Thermal Properties of Wood and Wood Products

W.P. Goss **R.G. Miller**

ABSTRACT

This paper presents the methods used to arrive at the revised thermal properties of wood included in Table 4, Chapter 22, 1989 ASHRAE Handbook—Fundamentals *(ASHRAE 1989). The procedures used to determine the specific heat, range of densities, and range of thermal conductivities of wood species generally used in building construction are presented. The rationale was to use the wood thermal property data available in publications (handbooks, journals, transactions, proceedings), from wood associations, and from new experimental data to determine the thermal properties of wood species not listed in previous editions of the Handbook. The moisture content is assumed to be 12%, which is considered the average for woods in service in buildings in the United States. This tends to give somewhat conservative values for the thermal resistance of wood but is probably more realistic than the two wood thermal resistances that appeared in the* 1981 Fundamentals *(ASHRAE 1981). The paper also documents the changes made in the building board section of the* 1989 Fundamentals *(ASHRAE 1989) and reports a set of test results for oven-dried waferboard.*

INTRODUCTION

This paper presents the methods used to arrive at the revised thermal properties of wood species and wood products that have been introduced into recent editions of *ASHRAE Fundamentals*. The thermal properties of wood were first included in Table 3A, Chapter 23, of the *1985 ASHRAE Handbook—Fundamentals* (ASHRAE 1985) and subsequently in Table 4, Chapter 22, of the *1989 ASHRAE Handbook—Fundamentals* (ASHRAE 1989). The thermal properties of several newer wood products were first included in Table 4, Chapter 22, of the 1989 *Fundamentals*. The objective was to use the thermal property data of wood species and wood products that are available in publications (handbooks, journals, transactions, proceedings), information obtained from wood associations, and any reliable new experimental data to develop improved thermal properties of wood species and wood products.

The building material, thermal conductivity, and specific heat property data that are listed in Table 4, Chapter 22, of the 1989 *Fundamentals* are used extensively in steady-state and transient calculations of building envelope thermal performance. The improved thermal property data for wood and wood-based products that are presented in this paper and the recommended ASHRAE research project are needed as building envelopes become more energy efficient and wood and wood-based materials become some of the components with higher thermal conductivities in a building's wall, roof, ceiling, or floor.

LITERATURE REVIEW

Wood Species

A primary source of information on the properties of wood and wood products is the *Wood Handbook* (FPL 1972), which is now available in a revised version (FPL 1989). Chapter 3 of the *Wood Handbook* (on the physical properties of wood) has a section on thermal properties that includes information on the thermal conductivity, specific heat, and thermal diffusivity of wood. This information, along with sections on moisture content and weight-density-specific gravity in the same chapter, provides a good starting point for understanding the thermal properties of wood.

Since wood is a hygroscopic material, which means it can absorb moisture, the thermal properties of wood are functions of the moisture content in addition to the dependence on density and temperature that other materials usually exhibit. A further complication is due to the wide variety of wood species (e.g., ash, maple, fir) and the subcategories within these (e.g., black ash, white ash, black maple, red maple, silver maple, sugar maple, balsam fir, white fir, etc.).

The basic structure of wood is nonhomogeneous with wood fibers that run in the general direction of the tree axis, called the longitudinal direction. Figure 1 is a photomicrograph picture (at 200 times magnification) taken of a fir wood sample looking approximately in the longitudinal direction. The 100 μ (0.00039 in.) line indicates that the diameter of a wood fiber cell is approximately 20 to 30 μ (0.00079 to 0.000118 in.) for this sample. The wood fiber cells are primarily made of the carbohydrate cellulose (the framework of the wood cells) "cemented" together by lignin, a complex polymer group. The wood cells are longer (0.04 to 0.33 inches [1 to 8 mm]) in the longitudinal direction and are normally closed at both ends. Some wood cells have open ends and, when they are set above each other, form continuous passages called vessels (FPL 1989).

William P. Goss is a professor in the Mechanical Engineering Department at the University of Massachusetts, Amherst; **R. Gerry Miller** is a research associate at the Center for Applied Engineering, Inc., St. Petersburg, FL.

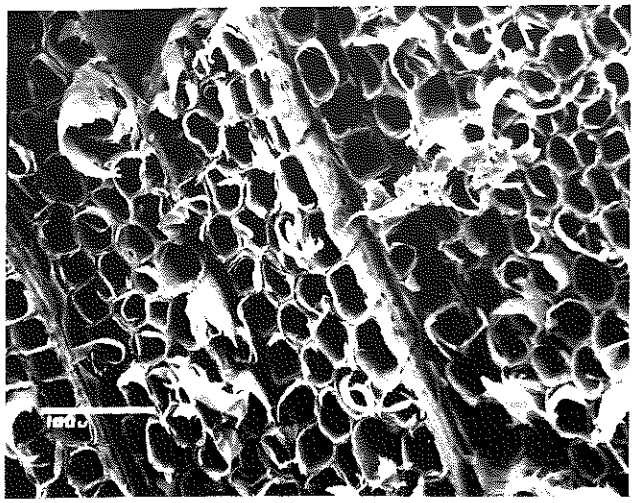

Figure 1 Photomicrograph of wood sample.

As new wood cells are made, rings are formed annually due to the difference in growth of the tree during the early and late portions of the growth season when more compact, smaller-diameter cells are formed. These longitudinal annular rings can be observed when a tree is cut. The other two directions are radial and tangential to these annular rings. Wood is normally cut with the longitudinal direction as the longest dimension, and in building applications, heat transfer usually occurs across the annular rings or grains.

Moisture can be absorbed by the wood fibers that make up the longitudinal cell walls up to a point, which is called the fiber saturation point. Beyond this, the water starts to fill the cells. The fiber saturation point is approximately 30% moisture content (defined as the mass of moisture [water] divided by the weight of the dry wood) (FPL 1989). Since wood is harvested in the green state, which can range from 25% to more than 200% moisture content, it is normally dried, usually in a kiln, before it is used in building construction so that it will remain in relative equilibrium with the atmosphere at a moisture content well below that of green wood. Therefore, this paper will concentrate on the thermal properties of wood that has moisture contained in the wood fibers and has a moisture content below that of green wood.

The thermal conductivity information provided in the *Wood Handbook* (FPL 1972, 1989) is based on the work of MacLean (1941). MacLean developed an expression for the thermal conductivity of wood as a function of the wood density and moisture content that is used in the *Wood Handbook* (FPL 1972, 1989). The thermal conductivity is shown to be linearly related to the wood density and moisture content and yields the thermal conductivity of air (which fills the cells) when the wood density (and, therefore, also the moisture content) goes to zero. This relatively simple relationship exists over a wide range of densities of wood species.

More recently, Wilkes (1979), in developing a data base of building products' properties, re-examined the thermal conductivity and specific heat data available at that time and developed empirical thermal conductivity and specific heat regression equations for wood. The thermal conductivity equation developed for conditions near room temperature was similar in form to MacLean's (1941) expression, yielding the thermal conductivity of air when the wood density went to zero. Wilkes (1979) also developed a relationship that showed the variation of the thermal conductivity of wood as a function of temperature. The specific heat of wood equation developed by Wilkes (1979) is a function of temperature and moisture content and is similar in form to one given in the *Wood Handbook* (FPL 1972, 1989).

Subsequent to Wilkes' (1979) work, Cardenas and Bible (1987) recommended that ASHRAE TC 4.4 revise the thermal properties of wood given in Table 3A, Chapter 23, of the *1981 Fundamentals* (ASHRAE 1981) from the two values given for hardwoods and softwoods to a wider range of wood species used in building construction. Cardenas and Bible (1987) summarized in tabular form density, moisture content, mean temperature, and thermal conductivity data from a number of references. They then statistically analyzed the data to arrive at mean values of the thermal conductivity as a function of selected wood species. In addition, they recommended a finer breakdown of the groups of wood species that are representative of those used in building construction and then developed average thermal conductivity values for these groups. Cardenas and Bible also compared their results with the empirical wood thermal conductivity equations of MacLean (1941) and Wilkes (1979) and concluded that Wilkes' equation gave more representative results.

After Cardenas and Bible submitted preliminary drafts of their work to ASHRAE TC 4.4, the wood species groups were modified somewhat based on input from the Forest Products Laboratory and the National Forest Products Association. It was also decided by ASHRAE TC 4.4 to use ranges of wood densities at 12% moisture content and, therefore, ranges of thermal conductivities to indicate the variability of wood properties. This moisture content may be conservative, as a recent report by Tsongas (1990) showed an average moisture content of 16.2% for 86 homes in Montana and Washington.

After the wood species' density, thermal conductivity, and specific heat changes recommended in the Cardenas and Bible (1987) paper were made in the *1985 Fundamentals*, TenWolde et al. (1988) published a report that examined the thermal properties of wood and wood panel products. This report is an excellent review of the current status of the thermal conductivity and specific heat data for wood and wood panel products that are used in building construction. TenWolde et al. (1988) compared the results of MacLean (1941) and Wilkes (1979) with the work of Kollmann and Malmquist (1956) and Siau (1983). In addition, TenWolde et al. developed a linear regression equation similar in form to those developed by MacLean (1941), Wilkes (1979), and Kollmann and Malmquist (1956) and a nonlinear regression

equation similar in form to that developed by Siau (1983). TenWolde et al. (1988) concluded that, at 12% moisture content, their linear regression equation gave essentially the same thermal conductivity results as Wilkes (1979), while MacLean's (1941) equation gave higher values. This is to be expected since TenWolde et al. used a data set quite similar to that used by Wilkes (1979). The primary difference in their regression analyses is that TenWolde et al. did not require that their equation's constant value be the thermal conductivity of air. TenWolde et al. also indicated that their nonlinear regression equation, which was quite similar to Siau's (1983), gave results that were marginally better than their linear regression equation for low densities and worse at higher moisture contents. They concluded that the linear thermal conductivity equation form is generally preferable due to its simplicity. TenWolde et al. also present tabulated values of the average ovendry and 12% moisture content thermal conductivities for a wide range of hardwoods and softwoods.

WOOD PANEL PRODUCTS

Wood Panel Products—Building Boards

In Table 4 of Chapter 22 of the *1989 Fundamentals* (ASHRAE 1989), the section dealing with wood-based building boards includes plywood (Douglas fir), vegetable fiberboard (eight different types), hardboard (three types, depending on density), particleboard (four density-dependent types), waferboard, and wood subfloor (the type of wood subfloor is not specified). As referenced in the "Wood Species" section of this paper, the *Wood Handbook* (FPL 1989) is also the primary source of infor-mation for wood panel products.

Chapter 21 of the *Wood Handbook* (FPL 1989) contains information on reconstituted wood products from fibers or fiber bundles. These products are the fiberboard and hardboard panels made by compressing and heating the wood fibers to specified thicknesses and densities and to which other materials, such as bonding agents, fire retardants, etc., have been added to improve specific properties. Much of the thermal properties work on fiber-based panel products was initially conducted by Lewis (1967), in which design curves of thermal conductivity vs. specific gravity were developed based on special laboratory-manufactured boards (no additives) and commercially available products in an ovendry condition. The thermal conductivity values were considerably less than that of solid wood, due, as Wangaard (1969) points out, to the large number of air spaces in the fiber-based panels.

Recently, TenWolde et al. (1988) reviewed the literature on the thermal properties of wood panel products, namely, plywood, particleboards, and fiberboards. The authors recommended the Lewis (1967) design values for fiberboards of various densities with moisture contents below 10%; above 10%, TenWolde et al. indicated that more data are needed.

Some new thermal property data on fiber-based wood panels were reported by Kamke and Zylkowski (1989). Three different commercially available fiber-based panels were tested in the "as-received condition" in a heat flowmeter apparatus. The data were consistent with those reported by Lewis (1967), and the authors point out the quite consistent agreement with the relationship of thermal conductivity as a function of specific gravity developed by Suzuki (1981).

Chapter 11 in the *Wood Handbook* (FPL 1989) describes the properties of plywood. The very short section on thermal properties lists average thermal conductivity values for the four-species group defined in APA (1983). The *Wood Handbook* (FPL 1989) assumes that the thermal conductivity of plywood is essentially the same as solid wood of the same species and density. The more recent works by TenWolde et al. (1988) and Kamke and Zylkowski (1989) do not support the above conclusion. TenWolde et al., reportedly based on limited data, estimated the thermal conductivity of plywood at 0.86 that of solid wood of the same species. Kamke and Zylkowski (1989) report thermal conductivity data even lower than TenWolde's prediction. The authors attributed the large differences in thermal conductivity values for similar panels to knots in the laminates. They concluded that the presence of knots in laminates or wood veneer distorts the grain orientation, causing an increase in the thermal conductivity. TenWolde et al. concluded that insufficient data are available and more measurements are needed.

Chapter 22 of the *Wood Handbook* (FPL 1989) divides wood-based particle panels into subgroups known as particleboards, flakeboards, waferboards, and oriented strandboards. The word *particleboard* is also used as a generic name for all particle panel products; however, in this paper, the more descriptive names for the particle panel products will be used.

Particleboard refers to panels made from small wood particles of mill residue (FPL 1989). After drying, these wood particles (or furnish) are blended with an adhesive binder (typically ureaformaldehyde resin is used for interior applications and phenol-formaldehyde is used for protected exterior applications) and formed into layers of mats. The mats are moved to a platen press where the panel is formed under pressure and heated to the desired density and thickness. It should be noted that, as a result of the pressing operation, a density gradient is produced through the thickness of the board, with the two faces containing higher-density furnish than the center layers.

Lewis (1967) measured and developed design thermal conductivity values for ovendried particleboards. The values were lower than that of solid wood, due, as TenWolde et al. (1988) point out, to the diminished contact among adjacent wood particles in the panel. TenWolde et al. also showed a curve of thermal conductivity as a function of dry density (based on Lewis' [1967] design values) and measured values for dry particleboard. The data agree well with the relationship. However, as mentioned by the authors, ad-

ditional data are needed to determine the effect of moisture on the thermal conductivity of the particleboard.

Kamke and Zylkowski (1989) measured one industrial particleboard per ASTM C518 (1976). The reported thermal conductivity value (k = 0.80 Btu·in./h·ft^2·°F [0.116 W/mK] at a density of 49 lbm/ft^3 [785 kg/m^3] and a moisture content of 6.6%) was lower than the design value developed by Lewis (1967) at a comparable density (k = 0.94 Btu·in./h·ft^2·°F [0.136 W/m·K] at a density of 50 lbm/ft^3 [801 kg/m^3]).

Table 22-4 in the *Wood Handbook* (FPL 1989) lists thermal conductivity ranges for three different densities of particleboard: low (25 to 37 lb/ft^3 [400 to 593 kg/m^3]), medium (37 to 50 lb/ft^3 [593 to 801 kg/m^3]), and high (50 to 70 lb/ft^3 [801 to 1,121 kg/m^3]). The ranges encompass the design thermal conductivity values developed by Lewis (1967).

Flakeboard is the generic name for waferboard and oriented strandboard (OSB). The main difference between flakeboards and particleboards is in the size of the particle; flakeboards contain larger wood particles called flakes. Waferboards are manufactured from wafers (wide flakes) randomly oriented and bonded with an exterior-type adhesive. OSB contains long, narrow flakes or strands aligned into layers. The strands in adjacent layers are aligned at right angles to each other. As with waferboards, an exterior-type adhesive is used. The *Wood Handbook* (FPL 1989) discusses these products in detail.

There is a minimum amount of thermal data on either waferboard or OSB. Table 22-6 of the *Wood Handbook* (FPL 1989) lists thermal conductivity values for three thicknesses of waferboard. From these data, it is unclear whether boards of different densities were tested and why thermal conductivity varied with thickness. Nanassy and Szabo (1978) published thermal data on waferboards using a transient technique. The thermal conductivity data were measured over a range of mean temperatures and moisture contents from 0 to 10% and represented two types of waferboard binders. As pointed out by TenWolde et al. (1988), the above thermal conductivity data were substantially below those of solid wood. This is consistent with the one flakeboard thermal conductivity (steady-state technique) data point reported by White and Schaffer (1981). All the above data are substantially lower than those listed in Table 22-6 of the *Wood Handbook* (FPL 1989).

Recently, Kamke and Zylkowski (1989) measured thermal conductivity values for OSB at an average moisture content of 5%. The values were consistent with those measured by Nanassy and Szabo (1978) for waferboard. TenWolde et al. (1988) recommended that until additional measurements are made on different types of flakeboards, the thermal conductivity of particleboard should be used.

The next section describes the procedures used to determine the range of densities and thermal conductivities and the specific heat of wood species generally used in building construction.

WOOD SPECIES

A large number of individual wood species are listed and described in the *Wood Handbook* (FPL 1972, 1989) and in several ASTM standards (ASTM 1981; 1987a, b; 1988).

Wood species groupings are given in NFPA (1982). Most publications give average values of the specific gravity (ratio of wood density to density of water) or the wood density itself. Since wood can absorb moisture, there are a number of density values that can be defined depending on its moisture content. Therefore, several moisture state conditions of wood will be defined first. The following definitions are from the glossary of the *Wood Handbook* (FPL 1989).

Fiber Saturation Point: The stage in the drying or wetting of wood at which the cell walls are saturated and the cell cavities free from water. It applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30% moisture content, based on ovendry weight.

Green: Freshly sawed or undried wood. Wood that has become completely wet after immersion in water would not be considered green but may be said to be in the "green condition."

Seasoning: Removing moisture from green wood to improve its serviceability.

Air-Dried: Dried by exposure to air in a yard or shed, without artificial heat. (Author's note: Air-dried lumber is usually between 15% and 25% moisture content.)

Kiln-Dried: Dried in a kiln with the use of artificial heat. (Author's note: Kiln-dried lumber is usually 12% moisture content or lower.)

Ovendry Wood: Wood dried to a relatively constant weight in a ventilated oven at 102°C to 105°C.

Moisture Content

The moisture content of wood is defined as the mass of moisture (water) divided by the ovendry mass of wood. If a wood sample at a particular moisture content is accurately weighed before and after being ovendried, the difference of the two measurements will be the mass of moisture contained in the wood sample, and the final measurement is the ovendry mass of the wood sample. If the volume of the wood sample is also accurately measured before and after being ovendried, several density (and, therefore, specific gravity) values can be defined. One is based on the dry wood itself, which is the ratio of the ovendry mass to the ovendry volume. A second is the ratio of the mass at moisture content M to the ovendry volume, and a third is the total density, which is the ratio of the total mass to the volume, both at moisture content M. In various publications, these and other density values are used, and it is important to know which definition is being used. Since the density of wood is so dependent upon the moisture content

of wood, the density of each wood species itself can vary, and there are a large number of wood species, it was decided that the thermal property data to be used in the *1985 Fundamentals* (ASHRAE 1985) should be for groupings of wood species at a moisture content that is characteristic of the equilibrium moisture contents found for wood in buildings. Table 14.1 and Figure 14.4 in the *Wood Handbook* (FPL 1989) show the range of "in-service" equilibrium (atmospheric air in contact with the wood) moisture contents in the United States to be from 7% to 14%. A moisture content of 12% was selected to yield wood thermal conductivity values that would tend to give more conservative values for the wood thermal resistance, yet more realistic values than the two wood thermal resistances per inch thicknesses of 0.91 $ft^2 \cdot h \cdot °F/(Btu \cdot in.)$ (6.31 m·K/W) for hardwoods and 1.25 $ft^2 \cdot h \cdot °F/(Btu \cdot in.)$ (8.67 m·K/W) for softwoods given in the 1981 *Fundamentals* (ASHRAE 1981).

Density

The specific gravities of some of the commercially important species of wood grown in the United States are given in Table 4.2 of the *Wood Handbook* (FPL 1972, 1989). The specific gravity values for the various species are given for both green and 12% moisture conditions. The specific gravity values for 12% moisture conditions are based on the weight when ovendried and the volume at 12% moisture content. ASTM (1983b) describes methods for determining the specific gravity of wood and wood-based materials. Table 1 in this paper gives the range of specific gravity values for 12% moisture content for the wood species (or combinations of wood species) selected for use in Table 3A, Chapter 22, of ASHRAE (1985). The species groupings were obtained from Table 4A of NFPA (1982). The range of specific gravity values at 12% moisture content for the various wood species or species combinations was then obtained from Table 4.2 of the *Wood Handbook* (1972). As a check of these values, the more recent specific gravity values given in the *Wood Structural Design Data Manual* (NFPA 1978) were compared with the specific gravity values shown in Table 1. The specific gravity values in NFPA (1978) were based on ovendry weight and volume and had to be converted to ovendry weight and 12% moisture content volume using Figure 3.4 of the *Wood Handbook* (FPL 1972). This figure accounts for the volume changes in the wood as the moisture content changes. The converted specific gravities in the *Wood Structural Design Data Manual* (NFPA 1978) all fell within the specific gravity ranges given in Table 1. Table 1 also gives the 12% moisture content density ranges for the wood species or species combinations listed. These were calculated from the specific gravity values using the following equation:

$$\rho = S_{wo}(1 + 0.01M)\rho_{H20} \qquad (1)$$

where

ρ = total (wood plus water) density of wood at moisture content M, lb_m/ft^3 (kg/m^3);
S_{wo} = specific gravity of wood based on ovendry weight and volume at moisture content M;
M = moisture content of wood in percent (e.g., $M = 12$ for 12% moisture content); and
ρ_{H20} = density of water (62.4 lb_m/ft^3 or 1,000 kg/m^3) at standard conditions.

Thermal Conductivity

The thermal conductivity of wood, as presented on pages 3-19 and 3-20 of the *Wood Handbook* (FPL 1972) or pages 3-24 and 3-25 of the revised *Wood Handbook* (FPL 1989), is a function of moisture content and density and is independent of the particular wood species. The thermal conductivity equation in inch-pound units on page 3-19 of the *Wood Handbook* (FPL 1972) or page 3-24 of the revised *Wood Handbook* (FPL 1989) is from the work of MacLean (1941) and is given below:

$$k = 0.165 + (1.39 + 0.028M)S_{wo} \qquad (2a)$$

where

k = thermal conductivity of wood, $(Btu \cdot in.)/(h \cdot ft^2 \cdot °F)$;
S_{wo} = specific gravity of wood based on ovendry weight and volume at moisture content M; and
M = moisture content (%) below 30%.

In SI units, Equation 2a becomes

$$k = 0.0238 + (0.2005 + 0.004039M)S_{wo} \qquad (2b)$$

where

k = thermal conductivity of wood, W/(m·K);
S_{wo} = specific gravity of wood based on ovendry weight and volume at moisture content M; and
M = moisture content (%) below 30%.

Substituting Equation 1 into Equation 2 to eliminate the specific gravity of wood, S_{wo}, yields the following expressions:

$$k = 0.165 + \frac{(0.0223 + 0.00045M)\rho}{1 + 001M} \qquad (3a)$$

where

k = thermal conductivity of wood $(Btu \cdot in.)/(h \cdot ft^2 \cdot °F)$;
ρ = total density of wood at moisture content M, lb_m/ft^3; and
M = moisture content (%) below 30%.

In SI units,

$$k = 0.0238 + \frac{(0.2005 + 0.004039M)\rho}{1000(1 + 0.01M)} \qquad (3b)$$

TABLE 1
Wood Species Specific Gravity and Density Ranges

Woods (12% Moisture Content)	Specific Gravity[a]	Density[b]	
	S_{wo}	$\rho(lb_m/ft^3)$	$\rho(kg/m^3)$
Hardwoods			
Oak	0.59 - 0.67	41.2 - 46.8	660 - 750
Birch	0.61 - 0.65	42.6 - 45.4	683 - 728
Maple	0.57 - 0.63	39.8 - 44.0	638 - 705
Ash	0.55 - 0.60	38.4 - 41.9	616 - 672
Softwoods			
Southern Pine	0.51 - 0.59	35.6 - 41.2	571 - 660
Douglas Fir-Larch (DF-L)	0.48 - 0.52	33.5 - 36.3	537 - 582
Southern Cypress	0.45 - 0.46	31.4 - 32.1	504 - 515
Hem-Fir (H-F), Spruce-Pine-Fir (S-P-F)	0.35 - 0.45	24.5 - 31.4	392 - 504
West Coast Wood, Cedars	0.31 - 0.45	21.7 - 31.4	347 - 504
Redwood	0.35 - 0.40	24.5 - 28.0	392 - 448

[a] Based on ovendry weight and volume at 12% moisture content

[b] Based on total weight and volume at 12% moisture content

where

k = thermal conductivity of wood, W/(m·K);
ρ = total density of wood at moisture content M; kg/m^3,
M = moisture content (%) below 30%.

Wilkes (1979) used a larger data base than MacLean (1941) by including the wood thermal conductivity data presented in MacLean (which were used to develop Equation 2a) and other references that gave wood thermal conductivity data. In Table 1 of Wilkes (1979), the thermal conductivity of wood is given as follows:

$$k = 0.1791 + \frac{(0.01874 + 0.0005753)\rho}{(1 + 0.01M)} \quad (4a)$$

where

k = thermal conductivity of wood (Btu·in.)/(h·ft^2·°F);
ρ = total density of wood at moisture content M, lb$_m$/ft^3; and
M = moisture content, %.

In SI units, Equation 4a becomes

$$k = 0.02582 + \frac{(0.1686 + 0.005177M)\rho}{1000(1 + 0.01M)} \quad (4b)$$

where

k = thermal conductivity of wood, W/(m·K);
ρ = total density of wood at moisture content M, kg/m^3; and
M = moisture content, %.

Since Equation 4 is based on a wider source of data than Equation 3, it was used to calculate the thermal conductivity values that were included in Table 3A, Chapter 23, of the *1985 Fundamentals* (ASHRAE 1985). Table 2 shows Wilkes' results of the thermal conductivity (k) and thermal resistance ($1/k$) ranges calculated from Equation 4a for the range of 12% moisture content densities of the wood species and wood species combinations that are given in Table 1. The thermal resistance ranges can be compared with the previous values used in the *1981 Fundamentals*, which were 0.91 $ft^2 \cdot h \cdot °F/(Btu \cdot in.)$ for hardwoods and 1.25 $ft^2 h \cdot °F/(Btu\ in.)$ for softwoods. As may be seen, the old hardwood value lies at the high end of the range in the lowest conductivity hardwoods—maple and ash—and the old softwood value falls about in the middle of the thermal resistance values of the lowest conductivity softwoods.

TenWolde et al. (1988), using essentially the same data base as Wilkes (1979), developed the following linear regression equation:

$$k = 0.1292 + \frac{(0.02155 + 0.000454M)\,\rho}{(1 + 0.01M)} \qquad (5a)$$

where

k = thermal conductivity of wood, $(Btu \cdot in.)/(h \cdot ft^2 \cdot °F)$;
ρ = total density of wood at moisture content M, lb_m/ft^3; and
M = moisture content, %.

In SI units, Equation 5a becomes

$$k = 0.01864 + \frac{(0.1941 + 0.004064M)\rho}{1000(1 + 0.01M)} \qquad (5b)$$

where

k = thermal conductivity of wood, $W/(m \cdot K)$;
ρ = total density of wood at moisture content M, kg/m^3; and
M = moisture content, %.

Table 2 shows the TenWolde results for the thermal conductivity (k) and thermal resistance ($1/k$) ranges calculated from Equation 5a for the range of 12% moisture content densities of the wood species and wood species combi-

TABLE 2
Wood Thermal Properties

	Density (lb_m/ft^3)	Thermal Conductivity (k) Wilkes	Thermal Conductivity (k) TenWolde	Resistance Per Inch Thickness (1/k) Wilkes	Resistance Per Inch Thickness (1/k) TenWolde	Specific Heat Btu/(lb_m °F)
WOODS (12% Moisture Content) a, b						
Hardwoods						0.39
Oak	41.2 - 46.8	1.12 - 1.25	1.12 - 1.26	0.80 - 0.89	0.80 - 0.89	
Birch	42.6 - 45.4	1.16 - 1.22	1.16 - 1.22	0.82 - 0.87	0.82 - 0.86	
Maple	39.8 - 44.0	1.09 - 1.19	1.09 - 1.19	0.84 - 0.92	0.84 - 0.92	
Ash	38.4 - 41.9	1.06 - 1.14	1.05 - 1.14	0.88 - 0.94	0.88 - 0.95	
Softwoods						0.39
Southern Pine	35.6 - 41.2	1.00 - 1.12	0.99 - 1.12	0.89 - 1.00	0.89 - 1.01	
Douglas Fir-Larch (DF-L)	33.5 - 36.3	0.95 - 1.01	0.94 - 1.00	0.99 - 1.06	1.00 - 1.07	
Southern Cypress	31.4 - 32.1	0.90 - 0.92	0.89 - 0.90	1.09 - 1.11	1.11 - 1.13	
Hem-Fir, Spruce-Pine-Fir (S-P-F)	24.5 - 31.4	0.74 - 0.90	0.72 - 0.89	1.11 - 1.35	1.13 - 1.39	
West Coast Woods, Cedars	21.7 - 31.4	0.68 - 0.90	0.65 - 0.89	1.11 - 1.48	1.13 - 1.53	
California Redwood	24.5 - 28.0	0.74 - 0.82	0.72 - 0.80	1.22 - 1.35	1.24 - 1.39	

Units: k = (Btu-in)/(h-ft²-°F); C = Btu/(h-ft²-°F); R = (h-ft²-°F)/Btu

To convert to SI units, multiply k values by 1.731/12 to obtain k values in W/(m-K) and multiply specific heat values by 4,187 to obtain specific heat values in J/(kg-K).

a There is a linear relationship between the thermal conductivity and density. The densities given are the ranges for the species groupings listed and the thermal conductivity ranges correspond to the density ranges. The mean value of the thermal conductivity range may be used in situations where the wood species density is not known.

b The thermal conductivity values given are for heat transfer in the radial and tangential directions with respect to the grain (e.g., growth rings). The thermal conductivity is 2.0 to 2.6 times larger than these values for heat transfer parallel to the grain.

nations that are given in Table 1. Comparison of the TenWolde results with the Wilkes results shows minor differences in the hardwood values and slightly lower thermal conductivity values and slightly higher thermal resistance values for softwoods. Therefore, building envelope thermal resistance calculations using the mean of the appropriate *1989 Fundamentals* (ASHRAE 1989) softwood thermal conductivity values based on the Wilkes (1979) equation (4a or 4b), will tend to produce almost imperceptibly lower thermal resistance values for walls, roofs, and floors containing 10% to 15% wood construction compared to using the TenWolde equation (5a or 5b).

Specific Heat

The specific heat of wood, as presented on pages 3-19 and 3-20 of the *Wood Handbook* (FPL 1972) or on page 3-25 of the revised *Wood Handbook* (FPL 1989), is a function of temperature and moisture content only and is independent of the particular wood species:

$$C_p = \frac{C_{po} + 0.01MC_{pw}}{1 + 0.01M} + A \qquad (6)$$

where

C_p = specific heat of wood at moisture content M, Btu/(lb$_m$·°F);
C_{po} = specific heat of dry wood, Btu/(lb$_m$·°F) = 0.25 + 0.0006T; and
C_{pw} = specific heat of water ≅ 1.0 Btu/(lb$_m$·°F);
A = additional specific heat due to wood-water bond energy, which ranges from 0.02 (at 85°F) to 0.04 (at 140°F) for 10% moisture content and 0.04 (at 85°F) to 0.09 (at 140°F) for wood at about 30% moisture content;
M = moisture content in percent (e.g., M = 12 for 12% moisture content); and
T = temperature, °F.
Note: To obtain C_p values in SI units of kJ/(kg·K), multiply values obtained from Equation 6 by 4.187.

Wilkes (1979) used the same basic expression as in the *Wood Handbook* for the specific heat of wood with different constant values obtained from a number of data sources.

In Table 1, Part II, of Wilkes (1979), the specific heat of moist wood is given as follows:

$$C_p = \frac{C_{po}+0.01MC_{pw}}{(1+0.01M)} + \delta C_p \qquad (7)$$

where

C_p = specific heat of wood at moisture content M, Btu/(lb$_m$·°F) or kJ/(kg·K);
C_{po} = specific heat of dry wood = $a_o + a_1T$;
C_{pw} ≅ specific heat of water = 1.0 Btu/(lb$_m$·°F) = 4.186 kJ/(kg·K);
δC_p = heat of sorption = $M(b_1 + b_2T + b_3M)$;
a_o = 0.2605 Btu/(lb$_m$·°F) = 1.031 kJ/(kg·K);
a_1 = 5.132×10^{-4} Btu/(lb$_m$·°F^2) = 3.867×10^{-3} kJ/(kg·K^2);
b_1 = -4.228×10^{-4} Btu/(lb$_m$·°F) = -6.191×10^{-2} kJ/(kg·K);
b_2 = 3.125×10^{-5} Btu/(lb$_m$·°F^2) = 2.355×10^{-4} kJ/(kg·K^2); and
b_3 = -3.168×10^{-5} Btu/(lb$_m$·°F) = 1.326×10^{-4} kJ/(kg·K).

TenWolde et al. (1988) recommend Equation 7 as the best available estimate of the specific heat of wood below the fiber saturation point for the temperature range of 45°F (280 K) to 297°F (420 K).

To obtain a value for the specific heat of wood for use in Table 3A, Chapter 23, of the *1985 Fundamentals* (ASHRAE 1985), the values of specific heat obtained from Equations 6 and 7 were compared. From the *Wood Handbook* (FPL 1972, 1989) Equation 6 method, for a temperature of 75°F, a moisture content of 12%, and an interpolated value of A of 0.022, the specific heat for wood is determined as follows:

C_{po} = 0.295 Btu/(lb$_m$·°F),
A = 0.022 Btu/(lb$_m$·°F), and
C_p = 0.3925 = 0.39 Btu/(lb$_m$·°F) = 1.63 kJ/(kg·K).

From the Wilkes (1979) Equation 7 correlation, for a temperature of 75°F and a moisture content of 12%, we obtain the specific heat of wood, determined as follows:

C_{po} = 0.299 Btu/(lb$_m$·°F),
δC_p = 0.0185 Btu/(lb$_m$·°F), and
C_p = 0.3926 = 0.39 Btu/(lb$_m$·R) = 1.63 kJ/(kg·K).

Since both methods agree and Wilkes (1979) indicated a 2.7% RMS deviation of the C_p equation with experimental data, a mean value of 0.39 was used, as given in Table 2.

BUILDING BOARDS—WOOD BASED

Wood-based building board materials are described in FPL (1989) and ASTM (1983a, 1986).

Changes to 1985 Fundamentals

Based on the Lewis paper (1967), the thermal conductance (C) and thermal resistance (R) values of intermediate-density fiberboard were changed from 0.82 h·ft^2·°F/Btu (0.14 K·m^2/W) and 1.22 h·ft^2·°F/Btu (0.21 K·m^2/W) to 0.92 h·ft^2·°F/Btu (0.16 K·m^2/W) and 1.09 h·ft^2·°F/Btu (0.19 K·m^2/W), respectively. The new values were based on a design thermal conductivity of 0.46 Btu·in./h·ft^2·°F (0.066 W/m·K). In addition, again based on Lewis' (1967)

work, the *C*- and *R*-values for nail-based sheathing were changed from 0.88 Btu/h·ft^2·°F (5 W/m^2·K) and 1.14 h·ft^2·°F/Btu (0.2 K·m^2/W) to 0.94 Btu/h·ft^2·°F (5.34 W/m^2·K) and 1.06 h·ft^2·°F/Btu (0.19 K·m^2/W), respectively. These new values were based on a design thermal conductivity of 0.47 Btu·in./h·ft^2·°F (0.068 W/m·K). These changes were consistent with the data for regular-density fiberboard sheathing, which were also from Lewis (1967).

Changes were also made to the low-density (37 lb$_m$/ft^3 [593 kg/m^3]) particleboard thermal conductivity (k) and thermal resistivity ($1/k$) data based on Lewis (1967). These values were changed from 0.54 Btu·in./h·ft^2·°F (0.078 W/m·K) and 1.85 h·ft^2·°F/Btu·in.(12.8 m·K/W) to 0.71 Btu·in./h·ft^2·°F (0.10 W/m·K) and 1.41 h·ft^2·°F/Btu·in. (9.77 m·K/W), respectively. These changes brought the low-density particleboard data into agreement with the medium- and high-density particleboard data shown in *Fundamentals* (ASHRAE 1985) and Lewis (1967).

Another change made to the building boards section was the addition of data on waferboards. The data were reported by Nanassy and Szabo (1978) and Jessome (1979) but were actually measured by the National Research Council of Canada in 1976. The data include a thermal conductivity of 0.63 Btu·in./h·ft^2·°F (0.091 W/m·K) and a thermal resistivity of 1.59 h·ft^2·°F/Btu·in. (11 m·K/W). These data were for a 37.1-lb$_m$/ft^3 (594-kg/m^3) waferboard with a very low moisture content of 1.5% measured at a mean temperature of 75°F (24°C).

New Waferboard Thermal Data

A series of five ASTM C518 (ASTM 1976) tests were conducted on ovendried nominal 7/16-inch (11-mm) APA-rated waferboard. All tests were conducted at a mean temperature of 75°F (24°C) and a temperature differential of 40°F (22°C). The test samples were conditioned at 73°F (23°C) and 50% RH for 48 hours prior to drying in an oven at 217°F (103°C) as per ASTM D4442 (ASTM 1984). After drying the test samples to constant weight, they were cooled to ambient temperature and the densities determined. Each waferboard sample was run three times and the averages of the three tests are summarized in Table 3.

If a linear relationship in density is assumed between the data reported in the *1989 Fundamentals* (ASHRAE 1989) and the above data, excellent agreement is observed:

$$0.63 \times \frac{40.2\ \text{lb}_m\ \text{ft}^3}{37\text{lb}_m\ \text{ft}^3} = 0.69\ \text{Btu}\cdot\text{in.}/\text{h}\cdot\text{ft}^2\cdot{}^\circ\text{F} \quad [0.098\ \text{W/m}\cdot\text{K}]$$

as compared to an average measured value of 0.667 Btu·in/h·ft^2·°F (0.096 W/m·K).

CONCLUSIONS AND RECOMMENDATIONS

The rationales and procedures used to determine the thermal properties of the wood and wood panel products shown in the *1989 ASHRAE Handbook-Fundamentals* (ASHRAE 1989) are presented in this paper.

While the thermal conductivity information on wood species as a function of moisture content and density is adequate, there is a definite need for improved thermal conductivity and specific heat data for wood-based building board products, especially some of the newer products such as waferboards and oriented strandboards. The specific products that need to be studied are plywood, particleboard, waferboard, and oriented strandboard. ASHRAE should sponsor a research project that looks at different versions (and thicknesses), of these products along with some spot checking of some of the wood species that are used most often in building construction. As pointed out by one reviewer of this paper, it should be recognized that the moisture content of wood-based materials containing fire retardants, preservatives, and other volatile materials may be more difficult to measure if the wood product is heated in an oven to approximately 105°C (221°F) as required by ASTM (1984). The ASHRAE research plan should recognize that errors in the moisture content may arise due to the driving off of chemically bound water of hydration in these materials.

The above-proposed ASHRAE research project—to develop better thermal property data for wood and wood-based building materials—is especially important for many building envelope heat transfer problems (e.g., thermal bridging in highly insulated wood-framed buildings and the multidimensional heat transfer through roof sheathing).

ACKNOWLEDGMENTS

The authors would like to acknowledge the work of T. J. Cardenas of Steven Winter Associates for the extensive materials he submitted to ASHRAE Technical Committee 4.4 for modifying the wood thermal conductivity values in Table 3A, Chapter 23, of the *1981 ASHRAE Handbook—Fundamentals*. These materials provided the impetus for a portion of the work presented in this paper.

The authors would also like to thank K.E. Wilkes, formerly with Owens-Corning Fiberglas, now at Oak Ridge National Laboratory, for sharing some of his extensive knowledge of wood thermal properties and wood thermal property literature; W. L. James of the Forest Products Laboratory for reviewing the proposed changes that were made to the wood thermal conductivity values in Table 3A, Chapter 23, of the *1985 Fundamentals*; and H. Roberts of Rmax, Inc., for permission to publish the waferboard thermal conductivity data.

REFERENCES

ASHRAE. 1981. *1981 ASHRAE handbook—fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1985. *1985 ASHRAE handbook—fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

TABLE 3a
Waferboard Thermal Data in I-P Units

Sample No.	Test (Dry) Density (lb_m/ft^3)	T_h (°F)	T_c (°F)	T_m (°F)	Thickness (inch)	k (Btu-in/hft²°F)	R (hft²°F/Btu)
1	40.6	95.0	54.9	75.0	0.452	0.657	0.69
2	40.7	95.0	54.9	75.0	0.464	0.712	0.65
3	39.9	94.9	54.9	74.9	0.465	0.702	0.66
4	40.7	95.1	55.0	75.0	0.464	0.611	0.76
5	39.0	95.1	54.9	75.0	0.438	0.654	0.67
Average	**40.2**	**95.0**	**54.9**	**75.0**	**0.457**	**0.667**	**0.69**

TABLE 3b
Waferboard Thermal Data in SI Units

Sample No.	Test (Dry) Density (kg/m^3)	T_h (°C)	T_c (°C)	T_m (°C)	Thickness (mm)	k (W/mK)	R (Km^2/W)
1	650	35.0	12.7	23.9	11.5	0.095	0.12
2	652	35.0	12.7	23.9	11.8	0.103	0.11
3	639	34.9	12.7	23.8	11.8	0.101	0.12
4	652	35.1	12.8	23.9	11.8	0.088	0.13
5	625	35.1	12.7	23.9	11.1	0.094	0.12
Average	**644**	**35.0**	**12.7**	**23.9**	**11.6**	**0.096**	**0.12**

ASHRAE. 1989. *1989 ASHRAE handbook—fundamentals.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASTM. 1987a. ASTM D1165, Nomenclature of domestic hardwoods and softwoods. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1986. ASTM D1554, Definitions of terms relating to wood-base fiber and particle panel materials. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1983a. ASTM D1038, Definitions of terms relating to veneer and plywood. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1976. ASTM C518, Standard test method for steady-state thermal transmission properties by means of the heat flow meter. *ASTM Annual Book of Stan-*

dards, part 18. Philadelphia: American Society of Testing and Materials.

ASTM. 1988. ASTM D2555, Method for establishing clear wood strength values. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1983b. ASTM D2395, Test methods for specific gravity of wood and wood-base materials. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. D 1987b. ASTM D9, Definitions of terms relating to wood. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1984. ASTM D4442, Test methods for direct moisture content measurement of wood and wood-base materials. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

ASTM. 1981. ASTM D245, Method for establishing structural grades and related allowable properties for visually graded lumber. *ASTM Annual Book of Standards*, Vol. 04.09. Philadelphia: American Society of Testing and Materials.

Cardenas, T.J., and G.T. Bible, 1987. ASTM STP 922, The thermal properties of wood-data base. *Thermal insulation: Materials and systems*, F.J. Powell and S.L. Matthews, eds., pp. 238-282. Philadelphia: American Society of Testing and Materials.

FPL. 1989. *Handbook of wood and wood-based materials for engineers, architects, and builders.* Forest Products Laboratory, U.S. Department of Agriculture. Washington, DC: Hemisphere Publishing Corp.

FPL. 1972. *Wood handbook: Wood as an engineering material. Agriculture Handbook No. 72*, August. Washington, DC: Forest Products Laboratory, U.S. Department of Agriculture.

Jessome, A.P. 1979. Canadian waferboard properties 1979. Technical Report 523E. Forintek Canada Corp.

Kamke, F.A., and S.C. Zylkowski. 1989. Effects of wood-based panel characteristics on thermal conductivity. *Forest Products Journal* 39 (5): 19-24.

Kollmann, F., and L. Malmquist. 1956. Uber die Warmleitzahl von Holz und Holzwerkstoffen (The thermal conductivity of wood and wood-based materials). *Holz als Roh- und Werkstoff* (Wood as a Raw Material and a Manufactured Material) 14 (6): 201-204.

Lewis, W. C. 1967. Thermal conductivity of wood-based fiber and particle panel materials. U.S. Forest Service Research Paper FPL 77, June. Madison: Forest Products Laboratory, U.S. Department of Agriculture.

MacLean, J.D. 1941. Thermal conductivity of wood. *Trans. ASHVE* 47: 323-354.

Nanassay, A. J., and T. Szabo. 1978. Thermal properties of waferboards as determined by a transient method. *Wood Science* 11 (1) 17-22.

NFPA. 1982. Design values for wood construction. A supplement to the 1982 edition of the *National Design Specification for Wood Construction.* Washington, DC: National Forest Products Association.

NFPA. 1978. *Wood structural design data, A manual for architects, builders, engineers, and others concerned with wood construction.* Washington, DC: National Forest Products Association.

Siau, J. F. 1983. *Transport processes in wood.* Springer-Verlag.

Suzuki, M. 1981. Physical characteristics of multilayer particleboard. *Mokuzai Gakkaishi* (27) 397-402.

TenWolde, A., J.McNatt, and L. Krahn. 1988. Thermal properties of wood and wood panel products for use in buildings. USDA Forest Products Laboratory Report for Oak Ridge National Laboratory, Oak Ridge, TN. U.S. Department of Energy, Report ORNL/Sub/87-21697/1, September.

Tsongas, G. 1990. The Northwest wall moisture study: A field study of excess moisture in walls and moisture damage in new Northwest homes. U.S. DOE/Bonneville Power Administrator, DOE/BP-91489-1.

APA. 183. U.S. Product Standard PS 1-83 1983, for construction & industrial plywood with typical APA trademarks. Tacoma, WA: American Plywood Association.

Wangaard, F. F. 1969. Heat transmissivity of southern pine wood, plywood, fiberboard, and particleboard. *Wood Science* 2 (1) 54-60.

White, R. H., and E. L. Schaffer. 1981. Thermal characteristics of thick red oak flakeboard. Forest Products Laboratory Research Paper FPL 407, August. Madison: Forest Products Laboratory, U.S. Department of Agriculture.

Wilkes, K.E. 1979. Thermophysical properties data base activities at Owens-Corning Fiberglas. *Proceedings of the ASHRAE/DOE-ORNL Conference, Thermal Performance of Exterior Envelopes of Buildings*, Kissimmee, FL, ASHRAE SP-28, pp. 662-677.