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# Thermal Properties of Wood and Wood Panel Products for Use in Buildings

Anton TenWolde
J. Dobbin McNatt
Lorraine Krahn

Part of
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Building Thermal Envelope Systems
and Materials

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# THERMAL PROPERTIES OF WOOD AND WOOD PANEL PRODUCTS FOR USE IN BUILDINGS

Anton TenWolde
J. Dobbin McNatt
Lorraine Krahn

United States Department of Agriculture
Forest Service
Forest Products Laboratory
Madison, Wisconsin

Part of
The National Program for
Building Thermal Envelope Systems and Materials

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# FOREWORD

This is one of a series of reports to be published describing research, development, and demonstration activities in support of the National Program for Building Thermal Envelope Systems and Materials. The National Program involves several federal agencies and many other organizations in the public and private sectors who are addressing the national objective of decreasing energy wastes in the heating and cooling of buildings. Results described in this report are part of the National Program through delegation of management responsibilities for the DOE lead role to the Oak Ridge National Laboratory.

George E. Courville
Program Manager
Building Thermal Envelope
  Systems and Materials
Oak Ridge National Laboratory

J. A. Smith
Program Manager, Building Systems
  Division
Office of Buildings Energy R&D
Department of Energy

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# THERMAL PROPERTIES OF WOOD AND WOOD PANEL PRODUCTS FOR USE IN BUILDINGS

by

Anton TenWolde
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## ABSTRACT

This report provides a review and evaluation of currently available information on the thermal conductivity and specific heat of wood building materials. We derived a linear equation for thermal conductivity of solid wood as a function of density and moisture content from data in the literature and used this to provide estimated conductivity values for various types of hardwoods and softwoods.

Far fewer data exist for the thermal conductivity of wood panel products. Current design values appear to be based on the premise that the conductivity of plywood is the same as that of solid wood of the same species, but the few reported results from measurements indicate a lower conductivity. More definitive information exists on the conductivity of conventional particleboard and fiberboard, but additional conductivity measurements of plywood and some of the most commonly used flakeboards, such as oriented strandboard (OSB), are needed. Additional measurements of the specific heat are needed for all wood panel products.

We discuss special problems of measuring thermal properties of wood products with high moisture contents and the practical relevance of such data to building design and performance, and we conclude that thermal properties above fiber saturation are of little practical significance. The report contains the authors' recommendations for design values for thermal properties and for further research and additional measurements, as well as a bibliography.

# INTRODUCTION

Because of the significant presence of wood and wood products in buildings, the energy design of wood frame buildings and the evaluation of their energy performance depends in part on thermal properties of wood products. Published data on thermal properties seem to show inconsistencies and variations, possibly due to differences in test methods and conditions or errors in measurement. Physical properties of wood also vary considerably due to variability in the material, even within one wood species. Moisture content (MC) of the wood product also plays a significant role in the outcome of the test. Inconsistencies in the data compromise the implementation of building energy efficiency standards as well as efforts to model energy performance.

Several new wood-based particle panel products have appeared on the market during the last few decades. Although products such as plywood, waferboard, and oriented strandboard (OSB) have replaced solid wood boards as wall and roof sheathing, few thermal design data are available for these board products. We do know, however, that the thermal properties of these particleboard are substantially different from those of solid wood (l). Wangaard (2), Wilkes (3), Beall (4), and Steinhagen (5), among others, have published reviews of thermal property data for wood and wood products. This study serves as an update on these reviews while including a wider range of wood panel products.

This study was part of a national building materials research agenda, which was conceived in support of the National Program for Building Thermal Envelope Systems and Materials. The objective of the program is to coordinate efforts to decrease energy waste in the heating and cooling of buildings. The National Progran Plan was last published in 1982 (Oak Ridge National Laboratory 1982). An update of the National Program Plan is currently in preparation through the Building Thermal Envelope Coordinating Council (BTECC).

# OBJECTIVES

The objectives of this study were to determine variability and significance of thermal properties of wood products as a function of MC and species and to identify voids in the data base.

These objectives are aligned with objectives in Project Description IA2, Task 1 and 2, in the Building Materials Research Agenda (6). This agenda was published as part of the National Program for Building Thermal Envelope Systems and Materials.

The properties of interest to thermal design and modeling are thermal conductivity and specific heat. Thermal diffusivity was not separately evaluated because it can be calculated if specific heat and conductivity are known: thermal diffusivity is defined as the ratio of conductivity to the product of specific heat and density. We included a table with calculated diffusivities for selected wood species. The principal thrust of the study was a review and evaluation of the literature and available data. No thermal measurements were conducted for this project. We did not consider the effect of nails and screws on the thermal performance of wood products in service.

## WOOD-BASED BUILDING MATERIALS

### DEFINITIONS

This study focused on the thermal properties of solid wood, as used in framing, and several commonly used structural wood panel products. These include plywood, fiberboard, and several types of particleboard. Figure 1 shows several of these wood panel products.

Fig. 1. Selected wood panel products: waferboard (left),-underlayment particleboard (center), and medium-density fiberboard (right).

Following are some descriptive definitions.

Plywood--a glued wood panel made of relatively thin layers of veneer with the grain of adjacent layers at right angles, or of veneer in combination with a core of lumber or reconstituted wood.

Fiberboard--panels manufactured of refined or partially refined wood fibers, fiberboard types vary widely in density. This category includes insulating board and hardboard.

Particleboard--generic term for panels manufactured from wood particles and a synthetic resin or other suitable binder. In this paper we use the term particleboard for particleboard not specifically identified as flakeboard.

Flakeboard--particleboard composed of flakes. A flake is a small wood particle of predetermined dimensions and uniform thickness, with fiber direction essentially in the plane of the flake.

Oriented Strandboard (OSB)--flakeboard composed of three or more layers of cross-aligned strandlike flakes that are purposefully aligned to improve strength, stiffness, and dimensional stability in the alignment direction.

Waferboard--flakeboard composed of wafer-type flakes. Usually manufactured to have equal properties in all directions parallel to the plane of panel.

## MOISTURE IN WOOD

Wood usually contains some water. This moisture may be chemically bound within the cell walls, or be present as liquid or water vapor in the cell cavity. Moisture content of wood is defined as the weight of the water as a fraction or percentage of the ovendry weight of the wood. Methods to determine MC are described in ASTM test specification D 2016, "Standard Test Methods for Moisture Content of Wood." Wood adsorbs moisture from the air with varying relative humidity. The equilibrium moisture content (EMC) is the MC of wood in equilibrium with the surrounding air. The fiber saturation point is defined as the stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities are free from water. It applies to an individual cell or group of cells, not to whole boards. It averages about 30 percent MC for solid wood (7). The fiber saturation point has also been defined as the MC below which the physical and mechanical properties begin to change as a function of MC. Wood also absorbs water in the cell cavity and may reach MCs well beyond the fiber saturation point.

# TEST METHODS FOR THERMAL PROPERTIES

## THERMAL CONDUCTIVITY

The thermal conductivity of a material is defined as the steady-state heat flow rate per unit area per unit of temperature gradient through unit thickness in the direction perpendicular to the isothermal surface. It is expressed in W/m-K (Btu-in-/$ft^2$-h- °F). The thermal conductivity of materials with low conductivities may be obtained from two standard linear heat flow test procedures. One method employs calibrated heat flowmeters and is described in ASTM test specification c 518, "Standard Test Method for Steady-state Thermal Transmission Properties by Means of the Heat Flow Meter." A steady-state unidirectional heat flux through the specimen is maintained between two parallel plates and measured with a calibrated heat flux transducer. The method provides a rapid means of determining conductivity.

Thermal conductivity can also be determined by nears of the guarded hot plate. This method is described in ASTM test specification c 177, "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Guarded Hot Plate" (8). This method has been most often used in the determination of thermal conductivity of wood and wood products. The guarded hot plate apparatus consists of a heating unit, cooling units, and edge insulation to help prevent excessive edge losses. The heating unit contains a central metering section and a guard section. Two test specimens are placed between the heating unit and the two cooling units. Essentially, the thermal conductivity is determined by measuring the power that needs to be supplied to the metering section of the hot plate in order to maintain a measured temperature differential across the specimen under steady-state conditions. Figure 2 shows the general features of the guarded hot plate apparatus.

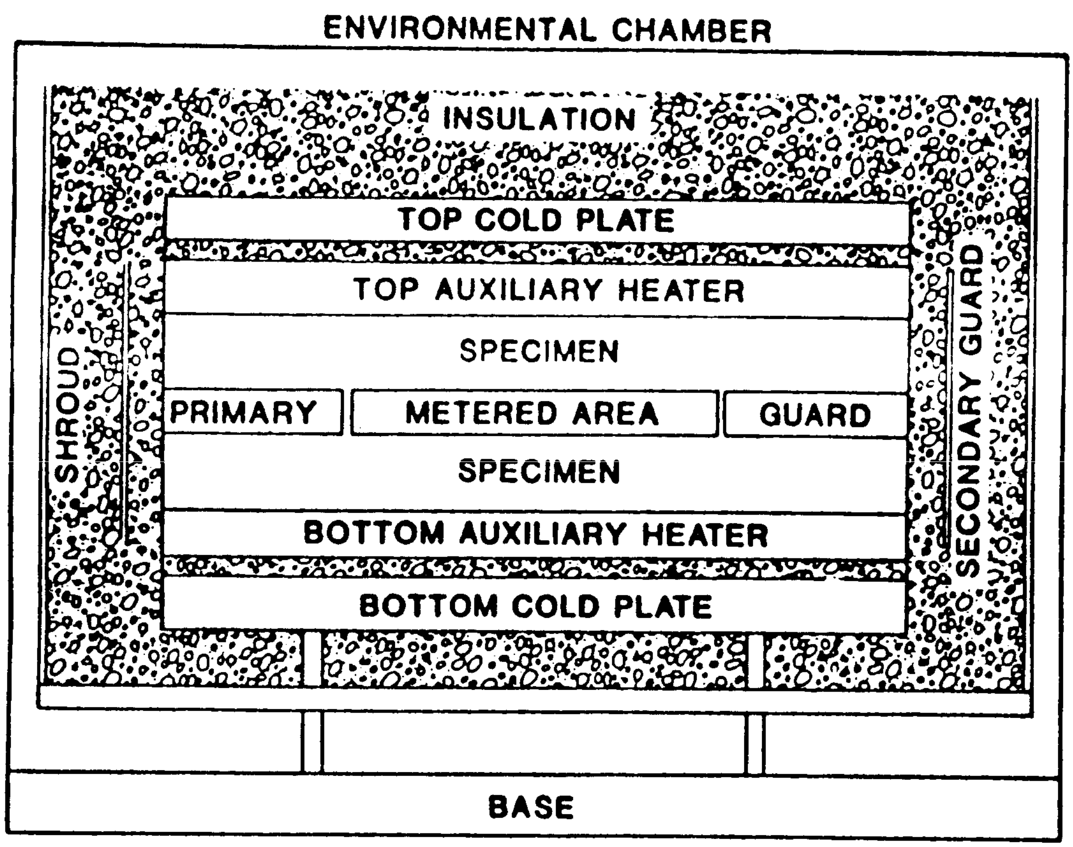


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Fig. 2. General features of the guarded hot plate apparatus.

## SPECIFIC HEAT

There is some confusion about the definition of specific heat; while some references define it as the dimensionless ratio of the material’s thermal capacity to that of water, other references define it as the quantity of heat required to change the temperature of a unit mass of the material 1°, with J/kg-K (Btu/lb °F) as the unit of measurement. Both ASTM (8) and ASHRAE (9) use the second definition, and we used that definition in this report.

The mean specific heat of a material may be obtained by test procedure ASTM C 351, "Standard Test Method for Mean Specific Heat of Thermal Insulation" (8). As stated in the standard, the test method is easily adapted to measurement of materials other than thermal insulation. The method employs a calibrated calorimeter: a test specimen of known mass is heated to a given temperature in a special brass capsule, The capsule with the specimen is then dropped into the calorimeter containing a known amount of water at a lower temperature. The original and equilibrium temperatures are recorded, and the change in enthalpy is found by equating the amount of heat gained by the water to the amount of heat lost by the sample. The change in enthalpy is measured as a function of temperature, and the mean specific heat is calculated from the derivative.

## COMBINED MEASUREMENT OF CONDUCTIVITY AND SPECIFIC HEAT

Combined measurement of specific heat and thermal conductivity is also possible by applying a continually changing temperature to the sample and a heat sink with known heat capacity. If specific boundary conditions are satisfied, there exists a simple relationship between the combination of conductivity and the specific heat of the specimen and the measured temperatures, By repeating the measurement with two or more different heat sinks, the conductivity and specific heat of the specimen can be calculated. Ward and Skaar applied this method to several particleboard specimens, and details of the measurements can be found in this reference (10). As will be discussed later in this report, their results do not agree with other published data. One possible reason for this is the moisture redistribution in the specimens under a changing thermal gradient. This produces high initial readings for thermal conductivity, as we discuss further in the next section.

## MEASUREMENTS AT HIGH MOISTURE CONTENTS

Several difficulties arise in determining thermal properties when the MC of the wood-based material is high. The effect of the moisture not only confounds the measurement but also raises some doubt about the practical significance of the results. These issues are discussed in the following section.

## Thermal Conductivity Measurements

When moist wood is subjected to a thermal gradient, a redistribution of the moisture takes place resulting in a transient heat flow. During redistribution the apparent conductivity is considerably larger than the steady-state conductivity. MacLean (11) observed that, in solid wood specimens of 0.5 to 0.75 in thickness with an initial MC below 12 to 15 percent, most of this redistribution generally took place within 24 h without significant change in conductivity after that. Usually equilibrium was reached after only 6 h. Above 15 percent initial MC, condensation on the cold plate was observed. The time to reach steady state was also considerably longer; some specimens with MC over 60 percent took several days to reach their final moisture distribution. Measured conductivity at the beginning of the test is significantly higher than at the end (11). Bomberg and Shirtliffe (12) observed a similar effect in moist concrete and mineral fiberboard. The final condition is not a true equilibrium condition; although there is no net flow of moisture, there are opposing flows of water vapor and bound/liquid moisture (12). In this quasi-steady-state condition, in contrast to the initial transient phase, the contribution of these moisture flows to the overall heat flow is usually very small and can generally be ignored.

As the moisture is redistributed the wood or wood-based panel may warp. Warp reduces the contact of the specimen with the plates, and this generally causes lower conductivity readings. Sufficient clamping force needs to be applied to resist the warp during the test.

Measurements at temperatures below freezing pose special hazards; all or part of the free water in wood above the fiber saturation point may freeze, producing heat in the process. The measured apparent conductivity would be smaller during this initial stage. The final steady-state conductivity is larger because thermal conductivity of ice is much greater than that of liquid water, This results in discontinuous behavior below freezing temperatures of wood above fiber saturation (5).

## Specific Heat Measurements

Specific heat of wood above fiber saturation also exhibits a discontinuity in behavior at freezing temperatures (5). The free water freezing at temperatures slightly below O C abruptly changes the specific heat due to the much lower specific heat of ice. No such sudden changes are present in wood below fiber saturation.

## Practical Significance of Measurements

Not only are measurements at high MC difficult to perform, the results have dubious practical benefit to the building community. The measured steady-state values differ greatly from instantaneous "apparent" values because of moisture movement and phase changes. In-service temperature and moisture conditions continually change, sometimes rapidly. The resulting moisture and heat flows are interdependent, complex, and virtually impossible to predict with great precision. Therefore measurement of steady-state properties of wet wood and wood products without better knowledge of the moisture movement does not necessarily lead to better information about in-service transient thermal performance. Moreover, the MC of wood in properly designed and constructed buildings stays well below fiber saturation. If wood is found to be above fiber saturation for significant periods of time, corrective measures are necessary to lower MC and prevent decay. Thermal conductivity of wood above fiber saturation is therefore of little practical significance to building design and performance.

Steady-state thermal properties are useful for comparisons among building materials. Values for dry wood or for wood at MC expected in normal service should be used to compare the thermal performance of wood with that of other materials and to design buildings for themal efficiency.

# THERMAL PROPERTIES OF SOLID WOOD

## THERMAL CONDUCTIVITY

### Background

The thermal conductivity of solid wood increases with density (or specific gravity), MC, and temperature. A number of other factors also play a role, such as extractive content and the number of checks and knots in the wood.[1] Wood is an anisotropic material, and conductivity along the grain is between 1.5 to 2.8 times the conductivity across the grain (Fig. 3). Wilkes reported an average measured ratio of 1.8 (3). The ratio is generally larger for dry wood than for time containing moisture. For practical building applications, the heat flow is primarily across the grain and we will limit our discussion to that situation.

MacLean was one of the first to systematically investigate conductivity as a function of MC and density (11). He essentially assumed additive parallel heat flows through the cell wall substance, the air, and the water in the wood. This assumption leads to a general

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[1]Extractives are substances in wood, not an integral part of the cellular structure, that can be removed by solution in hot or cold water, ether, benzene, or other solvents that do not react chemically with wood components. A check is a lengthwise separation of the wood that usually extends across the rings of annual growth and commonly results from stresses set up in wood during seasoning (7).

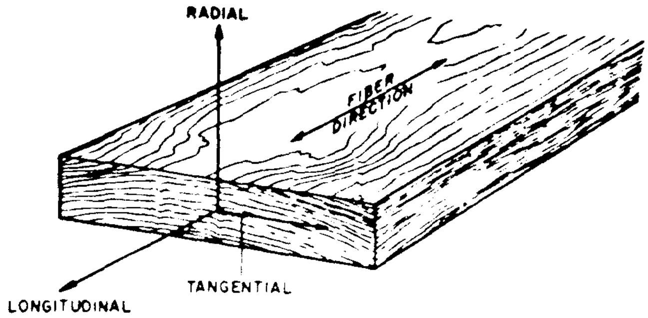


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Fig. 3. The three principal axes of wood with respect to grain direction and growth rings.

linear relationship among thermal conductivity, density, and MC, independent of species:

$$k = D(a_0 + a_1 M) + k_0 \tag{1}$$

where $k_0$ = constant (W/m-K)
$D$ = dry density ($kg/m^3$)
$M$ = moisture content (percent of dry weight)
$a_0$, $a_1$ = constants ($m^4/s^3$-K)

MacLean (11),and later Wilkes (3), postulated that $k_0$ should roughly equal the conductivity of air (approximately 0.024 W/m-K). Fitting this line to the results of his measurements, MacLean arrived at the following relationships:

$$k = (D/1000)(0.2001 + 0.004031M) + 0.02376 \tag{2}$$

for MCs below 40 percent, and

$$k = (D/1000)(0.2001 + 0.005472M) + 0.02376 \tag{3}$$

for MCs over 40 percent, with thermal conductivity expressed in W/m-K. Equations (2) and (3) can also be found in the Wood Handbook (7). Equation (2) is the-basis for the few design values listed in the ASHRAE handbook (9).

Kollman independently derived a linear equation for wood at 12 percent MC (13):

$$k = 0.219(D/1000) + 0.0256 \tag{4}$$

This equation is not very different from Equation (2) at 12 percent MC.

Wilkes essentially used the same approach, but used a larger data set for his linear regression (3). This resulted in the equation

$$k = (D/1000)(0.1686 + 0.005177M) + 0.02582 \tag{5}$$

for all MCs. This equation generally yields slightly lower conductivities than Equations (2) and (3). For 12 percent MC, it gives results very similar to Equation (4).

A literature review by Steinhagen mentions an alternative proposed linear relationship, based on a series of measurements of the conductivity of birch wood at a wide range of temperatures and MCs (5). The measurements appear to have been conducted with an instantaneously applied heat source, not with a steady-state guarded hot-plate device. To extend these results to different species an adjustment factor is proposed, assuming that conductivity increases proportionally with density. Steinhagen shows that this method produces values consistently above those measured by other researchers (5). For this reason and because of the unconventional measurement method we did not consider this approach in our analysis.

Siau (14) developed an alternative heat flow model. He calculated the total heat flow as the sum of several heat flows in parallel and series. With simplifying assumptions about the cell geometry and alignment, a theoretical formula for k may be derived. In this form k is a relatively complex function of the square root of the porosity (a). However, Siau found that the following linear approximation may be substituted for the more complex function for woods with a dry density range of 150 to 1400 kg/m$^3$:

$$k = 0.509547 - 0.471983a \tag{6}$$

where

$a = \sqrt{(1 - 0.000667D - 0.00001MD)}$

$D$ = dry density (kg/m$^3$)

$M$ = moisture content (percent of dry weight)

The differences in conductivities resulting from alternative Equations (2), (5), and (6) are shown in Figure 4 for dry wood and wood with a 25 percent MC.

## Available Data

References containing conductivity data for solid wood are listed in Table 1. Some sources list only average conductivity for a series of measurements of the same species of the same density and MC. Others contain results from individual observations. The bulk of the measurements were taken before 1942. Only one reference is more recent (18). There may be some value in repeating some of these measurements with more modern equipment to reestablish their accuracy. Assuming that the data are generally accurate, there are more than enough data points to determine the effect of density and MC. However, the variation in measurement temperature in the data was not sufficient to confidently establish the effect of temperature over a wide range of temperatures.

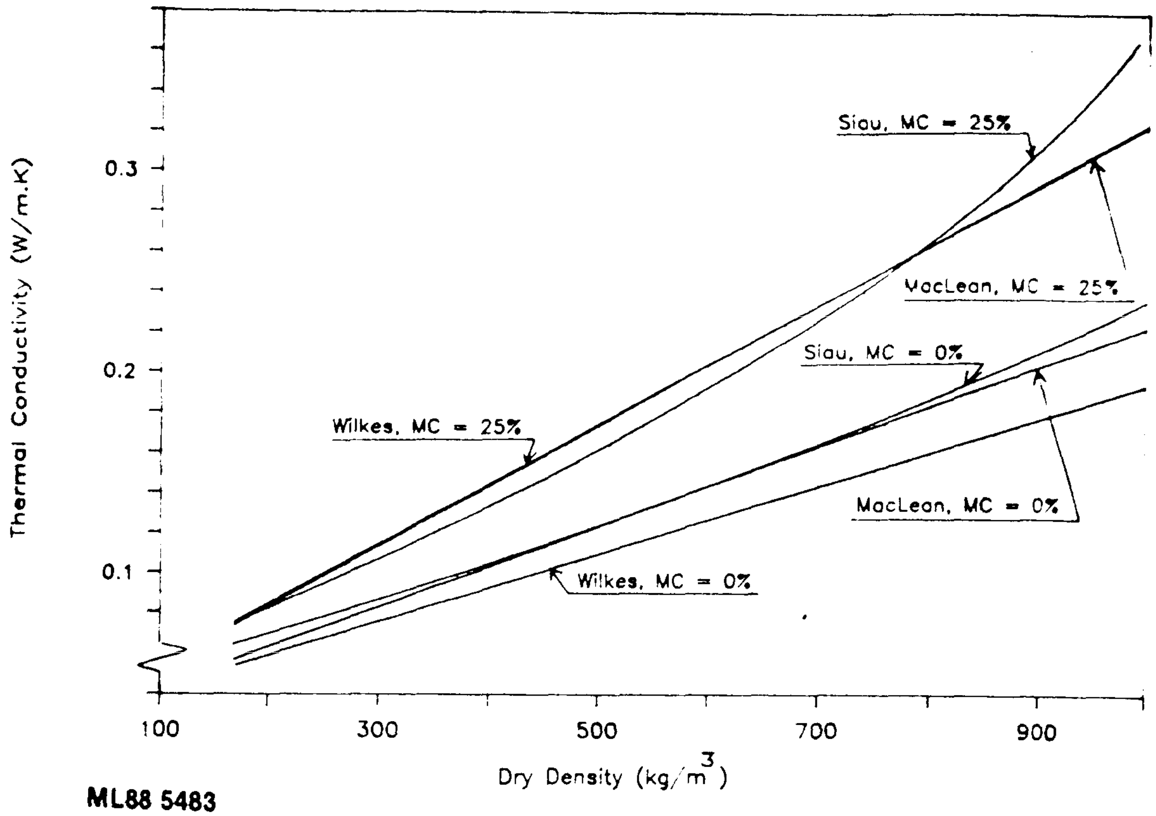



Fig. 4. Comparison of three alternative equations for conductivity of solid wood at 0 and 25 percent MC.

Effect of Moisture and Density

We evaluated two hypotheses: (a) thermal conductivity of solid wood is a linear function of density and MC of the form of equation (1), and (b) thermal conductivity of solid wood is a nonlinear function of density and MC of the form of Equation (6). We tested hypotheses to see if an equation similar to Equation (6) would better represent the data for wood with a high MC or with a very low density (e.g., balsa wood).

Most of the data were for heat flow across the grain. This is also the most common situation in buildings, and we therefore limited our analysis to heat flow across the grain. We essentially used the same data set as Wilkes, but he added the restriction that the conductivity equation should produce the conductivity of air if density and MC are equal to zero (3). We examined whether this had a significant effect on the slope of the line.

Most of the measurements were done at MCs below 25 percent on specimens with densities above 300 $kg/m^3$ (0.3 specific gravity). To avoid undue influence of extreme outliers we limited the regression to this range. This range includes all species commonly used for construction and covers moisture conditions most commonly found in

Table 1. Thermal conductivity measurements reported in the literature

| Type | Source | Number of data sets[a] | Number of observations |
|---|---|---|---|
| Solid wood | MacLean (11) | 56 | 477 |
| | Wangaard (15) | 236 | 236 |
| | Rowley (16) | 306 | 306 |
| | Griffiths and Kaye (17) | 29 | 29 |
| | Jespersen (18) | 11 | 11 |
| Plywood | MacLean (11) | 1 | 12 |
| | Rowley, Jordan, Lander (19) | 18 | 18 |
| | Lund, Lander, Kanninen (20) | 9 | 9 |
| | White and Schaffer (21) | 1 | 3 |
| Fiberboard | Lewis (1) | 21 | 84 |
| | Ratcliffe (22) | 10 | 10 |
| | Rowley, Jordan, Lander (19) | 18 | 18 |
| | Rowley et al. (23) | 4 | 4 |
| | Ball (24) | 12 | 12 |
| | Pratt and Ball (25) | 14 | 14 |
| Particleboard | Lewis (1) | 9 | 36 |
| | Ward and Skaar (10) | 1 | 23 |
| Flakeboard | Nanassy and Szabo (26) | 7 | 7 |
| | Ward and Skaar (10) | 3 | 70 |
| | White and Schaffer (21) | 1 | 3 |

[a]A data set is one observation or the average of several observations.

service. Where data points represented an average of several observations, the points were weighted by the number of observations, following the method used by Wilkes (3).

Linear equation. When we assume a linear relationship of the form of Equation (1) the results of the linear regression are as follows:

$$k = (D/1000)(0.1941 + 0.004064M) + 0.01864 \qquad (7a)$$

with thermal conductivity expressed in W/m-K., dry density in kg/m$^3$, and MC in percent. With English units this translates into

$$k = (D/1000)(21.55 + 0.4514M) + 0.1292 \qquad (7b)$$

with thermal conductivity expressed in Btu-in/h-ft$^2$-°F and dry density in lb/ft$^3$. The regression was restricted to densities above 300 kg/m$^3$ and MC below 25 percent. The root mean square error for the regression is 0.016 W/m-K; this means that Equation (7a) will predict conductivity within approximately 0.03 W/m-K and Equation (7b) within 0.2 Btu-in/h-ft$^2$- °F for densities above 300 kg/m$^3$ and MC below 25 percent.

Equation (7) may be used with caution outside this range but is likely to produce less accurate results: the maximum deviation was 25 percent for high MC measurements and 35 percent for low-density measurements.

Figure 5 compares individual data points with conductivity obtained with Equation (7). The figure includes data points outside the density and MC range used for the regression; conductivity values below 0.075 W/m-K are for dry specimens with densities below 300 kg/m$^3$; values over 0.25 W/m-K are for high-density specimens with MC over 25 percent. Equation (7) underpredicts for high conductivities (i.e., high densities and MC). However, as stated before, not enough data are available in that region to deduce better predictive equations.

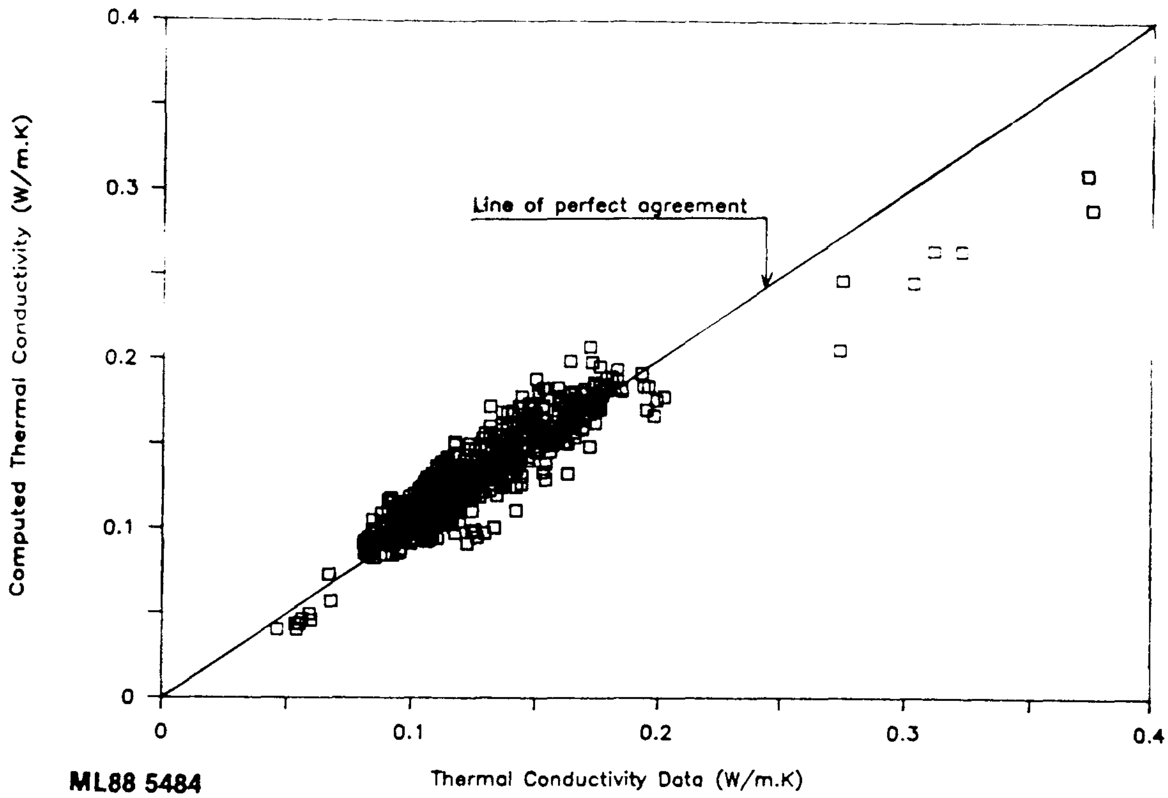
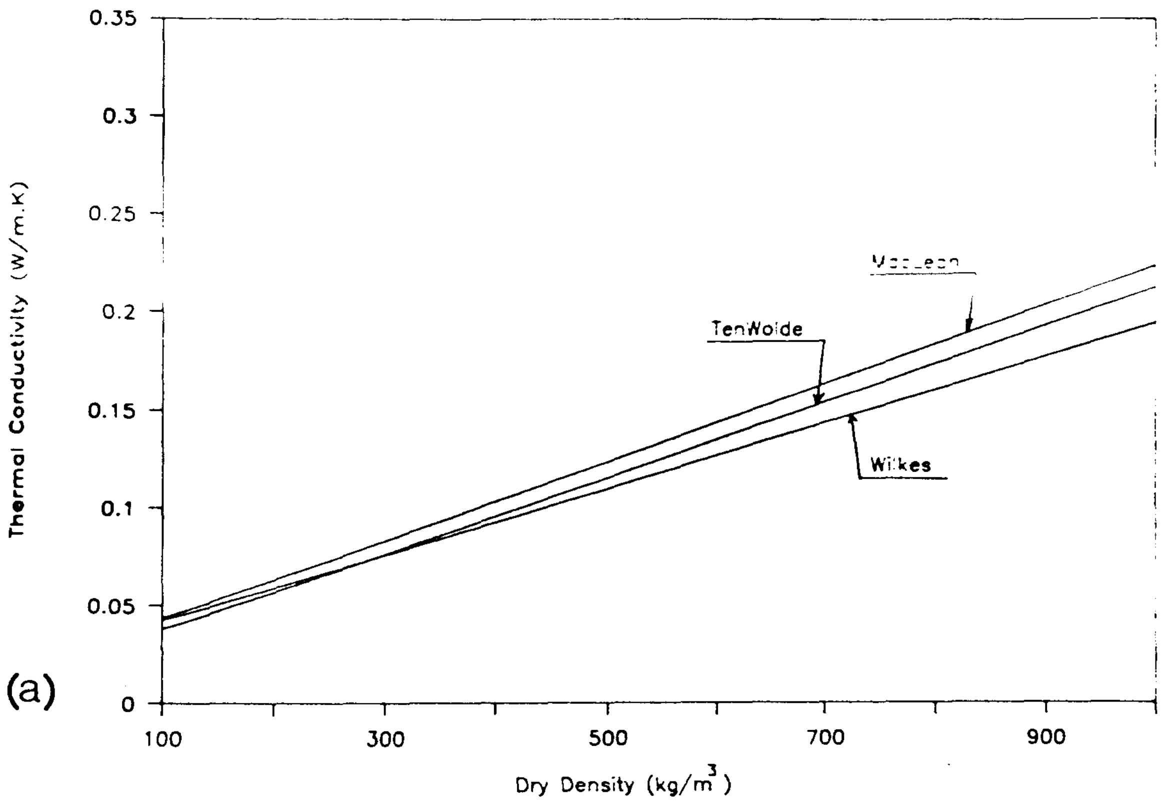


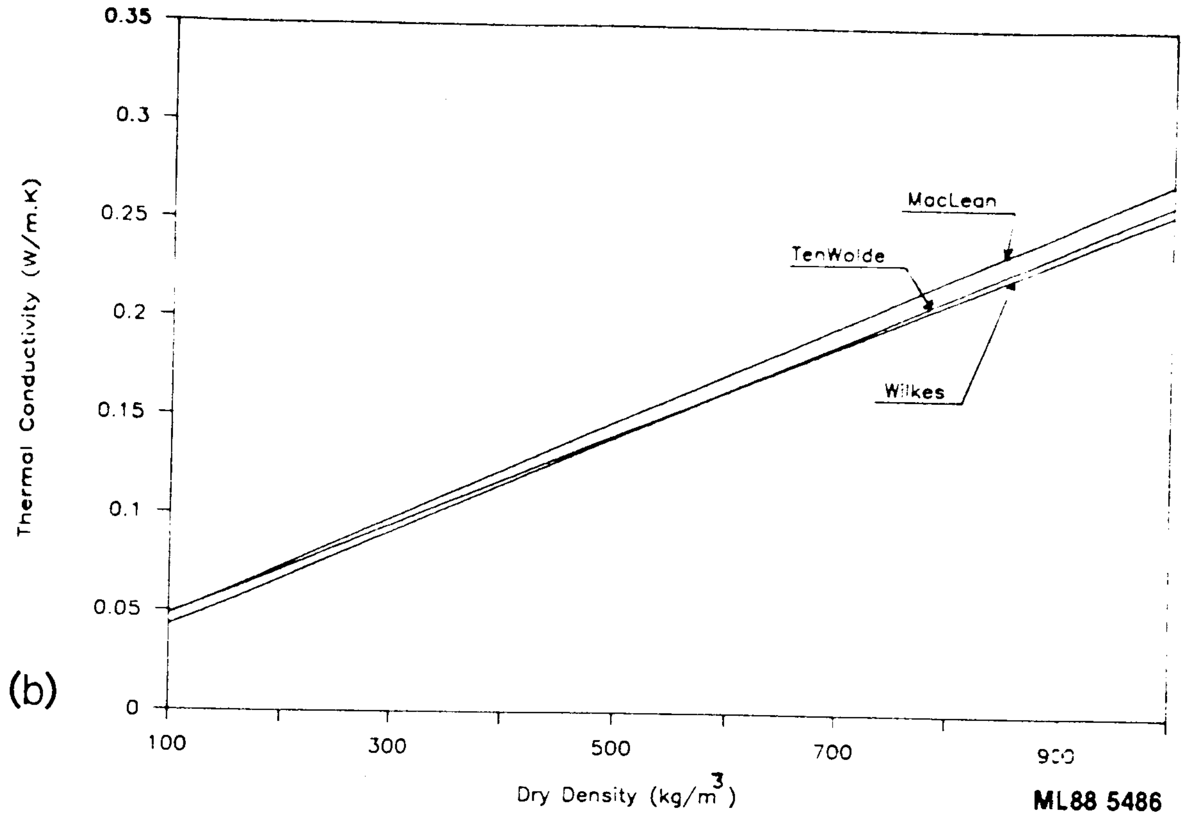

Fig. 5. Comparison of calculated conductivity of solid wood (Eq. (7a)) with conductivity data. All data on conductiavity across the grain are included.

Figure 6(a, b, and c) shows a comparison of this regrssion line, identified as "TenWolde" in the figures, with those of Wilkes and MacLean for several MCs (3,11). The differences for ovendry wood are the greatest, with Equation (7) yielding conductivities between the other two over most of the density range. The differences between "Wilkes" and "TenWolde" are primarily the effect of Wilkes forcing the regression line through the conductivity value of air because both lines are based on virtually the same data set. For MCs around 12 percent, Wilkes' formula gives almost identical results, and MacLean's formula gives slightly higher conductivities. At 25 percent MC, Equation (7) produces slightly lower values than the other two.




(a)

ML88 5485



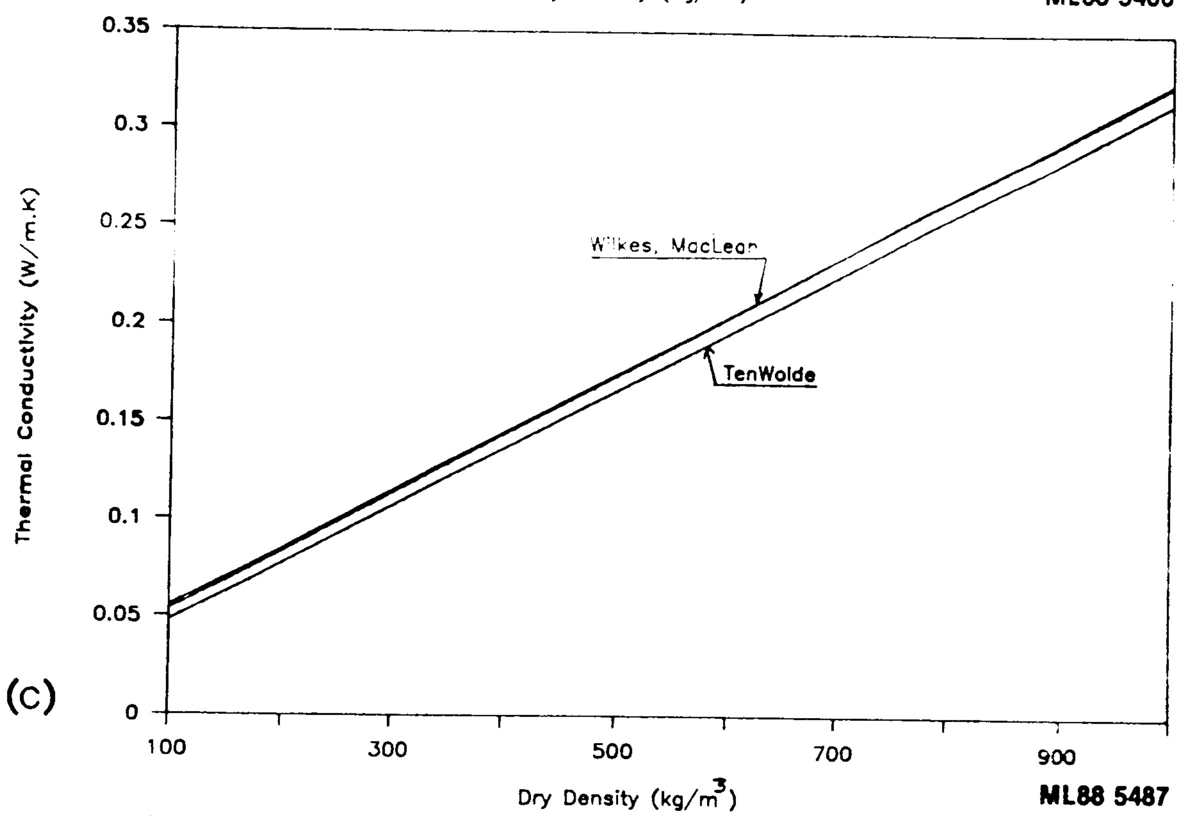




Fig. 6. Comparison of equations for conductivity of sclid wood at (a) 0, (b) 12 percent, and (c) 25 percent MC.

Tables 2 through 5 show some typical conductivities for different species calculated with Equations (7a) and (7b). These values are only approximate, actual conductivity will vary due to the inherent error in the equation and variations in density, MC, and direction in heat flow. ASTM Standard D 2555, "Standard Methods for Establishing Clear Wood Strength Values," lists coefficients of variation of about 10 percent for specific gravity within wood species (8). This produces a coefficient of variation in conductivity of between 5 and 10 percent. If we define the error as twice the coefficient of variation and add the inherent error in Equation (7), the total error in the values in tables 2 through 5 is approximately 20 percent.

Nonlinear equation, Taking a nonlinear equation of the form of Equation (6) as hypothesis for regression yields

$$k = 0.5166 - 0.4859a \qquad (8)$$

where

$a = \sqrt{(1 - 0.000667D - 0.00001MD)}$

$k$ = thermal conductivity (W/m-K)

$M$ = moisture content (percent)

$D$ = density ($kg/m^3$)

This result is quite similar to Siau's published equation (Eq. (6)) (14). However, there are no obvious advantages to using this more complex equation; it produces slightly better results for low densities but worse results for high MC. We therefore concluded that a linear equation is preferable because of its simplicity.

## Effect of Temperature

Most of the measurements were conducted at an approximate average specimen temperature of 24°C (297 K), Data were not sufficient to confidently determine the effect of temperature on thermal conductivity of solid wood. However, MacLean concluded from a limited number of experiments that the effect of temperature is relatively minor (11). Other data reported by Steinhagen indicate that the effect of temperature is in the order of 0.2 percent per kelvin (5). This is in fairly good agreement with the results reported by Wilkes (3). This means that conductivity increases approximately 10 percent for every 50°C (K) increase in temperature, a relatively small effect.

## Discussion

Equation (7) has some advantages over previously published equations for conductivity of solid wood. The equation is based on more than twice the number of data MacLean used to arrive at Equation (2) (11). It also has two minor advantages over Equation (5) proposed by Wilkes; it is not "forced" through any points and is not unduly influenced by a few extreme measurements (3), Both equations, however,

Table 2. Average thermal conductivity and resistivity of various hardwoods, as calculated with Equation (7b) (SI units)[a]

| Species, hardwoods | Specific gravity | Density ($kg/m^3$) | Conductivity, k (W/m-K) | | Resistivity, R (m-K/W)) | |
|---|---|---|---|---|---|---|
| | | | Ovendry | 12% MC | Ovendry | 12% MC |
| Ash | | | | | | |
| Black | 0.53 | 530 | 0.12 | 0.15 | 8.2 | 6.8 |
| White | 0.63 | 630 | 0.14 | 0.17 | 7.1 | 5.8 |
| Aspen | | | | | | |
| Bigtooth | 0.41 | 410 | 0.10 | 0.12 | 10 | 8.5 |
| Quaking | 0.40 | 400 | 0.10 | 0.12 | 10 | 8.6 |
| Basswood, American | 0.38 | 380 | 0.092 | 0.11 | 11 | 9.0 |
| Beech, American | 0.68 | 680 | 0.15 | 0.18 | 6.6 | 5.4 |
| Birch | | | | | | |
| Sweet | 0.71 | 710 | 0.16 | 0.19 | 6.4 | 5.2 |
| Yellow | 0.66 | 660 | 0.15 | 0.18 | 6.8 | 5.6 |
| Cherry, black | 0.53 | 530 | 0.12 | 0.15 | 8.2 | 6.8 |
| Chestnut, American | 0.45 | 450 | 0.11 | 0.13 | 9.4 | 7.8 |
| Cottonwood | | | | | | |
| Black | 0.35 | 350 | 0.087 | 0.10 | 12 | 9.6 |
| Eastern | 0.43 | 430 | 0.10 | 0.12 | 9.8 | 8.1 |
| Elm | | | | | | |
| American | 0.54 | 540 | 0.12 | 0.15 | 8.1 | 6.7 |
| Rock | 0.67 | 670 | 0.15 | 0.18 | 6.7 | 5.5 |
| Slippery | 0.56 | 560 | 0.13 | 0.15 | 7.9 | 6.5 |
| Hackberry | 0.57 | 570 | 0.13 | 0.16 | 7.7 | 6.4 |
| Hickory, pecan | 0.69 | 690 | 0.15 | 0.19 | 6.6 | 5.4 |
| Hickory, True | | | | | | |
| Mockernut | 0.78 | 780 | 0.17 | 0.21 | 5.9 | 4.8 |
| Shagbark | 0.77 | 770 | 0.17 | 0.21 | 5.9 | [illegible] |
| Magnolia, southern | 0.52 | 520 | 0.12 | 0.14 | 8.4 | 6.9 |
| Maple | | | | | | |
| Black | 0.60 | 600 | 0.14 | 0.16 | 7.4 | 6.1 |
| Red | 0.56 | 560 | 0.13 | 0.15 | 7.9 | 6.5 |
| Silver | 0.50 | 500 | 0.12 | 0.14 | 8.6 | 7.1 |
| Sugar | 0.66 | 660 | 0.15 | 0.18 | 6.8 | 5.6 |
| Oak, Red | | | | | | |
| Black | 0.66 | 660 | 0.15 | 0.18 | 6.8 | 5.6 |
| Northern red | 0.65 | 650 | 0.14 | 0.18 | 6.9 | 5.7 |
| Southern red | 0.62 | 620 | 0.14 | 0.17 | 7.2 | 5.9 |
| Oak, white | | | | | | |
| Bur | 0.66 | 660 | 0.15 | 0.18 | 6.8 | 5.6 |
| White | 0.72 | 720 | 0.16 | 0.19 | 6.3 | 5.2 |
| Sweetgum | 0.55 | 550 | 0.13 | 0.15 | 8.0 | 6.6 |
| Sycamore, American | 0.54 | 540 | 0.12 | 0.15 | 8.1 | 6.7 |
| Tupelo | | | | | | |
| Black | 0.54 | 540 | 0.12 | 0.15 | 8.1 | 6.7 |
| Water | 0.53 | 530 | 0.12 | 0.15 | 8.2 | 6.8 |
| Yellow-poplar | 0.46 | 460 | 0.11 | 0.13 | 9.3 | 7.7 |

[a] Values in this table are approximate and should be used with caution; actual conductivities may vary by as much as 20 percent.

Table 3. Average thermal conductivity and resistivity of softwoods, as calculated with Equation (7a) (SI units)[a]

| Species, softwoods | Specific gravity | Density ($kg/m^3$) | Conductivity, k (W/m-K) | | Resistivity, R (m-K/W)) | |
|---|---|---|---|---|---|---|
| | | | Ovendry | 12% MC | Ovendry | 12% MC |
| Baldcypress | 0.47 | 470 | 0.11 | 0.13 | 9.1 | 7.5 |
| Cedar | | | | | | |
| Alaska | 0.46 | 460 | 0.11 | 0.13 | 9.3 | 7.7 |
| Atlantic white | 0.34 | 340 | 0.085 | 0.10 | 12 | 9.9 |
| Eastern red | 0.48 | 480 | 0.11 | 0.14 | 8.9 | 7.4 |
| Northern white | 0.31 | 310 | 0.079 | 0.094 | 13 | 11 |
| Port Orford | 0.43 | 430 | 0.10 | 0.12 | 9.8 | 8.1 |
| Western red | 0.33 | 330 | 0.083 | 0.10 | 12 | 10 |
| Douglas-fir | | | | | | |
| Coast | 0.51 | 510 | 0.12 | 0.14 | 8.5 | 7.0 |
| Interior north | 0.50 | 500 | 0.12 | 0.14 | 8.6 | 7.1 |
| Interior west | 0.52 | 520 | 0.12 | 0.14 | 8.4 | 6.9 |
| Fir | | | | | | |
| Balsam | 0.37 | 370 | 0.090 | 0.11 | 11 | 9.2 |
| White | 0.41 | 410 | 0.10 | 0.12 | 10 | 8.5 |
| Hemlock | | | | | | |
| Eastern | 0.42 | 420 | 0.10 | 0.12 | 10 | 8.3 |
| Western | 0.48 | 480 | 0.11 | 0.14 | 8.9 | 7.4 |
| Larch, western | 0.56 | 560 | 0.13 | 0.15 | 7.9 | 6.5 |
| Pine | | | | | | |
| Eastern white | 0.37 | 370 | 0.091 | 0.11 | 11 | 9.2 |
| Jack | 0.45 | 450 | 0.11 | 0.13 | 9.4 | 7.8 |
| Loblolly | 0.54 | 540 | 0.12 | 0.15 | 8.1 | 6.7 |
| Lodgepole | 0.43 | 430 | 0.10 | 0.12 | 9.8 | 8.1 |
| Longleaf | 0.62 | 620 | 0.14 | 0.17 | 7.2 | 5.9 |
| Pitch | 0.53 | 530 | 0.12 | 0.15 | 8.2 | 6.8 |
| Ponderosa | 0.42 | 420 | 0.10 | 0.12 | 10 | 8.3 |
| Red | 0.46 | 460 | 0.11 | 0.13 | 9.3 | 7.7 |
| Shortleaf | 0.54 | 540 | 0.12 | 0.15 | 8.1 | 6.7 |
| Slash | 0.61 | 610 | 0.14 | 0.17 | 7.3 | 6.0 |
| Sugar | 0.37 | 370 | 0.090 | 0.11 | 11 | 9.2 |
| Western white | 0.40 | 400 | 0.10 | 0.12 | 10 | 8.6 |
| Redwood | | | | | | |
| Old growth | 0.41 | 410 | 0.10 | 0.12 | 10 | 8.5 |
| young growth | 0.37 | 370 | 0.090 | 0.11 | 11 | 9.2 |
| Spruce | | | | | | |
| Black | 0.43 | 430 | 0.10 | 0.12 | 9.8 | 8.1 |
| Engelmann | 0.37 | 370 | 0.090 | 0.11 | 11 | 9.2 |
| Red | 0.42 | 420 | 0.10 | 0.12 | 10 | 8.3 |
| Sitka | 0.42 | 420 | 0.10 | 0.12 | 10 | 8.3 |
| White | 0.37 | 370 | 0.090 | 0.11 | 11 | 9.2 |

[a]Values in this table are approximate and should be used with caution: actual conductivities may vary by as much as 20 percent.

Table 4. Average thermal conductivity and resistivity of hardwoods, as calculated with Equation (7b) (English units)[a]

| Species, softwoods | Specific gravity | Density (lb ft$^3$) | Conductivity, k (Btu-in/h-ft$^2$-F) | | Resistivity, R (h-ft$^2$-°F/Btu-in) | |
|---|---|---|---|---|---|---|
| | | | Ovendry | 12% MC | Ovendry | 12% MC |
| Ash | | | | | | |
| Black | 0.53 | 33 | 0.84 | 1.0 | 1.2 | 0.98 |
| White | 0.63 | 40 | 0.98 | 1.2 | 1.0 | 0.84 |
| Aspen | | | | | | |
| Bigtooth | 0.41 | 25 | 0.68 | 0.82 | 1.5 | 1.22 |
| Quaking | 0.40 | 25 | 0.66 | 0.79 | 1.5 | 1.26 |
| Basswood, American | 0.38 | 24 | 0.64 | 0.77 | 1.6 | 1.30 |
| Beech, American | 0.68 | 42 | 1.0 | 1.3 | 0.96 | 0.79 |
| Birch | | | | | | |
| Sweet | 0.71 | 44 | 1.1 | 1.3 | 0.92 | 0.75 |
| Yellow | 0.66 | 41 | 1.0 | 1.2 | 0.98 | 0.81 |
| Cherry, black | 0.53 | 33 | 0.84 | 1.0 | 1.2 | 0.98 |
| Chestnut, American | 0.45 | 28 | 0.74 | 0.89 | 1.4 | 1.1 |
| Cottonwood | | | | | | |
| Black | 0.35 | 22 | 0.61 | 0.72 | 1.7 | 1.4 |
| Eastern | 0.43 | 27 | 0.71 | 0.85 | 1.4 | 1.2 |
| Elm | | | | | | |
| American | 0.54 | 34 | 0.85 | 1.0 | 1.2 | 0.97 |
| Rock | 0.67 | 42 | 1.0 | 1.3 | 0.97 | 0.80 |
| Slippery | 0.56 | 35 | 0.88 | 1.1 | 1.1 | 0.94 |
| Hackberry | 0.57 | 35 | 0.89 | 1.1 | 1.1 | 0.92 |
| Hickory, pecan | 0.69 | 43 | 1.1 | 1.3 | 0.94 | 0.77 |
| Hickory, true | | | | | | |
| Mockernut | 0.78 | 49 | 1.2 | 1.4 | 0.85 | 0.69 |
| Shagbark | 0.77 | 48 | 1.2 | 1.4 | 0.86 | 0.70 |
| Magnolia, southern | 0.52 | 33 | 0.8 | 1.0 | 1.2 | 0.99 |
| Maple | | | | | | |
| Black | 0.60 | 38 | 0.94 | 1.1 | 1.1 | 0.87 |
| Red | 0.56 | 35 | 0.88 | 1.1 | 1.1 | 0.93 |
| Silver | 0.50 | 31 | 0.80 | 0.97 | 1.2 | 1.0 |
| Sugar | 0.66 | 41 | 1.0 | 1.2 | 0.99 | 0.81 |
| Oak, Red | | | | | | |
| Black | 0.66 | 41 | 1.0 | 1.2 | 0.98 | 0.81 |
| Northern red | 0.65 | 41 | 1.0 | 1.2 | 1.0 | 0.82 |
| Southern red | 0.62 | 39 | 0.96 | 1.2 | 1.0 | 0.85 |
| Oak, white | | | | | | |
| Bur | 0.66 | 41 | 1.0 | 1.2 | 0.98 | 0.80 |
| White | 0.72 | 45 | 1.1 | 1.3 | 0.91 | 0.75 |
| Sweetgum | 0.55 | 34 | 0.86 | 1.0 | 1.2 | 0.95 |
| Sycamore, American | 0.54 | 33 | 0.85 | 1.0 | 1.2 | 0.97 |
| Tupelo | | | | | | |
| Black | 0.54 | 34 | 0.85 | 1.0 | 1.2 | 0.97 |
| Water | 0.53 | 33 | 0.84 | 1.0 | 1.2 | 0.99 |
| Yellow-poplar | 0.46 | 29 | 0.75 | 0.91 | 1.3 | 1.1 |

[a]Values in this table are approximate and should be used with caution: actual conductivities may vary by as much as 20 percent.

Table 5. Average thermal conductivity and resistivity of softwoods, as calculated with Equation (7b) (English units)[a]

| Species, softwoods | Specific gravity | Density ($lb/ft^3$) | Conductivity, k ($Btu\text{-}in/h\text{-}ft^2\text{-}F$) | | Resistivity, R ($h\text{-}f^2\text{-}°F/Btu\text{-}in$) | |
|---|---|---|---|---|---|---|
| | | | Ovendry | 12% MC | Ovendry | 12% MC |
| Baldcypress | 0.47 | 29 | 0.76 | 0.92 | 1.3 | 1.1 |
| Cedar | | | | | | |
| Alaska | 0.46 | 29 | 0.75 | 0.91 | 1.3 | 1.1 |
| Atlantic white | 0.34 | 21 | 0.59 | 0.70 | 1.7 | 1.4 |
| Eastern red | 0.48 | 30 | 0.77 | 0.93 | 1.3 | 1.1 |
| Northern white | 0.31 | 20 | 0.55 | 0.66 | 1.8 | 1.5 |
| Port Orford | 0.43 | 27 | 0.71 | 0.86 | 1.4 | 1.2 |
| Western red | 0.33 | 21 | 0.58 | 0.69 | 1.7 | 1.4 |
| Douglas-fir | | | | | | |
| Coast | 0.51 | 32 | 0.82 | 0.99 | 1.2 | 1.0 |
| Interior north | 0.50 | 31 | 0.81 | 0.96 | 1.2 | 1.0 |
| Interior west | 0.52 | 33 | 0.83 | 1.0 | 1.2 | 0.99 |
| Fir | | | | | | |
| Balsam | 0.37 | 23 | 0.63 | 0.75 | 1.6 | 1.3 |
| White | 0.41 | 26 | 0.68 | 0.82 | 1.5 | 1.2 |
| Hemlock | | | | | | |
| Eastern | 0.42 | 26 | 0.70 | 0.84 | 1.4 | 1.2 |
| Western | 0.48 | 30 | 0.77 | 0.94 | 1.3 | 1.1 |
| Larch, western | 0.56 | 35 | 0.88 | 1.1 | 1.1 | 0.94 |
| Pine | | | | | | |
| Eastern white | 0.37 | 23 | 0.63 | 0.75 | 1.6 | 1.3 |
| Jack | 0.45 | 28 | 0.73 | 0.88 | 1.4 | 1.1 |
| Loblolly | 0.54 | 33 | 0.85 | 1.03 | 1.2 | 0.97 |
| Lodgepole | 0.43 | 27 | 0.70 | 0.85 | 1.4 | 1.2 |
| Longleaf | 0.62 | 38 | 0.96 | 1.2 | 1.0 | 0.86 |
| Pitch | 0.53 | 33 | 0.84 | 1.0 | 1.2 | 0.98 |
| Ponderosa | 0.42 | 26 | 0.70 | 0.84 | 1.4 | 1.2 |
| Red | 0.46 | 29 | 0.75 | 0.91 | 1.3 | 1.1 |
| Shortleaf | 0.54 | 33 | 0.85 | 1.0 | 1.2 | 0.97 |
| Slash | 0.61 | 38 | 0.96 | 1.2 | 1.0 | 0.86 |
| Sugar | 0.37 | 23 | 0.63 | 0.75 | 1.6 | 1.3 |
| Western white | 0.40 | 25 | 0.66 | 0.80 | 1.5 | 1.2 |
| Redwood | | | | | | |
| Old growth | 0.41 | 25 | 0.68 | 0.82 | 1.5 | 1.2 |
| Young growth | 0.37 | 23 | 0.62 | 0.74 | 1.6 | 1.3 |
| Spruce | | | | | | |
| Black | 0.43 | 27 | 0.71 | 0.85 | 1.4 | 1.2 |
| Engelmann | 0.37 | 23 | 0.63 | 0.75 | 1.6 | 1.3 |
| Red | 0.42 | 26 | 0.69 | 0.84 | 1.4 | 1.2 |
| Sitka | 0.42 | 26 | 0.69 | 0.83 | 1.4 | 1.2 |
| White | 0.37 | 23 | 0.63 | 0.76 | 1.6 | 1.3 |

[a] Values in this table are approximate and should be used with caution: actual conductivities may vary by as much as 20 percent.

yield generally quite similar results, and the differences are well within the margin of error of 0.03 W/m-K.

The root mean square error in the regression was 0.016 W/m-K. Differences in equipment and temperature caused part of this variation. The rest of the variation is probably due to variations in density distribution, moisture distribution, and variability in grain direction.

Solid wood building materials used on the building site also vary in basic properties. Wood used in construction usually has knots and checks. We therefore believe that improving Equation (7) would not only be difficult, but of very little practical value to builders or designers. Equation (7) yields adequate average conductivities for a given MC and density.

## SPECIFIC HEAT

### Background and Available Data

Although there are fewer data for specific heat than there are for conductivity of solid wood, there is sufficient information. Table 6 lists sources of data in the literature. Specific heat is expressed per unit of mass and is therefore essentially independent of the density of the wood. It is however influenced by temperature and MC.

Table 6. Specific heat measurements reported in the literature

| Type | Source | Number of data sets[a] | Number of observations |
|---|---|---|---|
| Solid wood | McMillin (27) | 4 | 4 |
| | Koch (28) | 3 | 3 |
| | Tye and Spinney (29) | 6 | 6 |
| | Hearmon and Burcham (30) | 5 | 20 |
| | Dunlap (31) | 115 | 115 |
| Fiberboard | Wilkes and Wood (32) | 2 | 2 |
| | Tye and Spinney (29) | 10 | 10 |
| | Pratt and Ball (25) | 8 | 8 |
| Particleboard | Ward and Skaar (10) | 1 | 23 |
| Flakeboard | Ward and Skaar (10) | 3 | 70 |
| | Nanassy and Szabo (26) | 6 | 6 |

[a]A data set is one observation or the average of several observations.

Effect of Temperature

In 1912 Dunlap published an empirical formula for the specific heat of dry wood $c_{p,0}$, as a function of temperature T:

$$c_{p,0} = 0.00485T - 0.212 \quad (9)$$

where specific heat is expressed in kJ/kg-K and temperture T in kelvins. This equation can also be found in the Wood Handbook (7).

As early as 1896, Volbehr S(33) had arrived at an equation that included the influence of temperature and MC (4):

$$c_{p,0} = 0.00506T - 0.297 \quad (10)$$

for MCs between 0 and 27 percent. Equations (9) and (10) are almost equivalent.

Since Dunlap's work, several researchers have performed measurements over a wider range of tempertures (31). The results do correspond with Equations (9) and (10). Wildes performed a regression on all available data from the references listed in Table 6 and arrived at the following equation for dry wood (3):

$$c_{p,0} = 0.003867T + 0.1031 \quad (11)$$

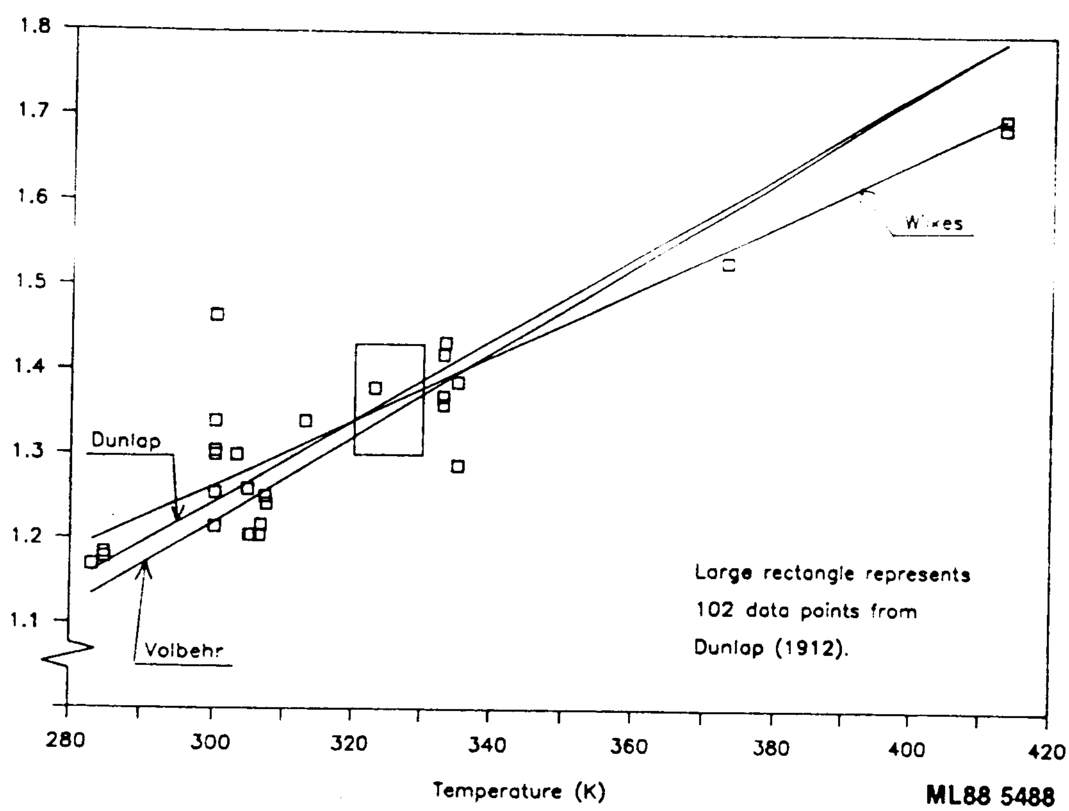



Fig. 7. Comparison of equations for specific heat of ovendry solid wood at 0 MC.

Effect of Moisture

Figure 7 compares Equations (9), (10), and (11) with measured data, Wilkes ' equation generally agrees with the data.

The specific heat of moist wood is greater than would be expected from the simple law of mixtures (7). This additional apparent specific heat is due to the energy absorbed by the wood-water bonds and can be represented by a correction term:

$$c_p = \frac{c_{p,0} + 0.01Mc_{p,w}}{1 + 0.01M} + A \qquad (12)$$

where:

$c_{p,0}$ = specific heat of dry wood (kJ/kg-K)

$c_{p,w}$ = specific heat of water, approximately 4.186 kJ/kg-K

M = moisture content (percent)

A = correction term (kJ/kg-K)

The correction term A is a function of temperature and MC. Although the available data are limited, Wilkes obtained good results by linear regression (3):

$$A = (0.0002355T - 0.0001326M - 0.06191)M \qquad (13)$$

Equations (11), (12), and (13) provide the best available estimate for the specific heat of solid wood below fiber saturation point at temperatures between 280 K (45°F) and 420 K (297 °F). The moisture above fiber saturation point should contribute to specific heat according to the simple law of mixtures. Some specific heat values for selected temperatures and MCs can be found in Table 7.

Table 7. Specific heat of solid wood at selected temperatures and moisture contents

| Temperature | Specific heat (W/m-K) | | | |
|---|---|---|---|---|
| | Ovendry | 5% MC | 12% MC | 20% MC |
| 280 K (7°C) | 1.2 | 1.3 | 1.5 | 1.7 |
| 297 K (24°C) | 1.3 | 1.4 | 1.6 | 1.8 |
| 300 K (27°C) | 1.3 | 1.4 | 1.7 | 1.9 |
| 320 K (47°C) | 1.3 | 1.5 | 1.8 | 2.0 |
| 340 K (67°C) | 1.4 | 1.6 | 1.9 | 2.2 |
| 360 K (87°C) | 1.5 | 1.7 | 2.0 | 2.3 |

## THERMAL DIFFUSIVITY

Thermal diffusivity is defined as the ratio of conductivity to the product of specific heat and density, and is expressed in $m^2/s$ ($in^2/s$). The thermal diffusivity of wood is approximately 100 times lower than that of steel and 40 times lower than that of mineral wool (7).

With Equation (7a) for thermal conductivity, and Equations (11), (12), and (13) for specific heat, we calculated thermal diffusivity for a range of densities and MCs. The results are shown in Table 8. The calculated average value for wood at 24°C (75°F) and 12 percent MC is $0.15 \times 10^{-6}$ $m^2/s$ (0.00023 $in^2/s$), similar to the value of $0.16 \times 0^{-6}$ $m^2/s$ (0.00025 $in^2/s$) listed in the Wood Handbook (7). Thermal diffusivity decreases slightly with density; it decreases approximately 15 percent for every 10 percent increase in MC.

# THERMAL PROPERTIES OF WOOD PANEL PRODUCTS

## THERMAL CONDUCTIVITY

We reviewed the literature for thermal data for the following structural wood panels: plywood, particleboard, and fiberboard.

Table 8. Calculated thermal diffusivity for selected wood species and MC at 24°C (297 K)

| Species | Specific gravity (ovendry) | Ovendry density (kg/m3) | Thermal diffusivity ($10^{-6}$ $m^2/s$) | | | |
|---|---|---|---|---|---|---|
| | | | Ovendry | 5% MC | 12% MC | 20% MC |
| Northern white cedar | 0.31 | 310 | 0.20 | 0.18 | 0.16 | 0.15 |
| Red pine | 0.46 | 460 | 0.19 | 0.17 | 0.15 | 0.14 |
| Loblolly pine | 0.54 | 540 | 0.18 | 0.17 | 0.15 | 0.14 |
| Yellow birch | 0.66 | 660 | 0.18 | 0.16 | 0.15 | 0.14 |
| White oak | 0.72 | 720 | 0.18 | 0.16 | 0.15 | 0.14 |

### Plywood

MacLean concluded that the thermal conductivity of Douglas fir plywood was approximately the same as that of solid wood of that species (11). This conclusion has been echoed by others and is apparent in design values for thermal conductivity of plywood currently in use. The American Plywood Association currently recommends a value of 0.12 W/m-K (0.8 Btu-in/h-ft$^2$-°F), which corresponds approximately with the average conductivity of Douglas-fir as calculated with MacLean's formula (Eq. (2)).

However, more recent measurements do not support this conclusion, MacLean's formula for conductivity results in significantly higher values than the measured data for plywood (11). When Equation (7) is used to predict the conductivity of plywood, it consistently yields values that are 10 to 15 percent higher than the measured conductivity of plywood. Figure 8 shows that only one data point coincides with the calculated value for solid wood--this is the average of measurements taken by MacLean. The reason for the lower conductivity of plywood is uncertain but may be related to possible voids in the interior plies.

The data in Figure 8 have been adjusted for temperature. Based on only a few measurements taken at different temperatures (23), we determined the average temperature coefficient to be in the order of 0.0002 W/m-K per kelvin. This agrees very well with the approximate temperature coefficient for solid wood reported earlier in this paper, 0.2 percent per kelvin. The relationship is quite linear with temperature.

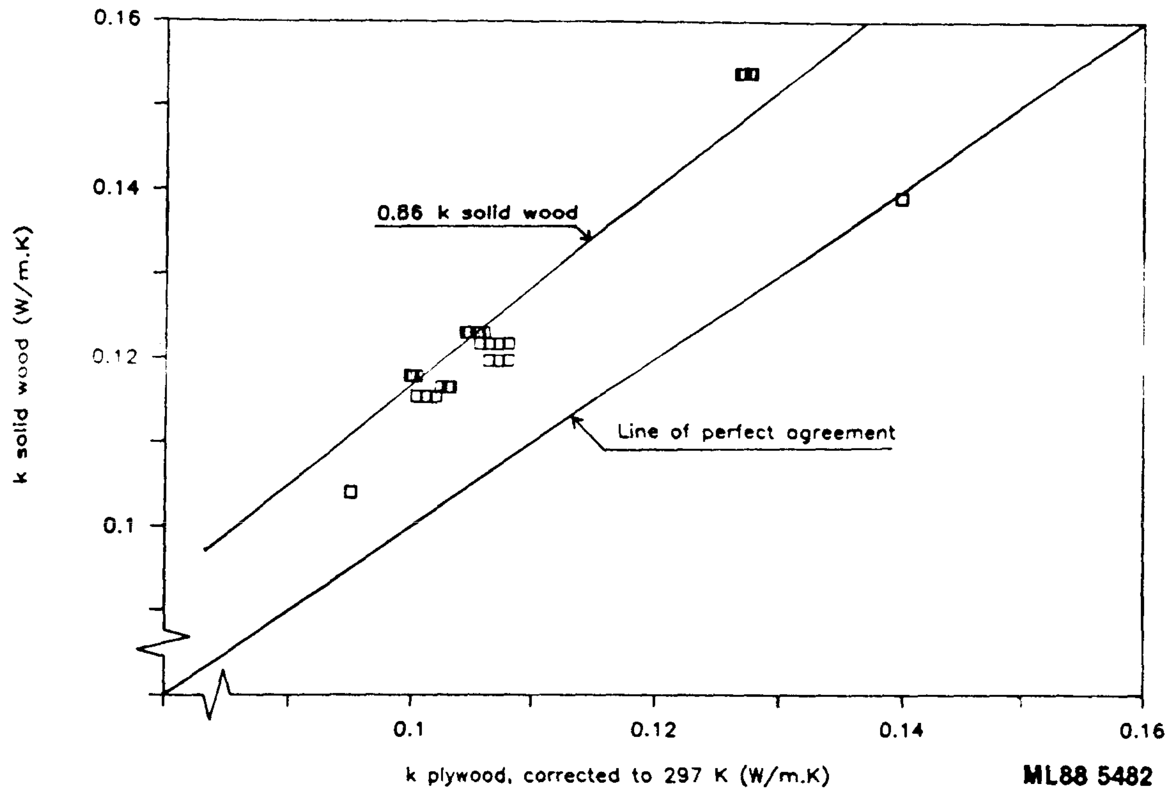



Fig. 8. Comparison of measured thermal conductivity of plywood with calculated valaues for solid wood (Eq. (7)) with the same density and MC. The data have beenm corrected for temperature.

We found that reducing the computed conductivity for solid wood at 24°C (297 K), as determined with Equation (7), yields satisfactory results for plywood:

$$k_{plywood} = 0.86k_{wood} \tag{14}$$

Figure 8 shows this equation with the measured data. However, the authors have only limited confidence in Equation (14) because of insufficient data. More measurements are required.

Particleboard

Thermal conductivity of dry particleboard is approximately 75 Percent of that of solid wood with the same density. This is evident from Figure 9 where measured conductivity of particleboard is compared with calculated values for solid wood. The lower conductivity is most likely due to the diminished contact among adjacent wood particles in the panel,

Lewis concluded that estimates of the conductivity of particleboards can be made on the basis of panel density (l). The proposed relationship for ovendry particleboard is given in Table 9, and Figure 9 shows that this relationship agrees well with results from measurements.

Lewis also determined the temperature coefficient for ovendry particleboard--approximately 0.00024 W/m-K per degree K (0.00093 Btu-in/h-ft$^2$-F per °F). The design values in Table 9 are based on a limited number of data, but appear to be the most reliable available.

To determine the effect of moisture on the conductivity of particleboard, additional measurements are needed; most measurements have been performed with ovendry samples. The literature contains only sporadic mesurments of samples containing moisture, or MC was not measured or reported.

Table 9. Thermal conductivity of ovendry wood fiberboard and particleboard (1)

| Density (kg/m$^3$) | (lb/ft$^3$) | Thermal conductivity (W/m-K (Btu-in/h-ft$^2$-°F)) Fiberboard | | Particleboard | |
|---|---|---|---|---|---|
| 200 | (12.5) | 0.050 | (0.35) | 0.052 | (0.36) |
| 400 | (25) | 0.066 | (0.46) | 0.075 | (0.52) |
| 600 | (37.5) | 0.082 | (0.57) | 0.104 | (0.72) |
| 800 | (50) | 0.105 | (0.73) | 0.136 | (0.94) |

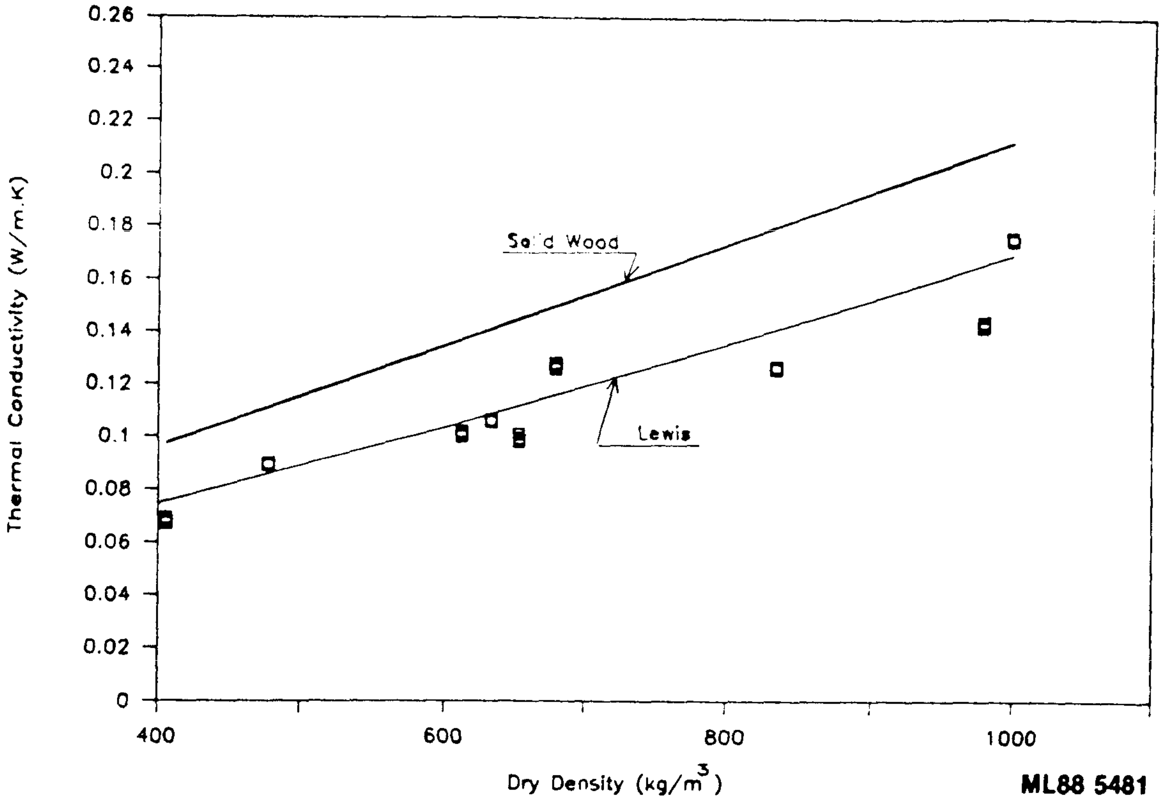
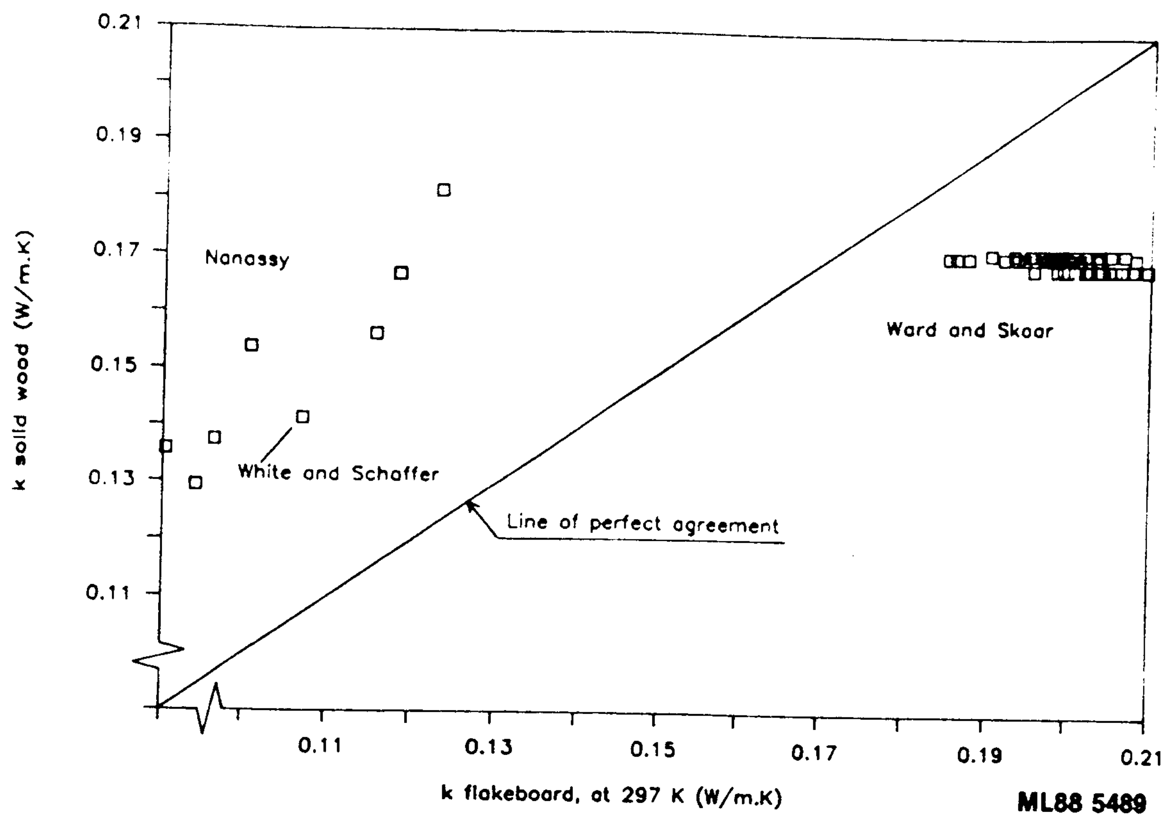



Fig. 9. Comparison of design values for thermal conductivity of dry particleboard proposed by Lewis (1) with measured values for dry particleboard and with calculated values for ovendry solid wood with the same density.

Flakeboard

Flakeboard may have a thermal conductivity different from other particleboard due to the orientation of the flakes. Ward and Skaar published results for flakeboard, obtained with transient measurement technique, measuring conductivity and specific heat simultaneously as discussed earlier in the section on measurement methods (10). As is shown in Figure 10, their results are inconsistent with data published by Nanassy and Szabo whose data indicate that conductivity of flake-board is substantially below that of solid wood (26), while Ward and Skaar’s data suggest the opposite, It is possible that the transient method used by the latter did not adequately compensate for the thermal effect of moisture movement. Nanassy and Szabo also used a transient measurement technique, but their results are consistent with one steady-state measurement as well as with the values for particleboard recommended by Lewis (Fig. 11) (l). Until specific measurements on different types of flakeboards are performed, the authors recommend that the conductivity of particleboard be used, as shown in Table 9.




Fig; 10, Comparison of measured thermal conductivity of flakeboard with calculated values for solid wood with the same density and MC. The data has been corrected for temperature.

Fiberboard

A moderate number of data is available for the thermal conductivity of fiberboard. Figure 12 shows that conductivity of fiberboard is an average of 35 percent below that of solid wood of the same density. Its conductivity is also an average of 15 percent below that of particleboard of the same density, most likely due to a reduced contact between individual fibers.

Lewis published design values for wood fiberboard (Table 9) (l). Measured data agree well with these values, even when moderate amounts of moisture are present (Fig. 13). Even several measurements of low-density board with 24 percent moisture resulted in conductivities very close to the values in Table 9. The authors therefore recommend use of the values in Table 9 for MCs below 10 percent. More measurements are needed to determine the conductivity at higher MCs.

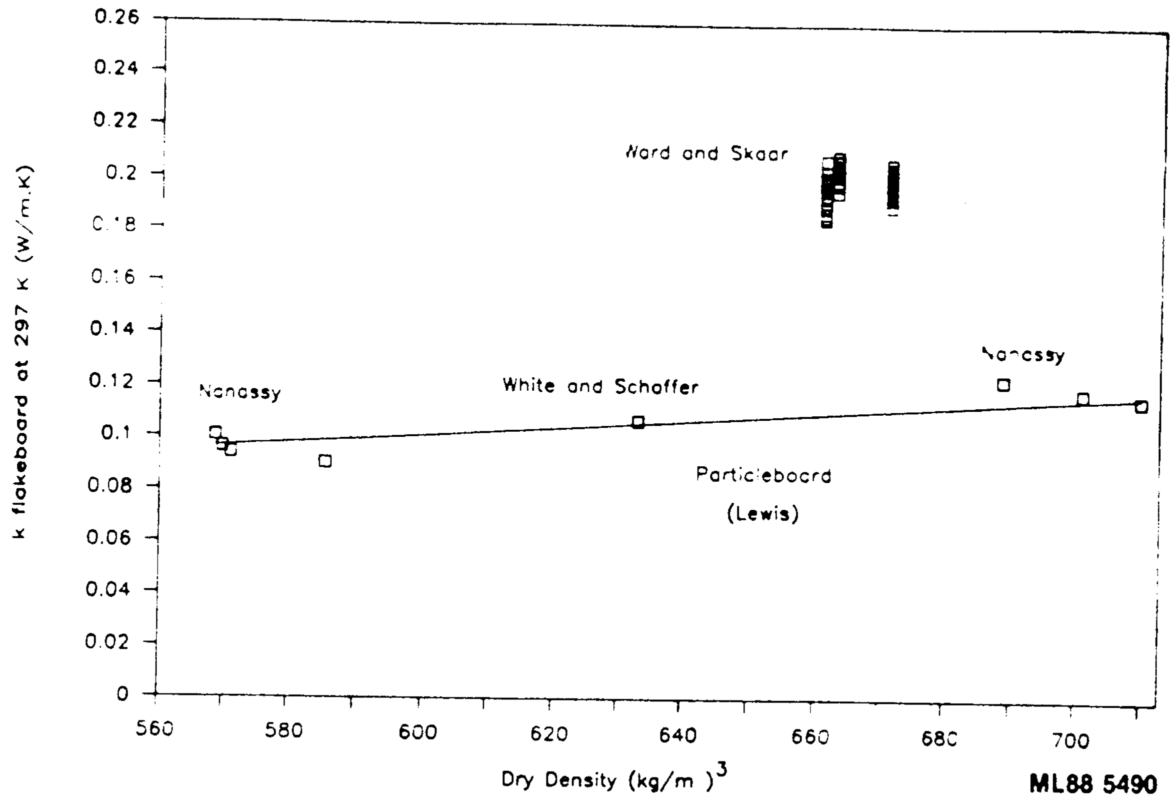



Fig. 11. Thermal conductivity of flakeboard as a function of dry density, compared with design values for particleboard proposed by Lewis (l),

As with other wood products, the effect of temperature on thermal conductivity is relatively small. Lewis determined the temperature coefficient as approximately 0.00014 W/m-K per K (0.00053 Btu-in/h-ft$^2$-°F per °F). Data shown in Figures 12 and 13 are all corrected for temperature with this coefficient.

## SPECIFIC HEAT

Information on specific heat of wood panels is scant compared to data on solid wood. The authors know of no specific heat data for plywood, but the specific heat of plywood is likely to be similar to that of solid wood.

Nanassy and Szabo measured the specific heat of particleboard and found values quite similar to those of solid wood (26). The data published by Ward and Skaar seem to suffer from the same inconsistencies as the conductivity data in that publication (10). For lack of further data, the authors recommend using the equations for solid wood (Eq, (11), (12), (13)) to approximate the specific heat of particleboard.

Most of the published specific heat data are for fiberboard. Figure 14 shows that the data are not consistent with the equation for specific heat of solid wood. The authors have no explanation for this variation, Without more measured data an average value of 1.2 kJ/kg,K (0.29 Btu/lb-°F) seems currently to be the most appropriate value to use. Neither the effect of moisture nor the effect of temperature can be accurately determined from currently available data.

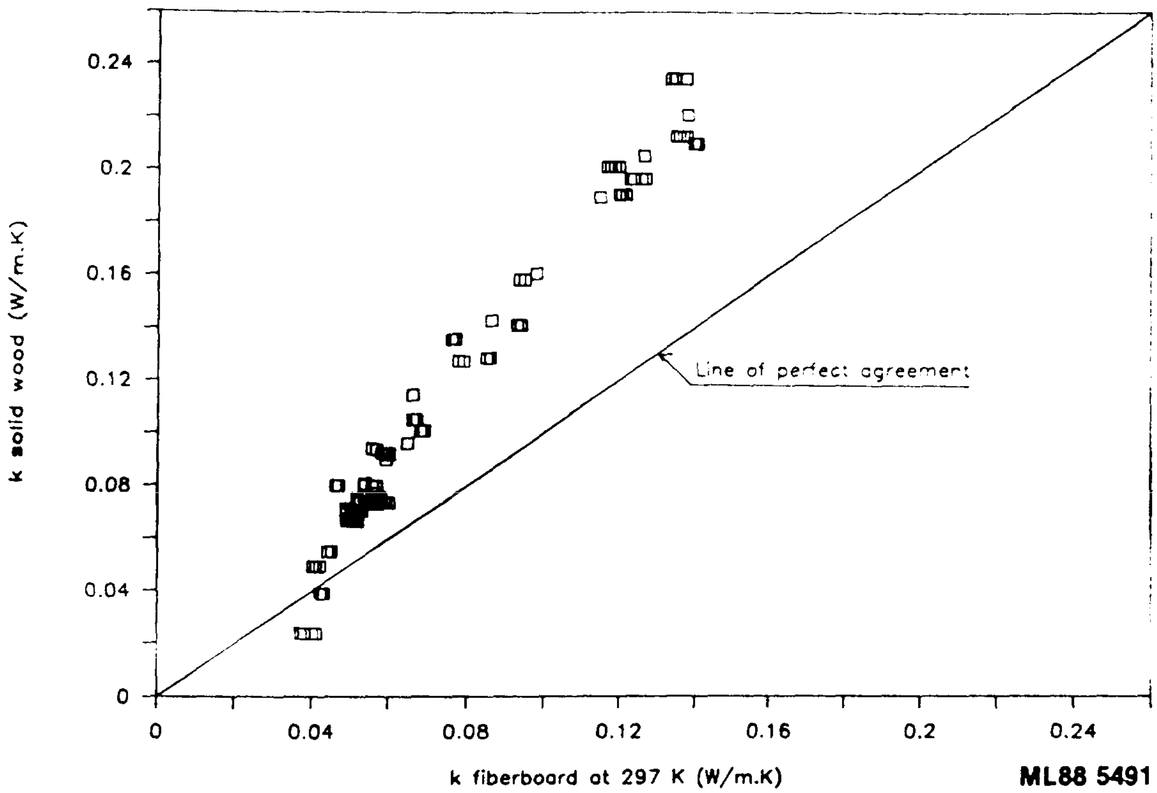



Fig. 12. Comparison of the measured thermal conductivity of fiberboard with calculated values for solid wood of the same density and MC.

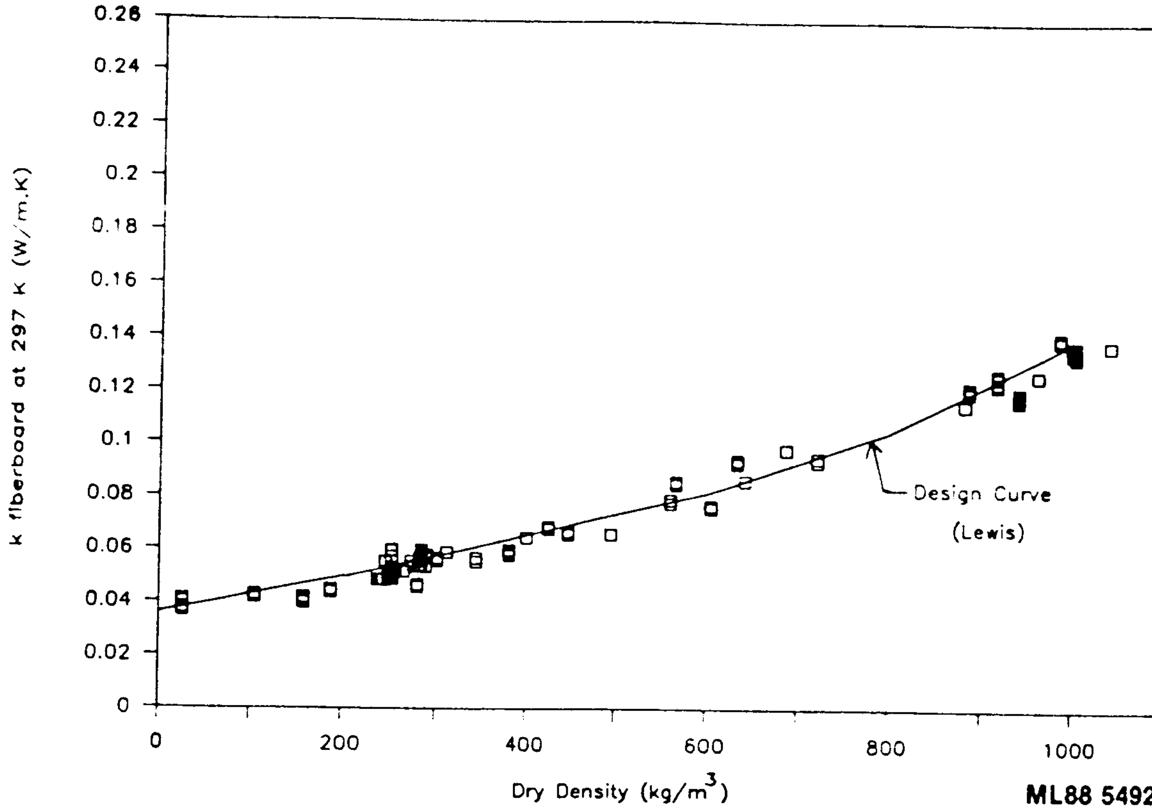



Fig. 13. Thermal conductivity of fiberboard as a function of dry density, compared with design values proposed by Lewis (1).

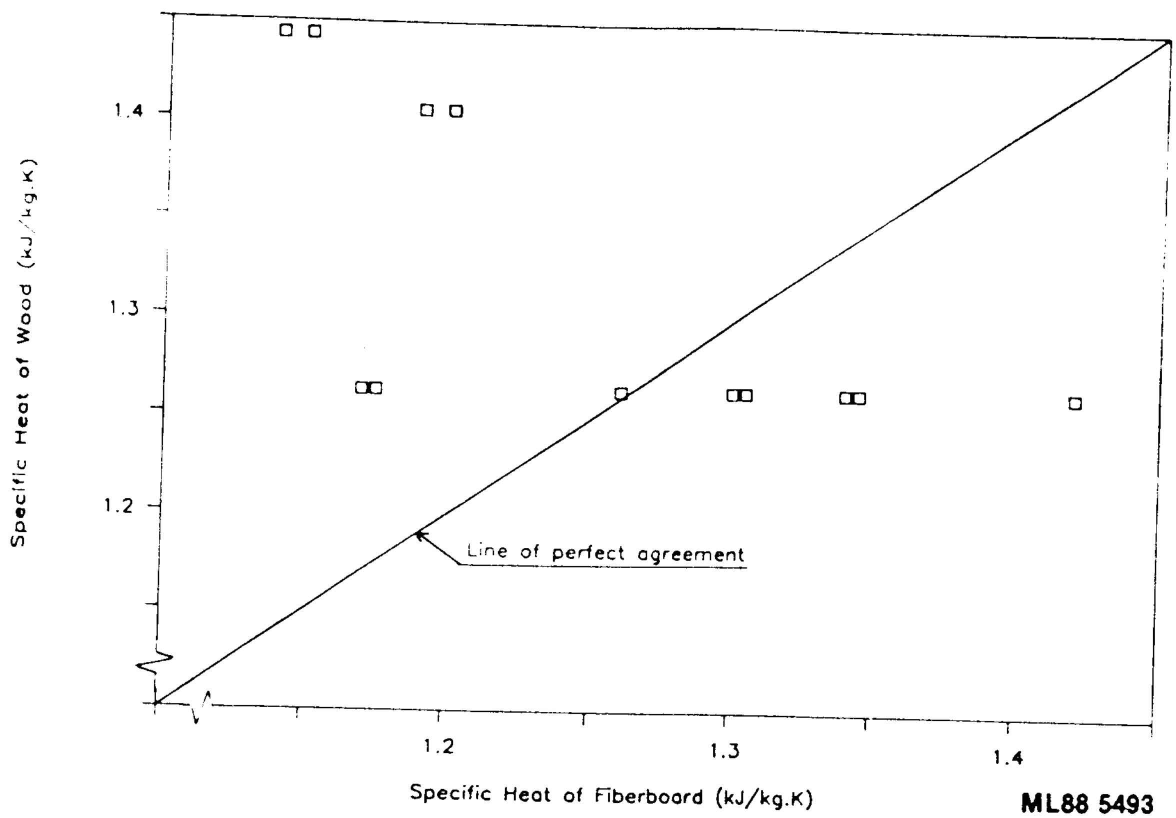



Fig. 14. Comparison of measured specific heat of fiberboard with calculated values for solid wood with the sdame density.

# CONCLUSIONS

## SOLID WOOD

Sufficient data for solid wood are available in the literature for solid wood to determine its conductivity at temperatures around 24°C (75°F) and its specific heat at temperatures between O°C (32°F) and 140°C (284°F) with sufficient accuracy, The authors recommend use of Equations (7a) (Eq. (7b) for English units) for conductivity and Equations (11), (12), and (13) for specific heat. The variation of conductivity of solid wood with temperature is not very well known especially for temperatures significantly different from 24°C. The effect of temperature however, is relatively minor.

## PLYWOOD

The conductivity of plywood is lower than that of solid wood but is not known with a sufficient degree of certainty. The specific heat of plywood is likely to be similar to that of solid wood, but to our knowledge, no measured values are available.

## PARTICLEBOARD

Viable data for the thermal conductivity of dry particleboard as a function of density are available. The conductivity is considerably below that of dry solid wood with the same density. The influence of moisture is not known. The few available data suggest that the specific heat of particleboard is similar to that of solid wood. The effects of temperature and moisture are not known.

## FLAKEBOARD

The few available data on thermal conductivity or specific heat for flakeboard are inconclusive.

## FIBERBOARD

The thermal conductivity of fiberboard is significantly lower than that of solid wood of the same density, Sufficient data are available to establish the thermal conductivity of wood fiberboards at MCs up to 10 percent. Conductivity at higher MC has not been determined. The specific heat of fiberboard appears to be different from that of solid wood, but the available data are inconsistent.

## TEST METHODS AND MEASUREMENTS

When measuring the thermal conductivity of wood products with MCs over 15 percent, test conditions should be maintained for a minimum of 24 h before taking a final reading to ensure that any significant moisture redistribution in the sample has ceased. Exact measurement of steady-state thermal properties of moist wood and wood products does not necessarily lead to better information about in-service transient thermal performance. Thermal properties of wood above fiber saturation are of little practical value to the building comunity.

# RECOMMENDATIONS

## DESIGN VALUES

Recommended design values or equations for thermal conductivity and specific heat for the different wood products are summarized in Table 10. Many of the recommendations are based on our best judgment, for lack of more and better data, and are identified with a footnote in Table 10. Those values should be used with the recognition that they are based on few, if any, measured data. Conductivity values of dry wood or wood at MC values expected in normal service should be used to compare thermal performance of wood with that of other materials.

Table 10. Recommendations for thermal property values

| Product | Thermal conductivity | Specific heat |
|---|---|---|
| Solid wood | Equation (7a) | Equations (11), (12), (13) |
| Plywood | 0.86 $k_{wood}$[a] | Same as solid wood[a] |
| Particleboard | See Table 6 | Same as solid wood[a] |
| Flakeboard | Same as particleboard[a] | Same as solid wood[a] |
| Fiberboard | See Table 6 | 1.2 kJ/kg-K (0.29 Btu/lb-°F)[a] |

[a]Authors' best judgment based on limited data. These values should be used with the recognition that they are supported by few, if any, measured data. More data are needed for a definitive value.

## ADDITIONAL RESEARCH

Additional measurements are needed to obtain the following data and relationships:

Solid wood. The effect of temperature on thermal conductivity. We suggest that the focus would be on commercial softwood species most prolifically used in construction today, such as spruce, fir, hemlock, and pine species, as well as cedar, redwood, and cypress. The temperature range of interest is from about -40°C to +60°C.

Plywood. Thermal conductivity as a function of density, MC, and temperature. Specific heat as a function of MC and temperature.

Particleboard. The effect of moisture and temperature on thermal conductivity and specific heat.

Flakeboard. Thermal conductivity as a function of density, MC, and temperature. Specific heat as a function of MC and temperature.

Fiberboard. Thermal conductivity at MC over 10 percect. Specific heat as a function of MC and temperature.

## ACKNOWLEDGMENTS

We wish to thank Dr, Ken Wilkes, currently with the Oak Ridge National Laboratory, and Dr. Merle F. McBride of Owens Corning Fiberglas Corporation for making their compilation of thermal property data for wood available to us.

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# APPENDIX

After we finalized this report, two recently published articles were brought to our attention that shed further light on the conclusions and recommendations in this report. Although it was too late to include these in the main body of this report, we include here a short summary of these articles and a discussion of their bearing on the information presented in this report.

1. T. J. Cardenas and T. G. Bible. "The thermal properties of wood--Data base," in Thermal Insulation: Materials and Systems. ASTM STP 922, F. J. Powell and S. L. Matthews, eds., American Society for Testing and Materials, Philadelphia, Pa., 1987.

The authors developed a data base for 15 wood species. The data were taken from a subset of the references used for this report. The article exclusively focuses on solid wood and thermal conductivity. The authors concluded that for solid wood the formula developed by K. E. Wilkes, Equation (5) in this report, gives very good estimates of average thermal conductivity (3). Equation (5) is very similar to Equation (7) recommended in this report.

By subdividing species into groups, such as Southern Pine and spruce-pine-fir (SPF), design values for these groups were derived that show less variability than the values for the broad categories of "softwoods" and "hardwoods" published in the ASHRAE handbook (9).

Cardenas and Bible further recommend that results of tests for thermal properties should be reported at 4.4, 23.8, and 43.3°C mean temperatures and an MC of 12 percent.

We take issue with two of the recommendations. Cardenas and Bible call for further validation of thermal conductivity of 15 representative solid wood species, and the measurement of specific heat and density. We are not convinced that further validation of thermal conductivity or specific heat of solid wood species is critical to building practitioners, given the large amount of data already available and the inevitable uncertainties due to variabilities in density, MC, and other parameters. We do agree that the effect of temperature on thermal conductivity needs to be determined. In addition, we feel that an effort to obtain better data for wood panel products should have a high priority.

2. F. A. Kamke. "Thermal conductivity of wood-based panels." Paper presented at the 20th International Thermal Conductivity Conference, Blacksburg, Va., October 1987.

This paper describes the results of measurements of the conductivity of the following nine types of wood panels: industrial particleboard, oriented strandboard (OSB), five types of plywood, and two types of fiberboard. The measurements showed that conductivity increases linearly with density and MC. For a given specific gravity the descending order of thermal conductivity is solid wood, plywood, particleboard, and fiberboard. The results confirm that the conductivity of plywood is considerably below that of solid wood of the same density and MC, but the results also show great variability among panels. The average measured conductivity of plywood is lower than values calculated with Equation (14) in this report. This confirms our recommendation that additional measurements are needed.

Measured conductivities for the different particleboard seem to fall somewhat below the design values that were published by Lewis (1) and suggested in this report as interim design values. Two of the three panels were oriented strandboard, which were classed as flakeboard in our report. These results confirm the need for additional measurements of thermal conductivity of flakeboard and other particleboard.

Finally, results for fiberboard were in good agreement with previous data published by Lewis (1). Thus our recommendation to use the Lewis design values for fiberboard is confirmed by this study.

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109. K. Mentzer, MIMA, 1420 King Street, Alexandria, VA
110. G. Miller, Jim Walter Research Corp., St. Petersburg, FL
111. M. Millspaugh, Reflectixs, Inc., Markleville, IN
112. M. Modera, Lawrence Berkeley Laboratory, Berkeley, CA
113. D. E. Morrison, Michigan State University, East Lansing, MI
114. J. R. Mumaw, Owens-Corning Fiberglas, Granville, OH
115. B. Nelson, Minnesta Dept. of Public Service Energy Div., St. Paul, MN
116. E. Nowman, Fi-Foil Company, Inc., Auburndale, FL
117. D. G. Ober, Manville Sales Corp., Denver, CO
118. T. J. Ohlemiller, National Bureau of Standards, Gaithersburg, MD
119. R. E. Oliver, DOE/CE, Washington, DC
120. A. M. Paranac, CARIERS/ASI, Arlington, VA
121. R. L. Perrine, University of California, Los Angeles, CA
122. H. F. Poppendiek, Geoscience, Ltd., Solana Beach, CA

123. F. J. Powell, 9919 Mayfield Drive, Bethesda, MD
124. D. E. Richards, Owens-Corning Fiberglas, Toledo, OH
125. W. J. Rossiter, National Bureau of Standards, Gaithersburg, MD
126. J, A. Roux, University of Mississippi, University, MS
127. J, Samos, NASA - Langley, Hampton, VA
128. E. Schaffer, U.S. Forest Products Lab, Madison, WI
129. R. C. Schroter, Product Technical Service Associates, Orinda, CA
130. W. W. Seaton, ASHRAE, Atlanta, GA
131. S. Selkowitz, Lawrence Berkeley Laboratory, Berkeley, CA
132. M. Sherman, Jim Walter Corporation, St. Petersburg, FL
133. C. J. Shirtliffe, National Research Council, Ottawa, Ontario, Canada
134. H. S. Smith, Cellin Manufacturing Inc., Lorton, VA
135. J. A. Smith, DOE/CE, Washington, DC
136. S. E. Smith, Holometrix, Inc., Cambridge, MA
137. L. G. Spielvogel, Wyncote House, Wyncote, PA
138. R. Sterling, University of Minnesota, Minneapolis, MN
139. R. Sullivan, National Center for Appropriate Technology, Butte, MT
140-149. A. TenWolde, USDA, Forest Products Lab, Madison, WI
150. S. Tewes, University of Illinois at Urbana, Champaign, IL
151. W. C. Thomas, VPI & State University, Blacksburg, VA
152. G. A. Tsongas, Portland State University, Portland, OR
153. A. Tuluca, Steven Winter Associates, Norwalk, CT
154. R. P. Tye, Thermatest Division of Holometrix, Inc., Cambridge, MA
155. M. G. Van Geem, Construction Technology Laboratories, Inc., Skokie, IL
156. C. R. Vander Linden, Vander Linden & Associates, Littleton, CO
157. J. R. Warner, ACEC Research and Management Foundation, Washington, DC
158. B. Wilcox, Berkeley Solar Group, Berkeley, CA
159. D. W. Yarbrough, Term. Tech. Univ., Cookeville, TN
160. R. Zarr, National Bureau of Standards, Gaithersburg, H9
161. Office, Assistant Manager, Energy Research and Development, DOE/ORO, Oak Ridge, TN
162-171. Office of Scientific and Technical Information Center, U.S. Department of Energy, Oak Ridge, TN