisture migration effects are significant. The form this equation takes is then

$$k = k_{air} + d_{dry}\,(a_o + a_1 M) \quad (1)$$

where k_{air} is the thermal conductivity of air, d_{dry} is the density based on oven-dry weight and volume at test conditions, M is the percentage moisture content expressed in terms of oven-dry weight, and a_o and a_1 are constants obtained by performing a linear regression analysis. In terms of the total density, d, this equation may be rewritten as

$$k_{297K} = k_{air,297K} + (a_o + a_1 M)d/(1 + 0.01M) \quad (2)$$

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*There are three major directions in wood. One is along the axis of the tree and is denoted as the longitudinal direction or the parallel to grain direction. The other two directions are in a plane perpendicular to this axis and are either radial or tangential to the annular rings. The radial and tangential directions are both across the grain.

As a second step, the much smaller amount of data containing information on temperature dependence was analyzed. The data for each specimen were fitted to an equation linear in temperature. The temperature coefficient near room temperature was then determined (here the temperature coefficient is defined as (dk/dT)/k with the conductivity evaluated at room temperature). These coefficients were then fitted to the equation

$$\frac{1}{k}\frac{dk}{dT} = \left(\frac{1}{k}\frac{dk}{dT}\right)_{air} + \alpha\, d \tag{3}$$

where $((dk/dT)/k)_{air}$ is the temperature coefficient for air near room temperature, d is the density of the specimen, and α is a constant to be determined by the regression analysis. In this case, as the density goes to zero, the equation is constrained to give the coefficient for air. The cross-grain conductivity at any temperature, T, may then be predicted from the following:

$$k_{T,\perp} = k_{297K}\left[1 + \left(\left(\frac{1}{k}\frac{dk}{dT}\right)_{air} + \alpha\, d\right)(T-297)\right] \tag{4}$$

As a final step, the data available for heat flow parallel to the grain were examined. Only eight sets of such data were found, and for each set the ratio $k_{\parallel}/k_{T,\perp}$ was formed with $k_{T,\perp}$ being calculated from Eq. 4 for the appropriate values of T, d, and M. Since the data of this type are so sparse, the average value of this ratio was taken as a rough approximation of the anisotropy effect.

Next consider the specific heat of wood. Since the mass of air enclosed within solid wood is negligible, the specific heat can be considered to be independent of density. As with the thermal conductivity, previous research has shown the specific heat of wood to be nearly independent of species[13]. Thus, the major independent variables are considered to be temperature and moisture content. As a first step in the analysis, all the data on dry wood were fitted to the following linear equation

$$C_{po} = a_o + a_1 T \tag{5}$$

One would then expect that the specific heat of moist wood could be computed by adding the heat capacities of the dry wood and the water contained in it. However, research has shown that this addition does not agree with experiment and that an extra term must be added to account for the heat of sorption[14]. Denoting this extra term as ΔC_p, the total specific heat is given by

$$C_p = \frac{C_{po} + 0.01M\, C_{pw}}{1 + 0.01M} + \Delta C_p \tag{6}$$

where C_{pw} is the specific heat of water. The ΔC_p term is a function of both temperature and moisture content, but should vanish as the moisture content goes to zero. It was thus assumed to be of the form

$$\Delta C_p = M\,(b_1 + b_2 T + b_3 M) \tag{7}$$

The specific heat data for moist wood were used with Eq. 6 to derive values of ΔC_p. The quantity $\Delta C_p/M$ was then multiply regressed against T and M to determine the constants in Eq. 7.

As a final step in the analysis of the data, the derived sets of equations were used to compare predicted values against experimental values for both thermal conductivity and specific heat. The comparisons were expressed as maximum, mean, and RMS percentage deviations from the equations. These values are valuable in that they give the user some idea of the uncertainty in the property values predicted by the equations.

DATA ANALYSIS FOR GLASS FIBER INSULATION

Heat transfer in fibrous insulation is known to be a complex phenomenon in which modes of heat transfer in addition to conduction will be present. Therefore, in a strict sense, it is not possible to define a unique thermal conductivity for materials of this class. However, for practical purposes, it is often useful to define an apparent thermal conductivity which may include effects due to other modes of heat transfer. It is also known that the thermal conductivity of fibrous insulation is sensitive to many variables, such as density, nominal fiber size, distribution of fiber sizes, orientation of fibers, and amount of binder. Normal production variations naturally result in a product whose thermal conductivity will vary from one piece to another. Nevertheless, it is still considered useful to present equations which may be used to predict nominal thermal conductivity values for batt and blanket building insulation produced by our company. These equations, based on in-house information, would thus apply only to certain of our company's products and similar equations would be needed for products of other companies as well as for other products made by Owens-Corning.

Several years ago, a large quantity of thermal conductivity data was statistically analyzed and an equation of the following form was found to fit the room temperature thermal conductivity:

$$k_{297\ K} = A + B\cdot d + C/d \tag{8}$$

where d is the bulk density, and A, B, and C are constants. The curve resulting from this analysis is presently used as a standard for quality control purposes.

In addition to the 297 K curve, statistical analyses were also performed on data obtained at 422 K. Since it has been observed that the thermal conductivity of glass fiber insulation varies exponentially with temperature, an approximate equation for the temperature dependence was obtained from the k versus d curves at 297 K and 422 K. The nominal thermal conductivity at temperature T for this class of insulation products is then given by

$$k_T = k_{297\ K} \exp\left[(\alpha_1 + \alpha_2/d)(T - 297)\right] \tag{9}$$

where α_1, and α_2, are constants obtained from the standard curves and apply to densities between 9.6 and 16 kg/m^3.

Only a small amount of data on the specific heat of glass fiber insulation was found in the literature. The specific heat is expected to vary from one type of insulation to another, depending to some extent upon the composition of the glass and type and amount of binder. An equation linear in temperature was fitted to selected data points, resulting in an equation that must be considered tentative at this time.

RESULTS OF DATA ANALYSES

When the analysis procedures described above were applied to the data for wood, the equations presented in Table 1 were derived. This table lists the numerical results in a format that would be used in a data book. It should be noted that these equations are based on the information available at the time, and may be subject to change as additional information is obtained. In the presentation of equations, the accepted SI symbol for thermal conductivity " λ ", has been used; when dealing with English units, simply read k or k_{75^oF} in place of λ or λ_{297K}.

To use these equations, one must know the density and moisture content of the piece of wood of interest. These quantities are very easy to measure if a sample of the wood is on hand. In case it is not possible to measure these quantities (e.g. for wood already in a building, or for a hypothetical case), an intelligent guess must be made. The density of wood varies significantly both from species to species and from one sample to another within a given species. Table 2 presents a list of average densities for several types of wood. These numbers represent averages over several species within each type of wood, and were computed from values given in the FPL Wood Handbook[15]. In the absence of other information, these values may be used for estimation purposes.

A plot of the thermal conductivity of wood near room temperature is given in Figure 2. For clarity, this plot shows only 144 data points along with the curve representing the equation. In order to represent the data on a two-dimensional plot, the thermal conductivity has been plotted against an "adjusted density", which is defined in terms of the quantities in Eq. 2 as:

$$d_{adj} = d\,(1 + \frac{a_1}{a_0} M)/(1 + 0.01M) \qquad (10)$$

For dry specimens, the adjusted density is equal to the true density. Also on this graph are shown the two points listed in the ASHRAE Handbook of Fundamentals. These values are seen to be in reasonable agreement with the derived equation. At very high densities, it is clear that the equation is not adequate. Fortunately these densities are outside the normal range for wood used in buildings, so that this is not a serious limitation of the equation.

Although several sets of data are available that show a temperature dependence, only one set of data covers a wide temperature range[9]. This set is plotted in Figure 3 along with the predicted curve appropriate to the density of this particular specimen. Unfortunately the moisture content of the specimen was not reported, so a nominal value of 6 percent was assumed. Looking at Figure 3, it would appear that the derived equation does not fit the data very well. However, the maximum deviation is only about 10 percent and this occurs at the very low temperature of 220 K(-64^{o}F). Nevertheless, there is definitely a need for more information on the temperature dependence of wood, as well as of other building materials.

With regard to anisotropy, it was found from eight sets of data that the ratio of conductivity parallel to the grain to that across the grain varied from 1.55 to 2.06 and had an average value of about 1.8. This ratio probably should depend upon temperature, density, and moisture content, but the available data are too scant to draw any conclusions. Therefore, the constant ratio of 1.8 is recommended as a reasonable approximation for all conditions.

The specific heat data on dry wood are shown in Figure 4, along with the curve representing the recommended equation. The specific heat data for moist wood are shown in Figure 5, along with curves from the equation for each of the moisture contents. The agreement between the curves and the measured data is fairly good, with the maximum deviation being about 16 percent. It should be noted that no data on moist wood below the freezing point of water were found, and so in this region the equations should be used with caution.

The numerical results for Fiberglas building insulation, again in a format that would be used in a data book are listed in Table 3. As was noted above, the equation for the thermal conductivity of Fiberglas building insulation is a standard curve against which current production is compared. This curve is shown in Figure 6, along with a recent set of data obtained on 38 mm thick specimens of product material from one machine using an ASTM C 518 apparatus. The density of each specimen was measured and was used in the equations to derive percentage deviations between measured and predicted values. The deviations were found to be small. The maximum deviation was 3.6 percent, while the mean deviation was only 1.1 percent. In the case of the maximum deviation, it is of interest to note that the measured conductivity value was lower than that predicted by the equation.

As with other building materials, the thermal conductivity data for Fiberglas building insulation at room temperature is much more voluminous than at other temperatures. Two recently measured sets of data are shown in Figure 7, along with the predicted curves for the two densities. The conductivity values are normalized to unity at 297 K to better illustrate the temperature dependence of the property. The agreement between the measured data and the predictions is seen to be very good.

Finally, Figure 8 shows a plot of the specific heat data on glass fiber insulation. As noted above, some judgement was used in selecting data for fitting the equation, and the resulting equation must be considered tentative. When all the data points are compared to the fitted curve, the maximum disagreement is found to be about 19 percent. This may not be a serious limitation from a practical point of view, since only a small fraction of the heat capacity of a structure is attributable to the insulation. However, from a scientific point of view, a more definitive knowledge of this property is desirable.

Specific heat measurements of light insulations are usually performed on highly compressed specimens. The quantity measured is thus the heat capacity of the solid materials and does not include the heat capacity of the air which would normally be enclosed. An approximate analysis shows that the error introduced into the specific heat measurement by this technique is less than the discrepancies between different sets of data.

In order to use the equations for thermal conductivity, the density of the insulation must be known. The equations presented above are based on the bulk density, which is the quantity obtained by dividing the scale weight of a sample by its volume. For reference purposes, Table 4 presents a listing of nominal product bulk densities. In a transient thermal calculation, the density to be used should correspond to the total mass, including the air enclosed within the insulation. For lightweight insulations, the mass of enclosed air is significant, and a true density should be used which is equal to the sum of the bulk density and the density of air. Table 4 presents a listing of nominal true densities for batt and blanket building insulations.

CONCLUSION

The thermophysical property data base activities at our laboratory have been described. The reasons for undertaking this work and the steps taken to collect and tabulate property data on building materials have been explained. Examples have been given of the data tables being constructed and of the analyses performed on the data once collected. For the two very important building materials, wood and glass fiber insulation, detailed recommended equations and graphical displays of thermal conductivity and specific heat data have been presented. It is concluded that more experimental data are needed to characterize the temperature dependence and anisotropy of the thermal properties of building materials in general. In particular, it is desirable to have additional data on the thermal conductivity and specific heat of the types of wood most commonly used in building construction (e.g., spruce, fir, pine, redwood). This data should cover the temperature and moisture content ranges normally encountered in buildings (say, 250 to 350 K and from oven-dry up to the fiber saturation point). For thermal conductivity, data should be obtained with heat flow both parallel and perpendicular to the grain. For glass fiber insulation, it is desirable to have additional specific heat data over the same temperature range for a variety of products. To be worthwhile, any property data generated should be accompanied by as complete a specimen characterization as possible. This should include items such as the source and composition of the material, the density and moisture content, specimen size and orientation, and observations of gross inhomogeneities. Ideally, specimen characterizations should be made both before and after the thermal property measurements.

NOMENCLATURE

a_o, a_1, b_1, b_2, b_3, A, B, C	constants in equations
c_p	specific heat, kJ/(kg•K) in SI units, or Btu/(lb•°F) in English units
c_{po}	specific heat of dry wood
c_{pw}	specific heat of water
Δc_p	contribution to specific heat of moist wood due to heat of sorption
d	density, kg/m^3 in SI units, or lb/ft^3 in English units, based on weight and volume at test conditions
d_{dry}	density of material based on dry weight but volume at test conditions
k	thermal conductivity, W/(m•K) in SI units, or Btu•in/(hr•ft^2•°F) in English units
k_{air}	thermal conductivity of air
M	moisture content, based on percentage of dry weight
T	temperature, K in SI units, or °F in English units
λ	thermal conductivity
λ_{air}	thermal conductivity of air
α, α_1, α_2	constants in equations

REFERENCES

1. ASHRAE HANDBOOK and Product Directory, 1977 Fundamentals, Chap. 22, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., New York, NY, 1977.

2. Touloukian, Y. S., et.al., editors, Thermophysical Properties of Matter, IFI/Plenum, New York, 1970.

3. Touloukian, Y. S., editor, Retrieval Guide to Thermophysical Properties Research Literature, McGraw-Hill, New York, Vol. 1-3, 1960.

4. Touloukian, Y. S., et.al., editors, Thermophysical Properties Research Literature Retrieval Guide, Supplement I, IFI/Plenum, New York, 1973.

5. MacLean, J. D., "The Thermal Conductivity of Wood," Trans. ASHVE, 47, 323, 1941.

6. Wangaard, F. F., "Transverse Heat Conductivity of Wood", Heating, Piping, and Air Conditioning, 12, 459-464, July, 1940.

7. Rowley, F. B., "The Heat Conductivity of Wood at Climatic Temperature Differences", Heating, Piping, and Air Conditioning, 5, 313, 1933.

8. Rowley, F. B., "The Heat Conductivity of Wood at Climatic Temperature Differences", Trans. ASHVE, 39, 329, 1933.

9. Rowley, F. B., Jordan, R. C., and Lander, R. M., "Low Mean Temperature Thermal Conductivity Studies", Refrigerating Engineering, 53, 35, January, 1947.

10. Lander, R., "Effect of Surface Resistance on Thermal Conductivity by the Hot Plate Method", University of Minnesota Engineering Experiment Station Technical Paper No. 40, May, 1942.

11. Griffiths, E. and Kaye, G. W. C., "The Measurement of Thermal Conductivity", Proc. Roy. Soc. (London), A104, 71-98, 1923.

12. Jespersen, H. B., "Thermal Conductivity of Moist Materials and its Measurement", J.I.H.V.E., 21, 157-174, 1953.

13. Dunlap, F., "The Specific Heat of Wood", USDA Forest Service Bulletin 110, Govt. Printing Office, 1912.

14. Hearmon, R. F. S. and Burcham, J. N.,"Specific Heat and Heat of Wetting of Wood", Nature, 176, 978, November, 1955.

15. Wood Handbook: Wood as an Engineering Material, by Forest Products Laboratory, Forest Service, U.S.D.A., Agriculture Handbook No. 72, US GPO, August, 1974.

16. McMillin, C. W., "Specific Heat of Ovendry Loblolly Pine Wood", Wood Science, 2, 2: 107, 1969.

17. Koch, P., "Specific Heat of Ovendry Spruce Pine Wood and Bark", Wood Science, 1, 4: 203, 1969.

18. Tye, R. P. and Spinney, S. C., "Measurement of the Specific Heat of Building Materials", Trans. ASHRAE, 84, Part 1, 675-687, 1978.

19. Wilkes, G. B. and Wood, C. O., "The Specific Heat of Thermal Insulating Materials", Trans. ASHVE, 48, 493, 1942.

Table 1. Thermophysical Properties of Wood

I. Thermal Conductivity

A. Across Grain, Near Room Temperature:

$$\lambda_{297K} = \lambda_{air} + (a_o + a_1 M)d/(1 + 0.01M)$$

SI Units	English Units
$\lambda_{air} = 0.02582$	$\lambda_{air} = 0.1791$
$a_o = 1.686 \times 10^{-4}$	$a_o = 1.874 \times 10^{-2}$
$a_1 = 5.177 \times 10^{-6}$	$a_1 = 5.753 \times 10^{-4}$

B. Temperature Dependence, Across Grain:

$$\lambda_{T,\perp} = \lambda_{297K}\left[1 + \left(\left(\frac{1}{\lambda}\frac{d\lambda}{dT}\right)_{air} + \alpha\, d\right)(T - T_R)\right]$$

SI Units	English Units
$\left(\frac{1}{\lambda}\frac{d\lambda}{dT}\right)_{air} = 2.927 \times 10^{-3}$	$\left(\frac{1}{\lambda}\frac{d\lambda}{dT}\right)_{air} = 1.626 \times 10^{-3}$
$\alpha = -3.736 \times 10^{-7}$	$\alpha = -3.326 \times 10^{-6}$
$T_R = 297$	$T_R = 75$

C. Parallel To Grain:

$$\lambda_{||} = 1.8\lambda_{T,\perp}$$

D. Statistics

Number of data points:	1094
Mean deviation from equations:	7.5%
RMS deviation from equations:	9.3%
Maximum deviation from equations:	36%

II. Specific Heat

A. Dry Wood

$$C_{po} = a_o + a_1 T$$

SI Units	English Units
$a_o = 0.1031$	$a_o = 0.2605$
$a_1 = 0.003867$	$a_1 = 0.0005132$

B. Moist Wood

$$C_p = (C_{po} + 0.01M\, C_{pw})/(1 + 0.01M) + \Delta C_p$$

$$\Delta C_p = M(b_1 + b_2\, T + b_3\, M)$$

SI Units	English Units
$C_{pw} = 4.186$	$C_{pw} = 1$
$b_1 = -0.06191$	$b_1 = -4.228 \times 10^{-4}$
$b_2 = 0.2355 \times 10^{-3}$	$b_2 = 3.125 \times 10^{-5}$
$b_3 = -0.1326 \times 10^{-3}$	$b_3 = -3.168 \times 10^{-5}$

C. Statistics

Number of data points:	142
Mean deviation from equations:	1.9%
RMS deviation from equations:	2.7%
Maximum deviation from equations:	16%

Table 2. Nominal Density of Wood at 12% Moisture Content

Type	Density, kg/m^3
Alder	460
Ash	620
Aspen	430
Basswood	415
Beech	715
Birch	680
Butternut	425
Cherry	560
Chestnut	480
Cottonwood	405
Elm	620
Hackberry	595
Hickory, pecan	710
Hickory, true	805
Honeylocust	675
Locust, black	775
Magnolia	550
Maple	600
Oak, red	715
Oak, white	780
Sassafras	515
Sweetgum	580
Sycamore, American	550
Tanoak	650
Tupelo	560
Walnut	615
Willow	435
Yellow-poplar	470
Baldcypress	515
Cedar	425
Douglas-fir	540
Fir	420
Hemlock	485
Larch	580
Pine	520
Redwood	420
Spruce	440
Tamarack	595

Table 3

Thermophysical Properties of Fiberglas Building Insulation

I. Apparent Thermal Conductivity*

A. Near Room Temperature

$$\lambda_{297K} = A + B \cdot d + C/d$$

SI Units	English Units
$A = 0.028572$	$A = 0.19815$
$B = 2.268 \times 10^{-5}$	$B = 2.521 \times 10^{-3}$
$C = 0.16851$	$C = 7.292 \times 10^{-2}$

B. Temperature Dependence

$$\lambda_T = \lambda_{297K} \exp\left[(\alpha_1 + \alpha_2/d)(T-T_R)\right]$$

SI Units	English Units
$\alpha_1 = 0.0036361$	$\alpha_1 = 0.0020201$
$\alpha_2 = 0.033275$	$\alpha_2 = 0.0011535$
$T_R = 297$	$T_R = 75$

C. Statistics (for sample of data)

Number of data points:	139
RMS deviation from equation in A.:	1.4%
Mean deviation from equation in A.:	1.1%
Maximum deviation from equation in A.:	3.6%

II. Specific Heat

$$C_p = a_o + a_1 T$$

SI Units	English Units
$a_o = 0.4205$	$a_o = 0.1794$
$a_1 = 0.001294$	$a_1 = 1.717 \times 10^{-4}$

Statistics:

Total number of data points:	9
Maximum deviation of any point from equation:	19%
Number of data points used for fit:	5
Maximum deviation of fitted points from equation:	4.5%

* Values for thermal conductivity apply to Owens-Corning batt and blanket products.

Table 4. Density of Fiberglas Insulation*

Resistance**	Bulk Density, kg/m^3	True Density, kg/m^3
R-8	11.2	12.4
R-11	9.86	11.1
R-13	14.8	16.0
R-19	10.1	11.3
R-22	13.0	14.2

*Applies to Owens-Corning batt and blanket insulation.

**Nominal resistances in usual English units.

THERMAL CONDUCTIVITY OF WOOD

Data Set No.	Ref. No.	Year	Temp. (K)	Thermal Conductivity (W/(m·K))	Density (kg/m^3)	Moisture Content; %	Specimen Description and Remarks
1	5	1941	303	0.102	410	0 (oven-dry)	Bigtooth aspen; average of 5 runs; density range - 400 to 420 kg/m^3; both heartwood and sapwood; measured with guarded hot plate (twin specimens), specimen size: 13 1/2 in. x 13 1/2 in. x 1/2 to 3/4 in.; ΔT = 22 to 33 degrees K; direction of heat flow partly radial and partly tangential.
2	5	1941	303	0.108	390	0 (oven-dry)	Baldcypress; average of 5 runs; density range - 360 to 440 kg/m^3; mostly heartwood; technique and orientation same as above.
3	5	1941	303	0.0591	160	0 (oven-dry)	Balsa; average of 4 runs; density range - 110 to 210 kg/m^3; technique and orientation same as above.
4	5	1941	303	0.0995	380	0 (oven-dry)	Basswood; average of 7 runs; density range - 350 to 410 kg/m^3; both heartwood and sapwood; technique and orientation same as above.
5	5	1941	303	0.110	460	0 (oven-dry)	Douglas-fir; average of 8 runs; density range - 370 to 490 kg/m^3; heartwood, technique and orientation same as above.
6	5	1941	303	0.167	760	0 (oven-dry)	Rock elm; both heartwood and sapwood; technique and orientation same as above.

Figure 1 Example of Page from Data Tables

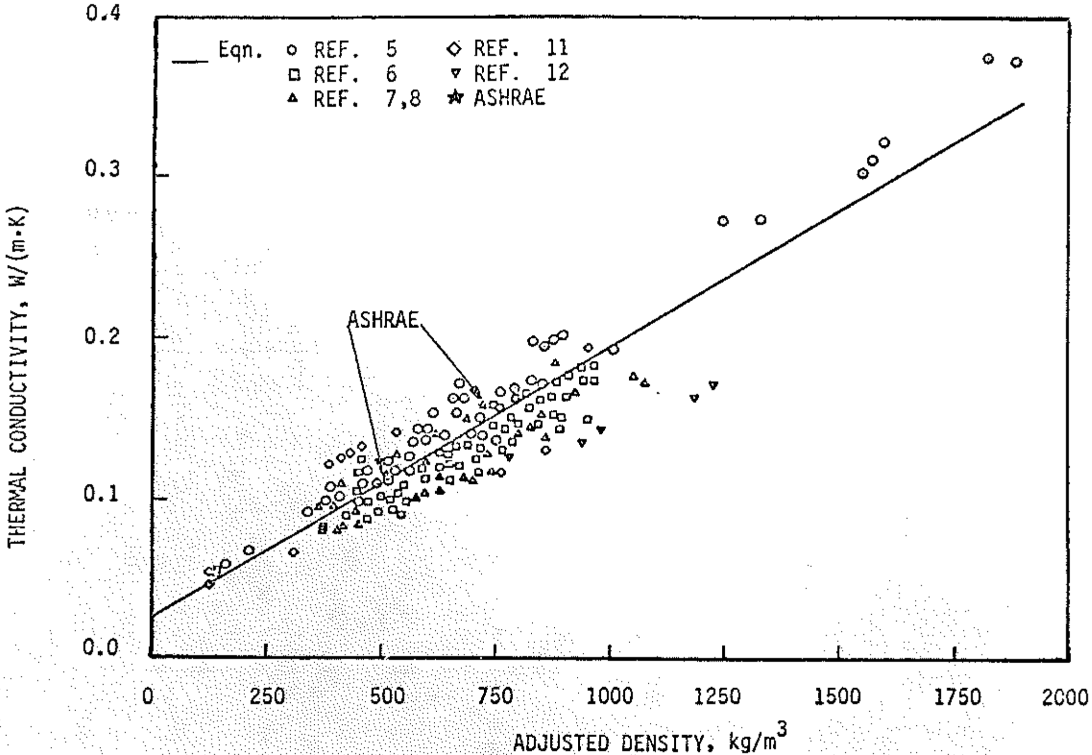

Figure 2 Thermal Conductivity of Wood Near 297K

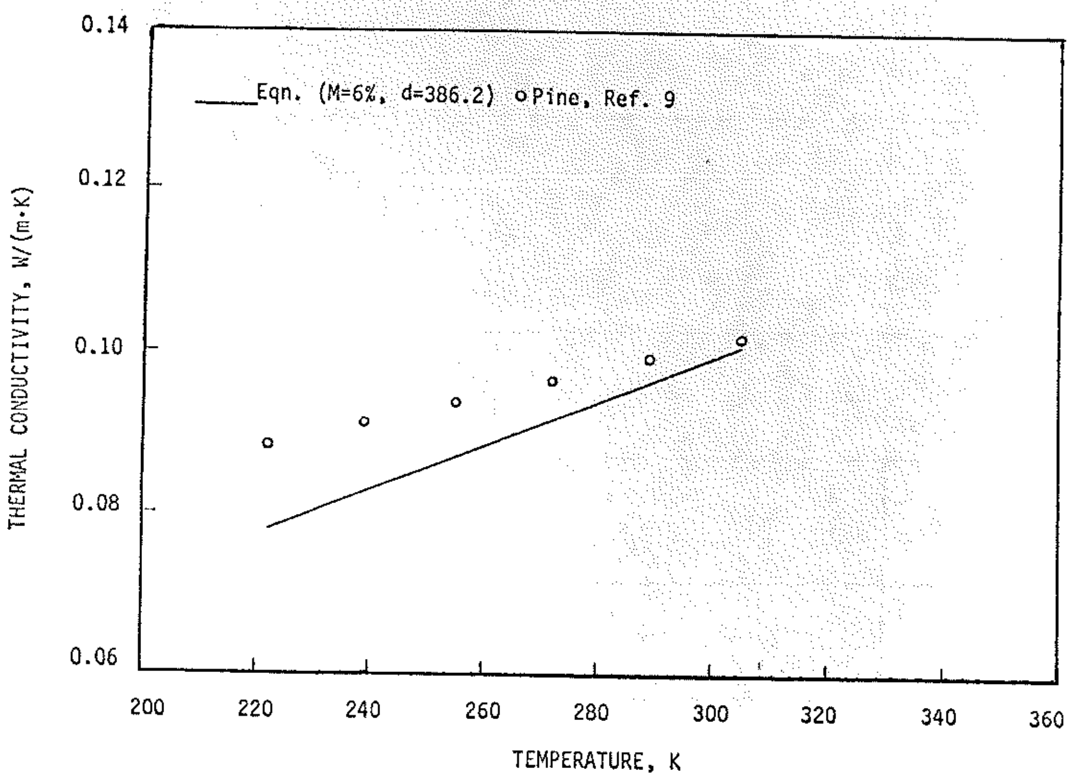

Figure 3 Thermal Conductivity of Wood

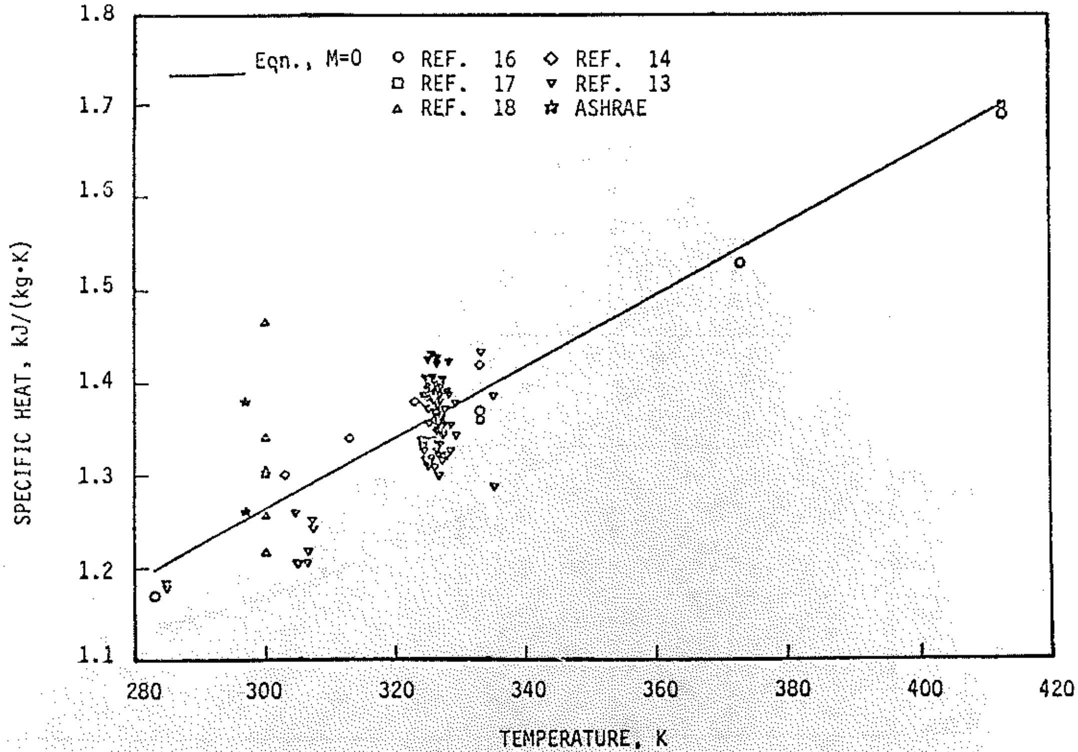

Figure 4 Specific Heat of Dry Wood

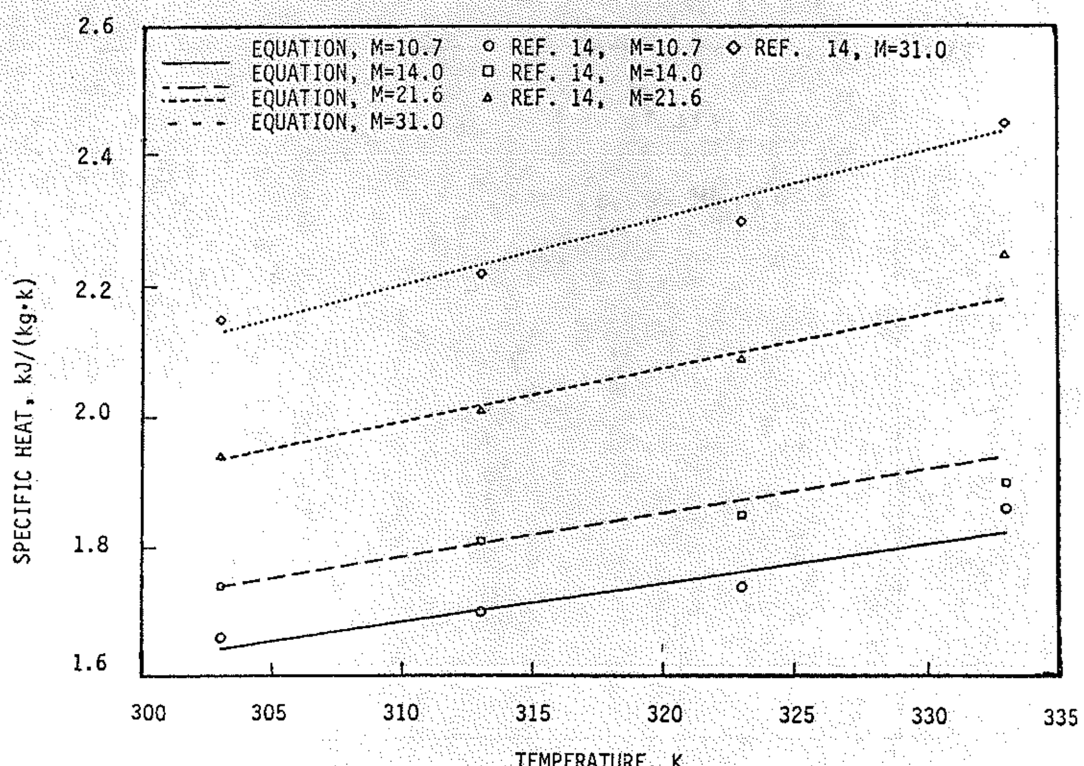

Figure 5 Specific Heat of Moist Wood

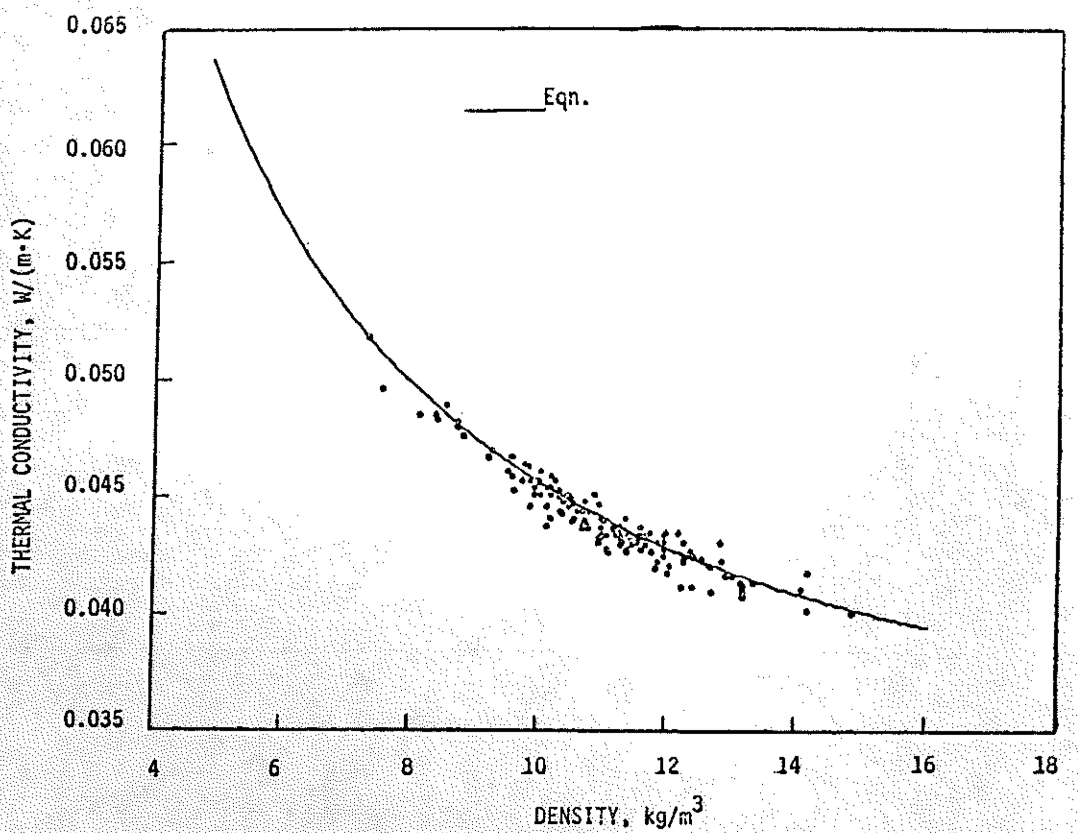

Figure 6 Apparent Thermal Conductivity of Owens-Corning Fiberglas Insulation near 297K

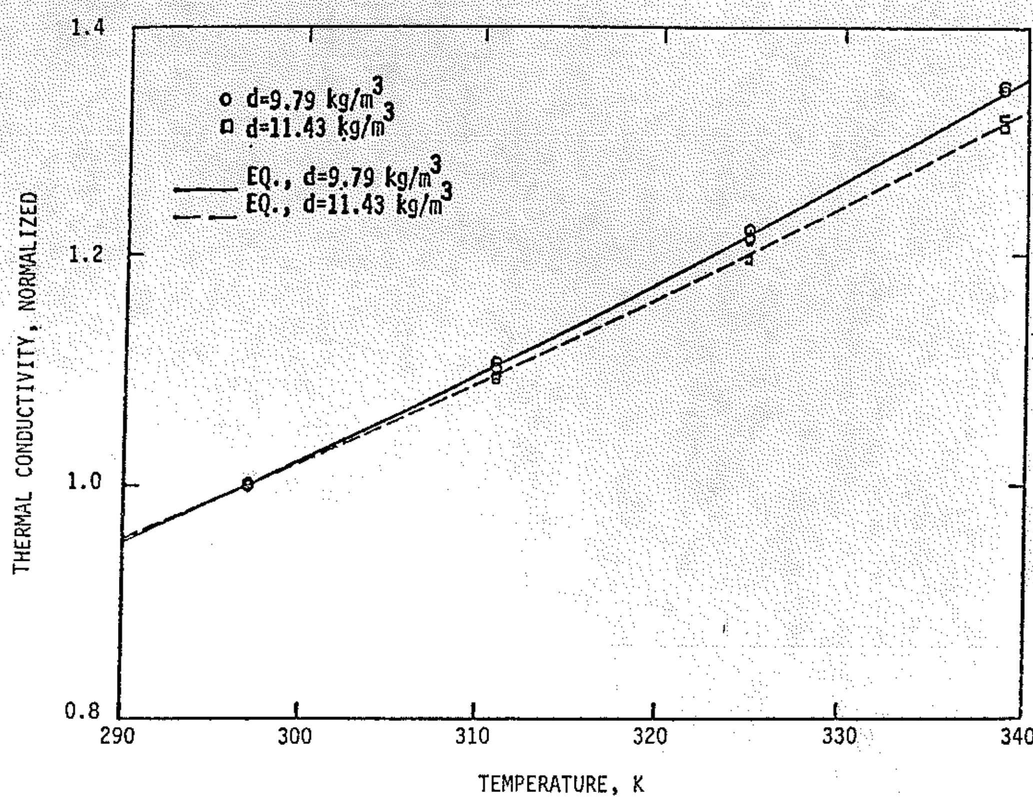

Figure 7 Apparent Thermal Conductivity of Owens-Corning Fiberglas Insulation

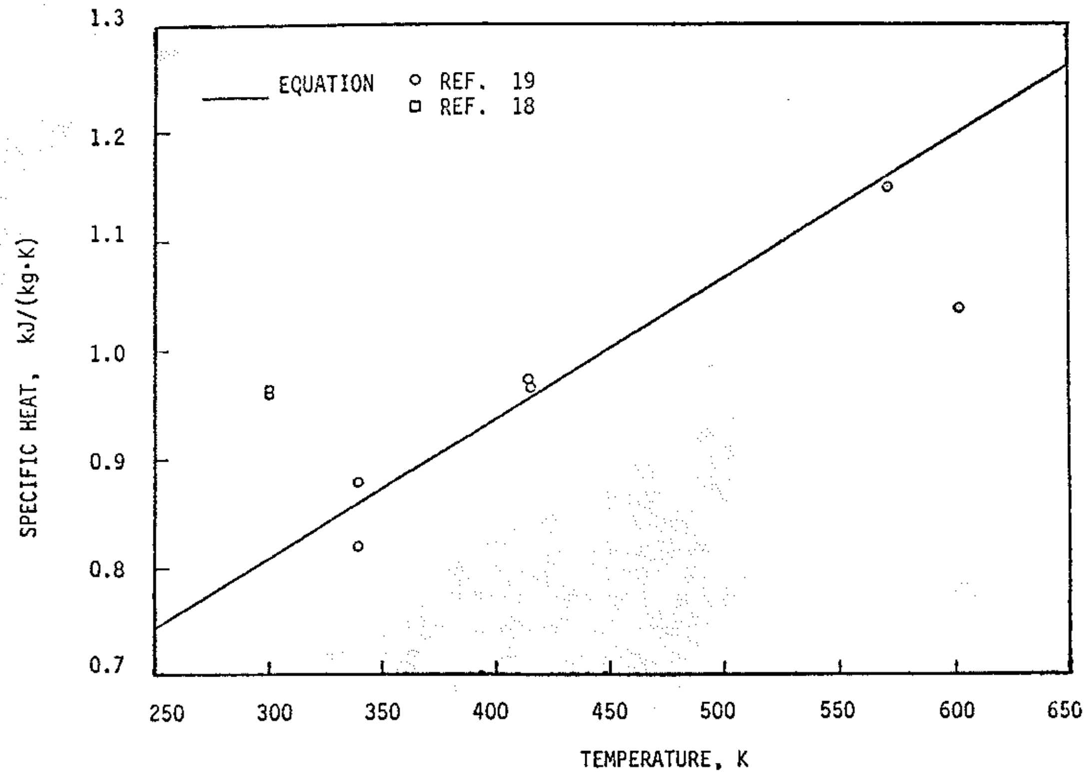

Figure 8 Specific Heat of Glass Fiber Insulation