CHAPTER 20

Heat Sterilization of Wood

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Contents

Insects and other pests can travel between countries in pallets and other wood packaging materials through international trade. Because these pests can cause significant ecological damage, their invasion into non-native countries is undesirable. Heat sterilization is currently the most practical and environmentally friendly treatment to kill pests in solid wood materials and prevent their transfer between continents and regions. Consequently, regulations requiring heat sterilization are becoming more common.

Two important questions should be considered in heat sterilizing solid wood materials: First, what temperature–time regime is required to kill a particular pest? Second, how much time is required to heat the center of any wood configuration to the kill temperature? The entomology research on the first question has facilitated the development of international standards for heat sterilization of various solid wood materials. This chapter primarily addresses the second question. It focuses on various factors that should be considered when planning and implementing a heat treatment process using a conventional steam or dry kiln heat chamber, discusses experimentally derived heating times for commonly used wood products, and presents analytical and empirical methods for estimating heating times that can be used as starting points in the development of heat treatment schedules. Current wood packaging material enforcement regulations and several additional practical considerations for heat treatment operations are also presented.

Heat Treatment Standards

The current international standard for heat sterilization of solid wood packaging materials is the International Standard for Phytosanitary Measures (ISPM) 15, "Guidelines for Regulating Wood Packaging Material in International Trade," which requires heating wood to a minimum core temperature of 56 °C (133 °F) for a minimum of 30 min when using conventional heat chamber technology (IPPC 2002, 2017; APHIS 2004). (Note: In 2013, the Eighth Session of the Commission on Phytosanitary Measures (CPM-8) adopted revised Annex 1 to ISPM 15 to include heat treatment using dielectric heating. Where dielectric heating (microwave or radio waves) is used, wood packaging material must be heated to achieve a minimum temperature of 60 °C (140 °F) for 1 min continuously throughout the entire profile of the wood, including its surfaces.) These guidelines are for all forms of wood packaging material that may serve as a pathway

Table 20–1. Pest groups that are practically eliminated by heat treatment under ISPM 15 standard

Insects	
	Anobiidae
	Bostrichidae
	Buprestidae
	Cerambycidae
	Curculionidae
	Isoptera
	Lyctidae (with some exceptions for HT)
	Oedemeridae
	Scolytidae
	Siricidae
Nematodes	
	Bursaphelenchus xylophilus

for plant pests posing a threat mainly to living trees. This temperature–time regime is chosen in consideration of the wide range of pests for which this combination is documented to be lethal and a commercially feasible treatment. Table 20–1 lists the pest groups associated with wood packaging material that can be practically eliminated by heat treatment under ISPM 15 standard. Although some pests are known to have a higher thermal tolerance, quarantine pests in this category are managed by the National Plant Protection Organizations (NPPOs) on a case-by-case basis (IPPC 2002). One example is the emerald ash borer (*Agrilus planipennis*), which requires heating wood to a minimum core temperature of 60 °C (140 °F) for a minimum of 60 min (USDA APHIS PPQ 2016). Future development may identify other temperature–time regimes required to kill specific insects or fungi.

Factors Affecting Heating Times

From a practical standpoint, the time required for the center of solid wood material to reach the kill temperature depends on many factors, including the type of energy source used to generate the heat, the medium used to transfer the heat (for example, wet or dry heat), the effectiveness of the air circulation in the heating facility, the species and physical properties (configurations, specific gravity, moisture content, initial wood temperature) of the wood and wood products being sterilized, and the stacking methods used in the heat treatment process.

Energy Source

Energy is the amount of heat supplied during the heat treatment process. The choice of heat energy primarily depends on the heat treatment method, energy resources available, and the cost of the energy. Heat-treating chambers typically employ systems that utilize steam directly or use steam, hot water, or hot oil pipes to heat the air. Electricity (resistive) is generally the most expensive way to generate heat. Burning waste wood to heat water or oil or to make steam is likely the least expensive method. Another option is direct fire combustion, which uses the heat exhaust from burning a fuel. This approach may be the least expensive source of energy, but it is also the most dangerous because a spark could ignite the firewood load. When time duration is critical, dielectric heating would be the fastest technique because it uses electromagnetic waves (microwaves or radio-frequency waves) to create heat and the target temperature can be achieved rapidly. The cost of heat treatment with dielectric heating will vary depending on the design and approach of each facility (IPPC 2014).

Heating Medium

The temperature and humidity of the heating medium significantly affects the heating times. Higher heating temperatures yield shorter heating times, and heating wood in saturated steam (wet heat) results in the shortest heating times. When the heating medium is air that is not saturated with steam, the relative humidity is less than 100% (wet-bulb depression is greater than zero) and drying occurs as water evaporates from the wood surface. As the heating medium changes from wet to dry heat, the time needed to reach the required temperature increases. This is illustrated in Figure 20–1, which shows heating times as a function of wet-bulb depression for a series of lumber and timber products.

When the wet-bulb temperature in the heating medium approaches or falls below the target center temperature, heating time becomes much longer than with wet heat (Simpson 2002, Simpson and others 2003) because evaporation of water from the wood surface with dry heat cools the surface and lowers its temperature, reducing the surface-to-center temperature gradient that is the driving force for transferring heat. With wet heat there is little or no evaporation of moisture and thus little surface cooling to slow heat transfer.

Air Circulation

Maintaining adequate air circulation is important in heat sterilization. The circulating air performs two functions, as it does in kiln drying: it carries heat to the wood to effect evaporation, and it removes the evaporated water vapor. Good air circulation ensures uniform heat distribution in the chamber and keeps the wood surface temperature high so that the surface-to-center temperature gradient is as high as possible. This is usually accomplished with fans and baffles in a treatment chamber. However, it should be noted that water evaporation is generally not desired when heat treatment is the goal. For heat treatment to be most efficient, the wet-bulb depression should be kept as low as possible so that most energy goes into heating wood alone and less energy is wasted by drying wood.

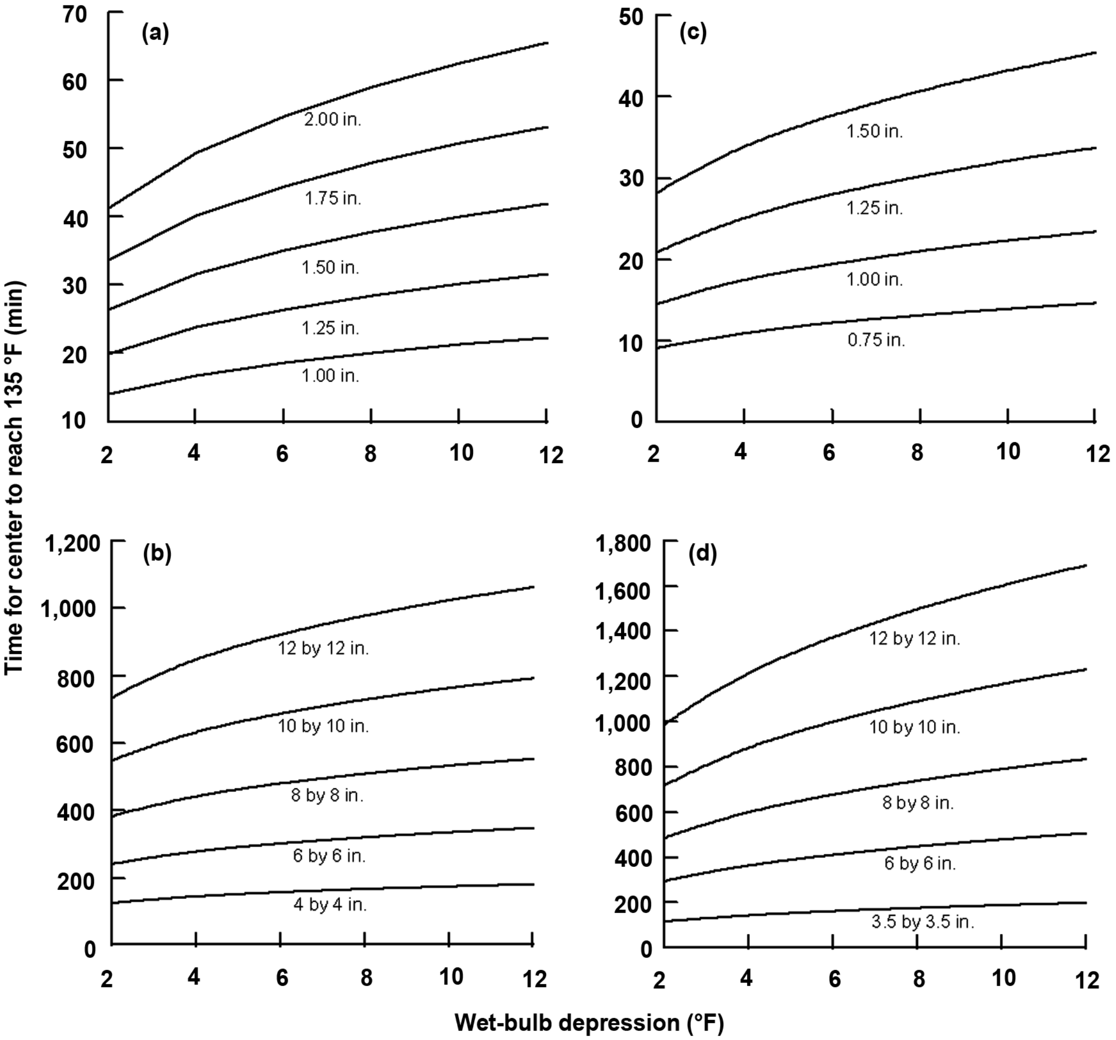


Figure 20–1. Dependence of heating time on wet-bulb depression for (a) 1- to 2-in.-thick ponderosa pine boards; (b) 4- to 12-in. ponderosa pine timbers; (c) 3/4- to 1-1/2-in.-thick Douglas-fir boards; and (d) 3-1/2- by 3-1/2-in. Douglas-fir timbers. (Note: Heating times were estimated based on multiple regression equations developed by Simpson and others (2003) for a heating environment of nominal 160 °F dry-bulb temperature and various web-bulb temperatures. Initial temperature of wood was 60 °F. Average green moisture content of wood was 112% for ponderosa pine and 97% for Douglas-fir.) (°C = (°F – 32)/1.8; 1 in. = 25.4 mm)

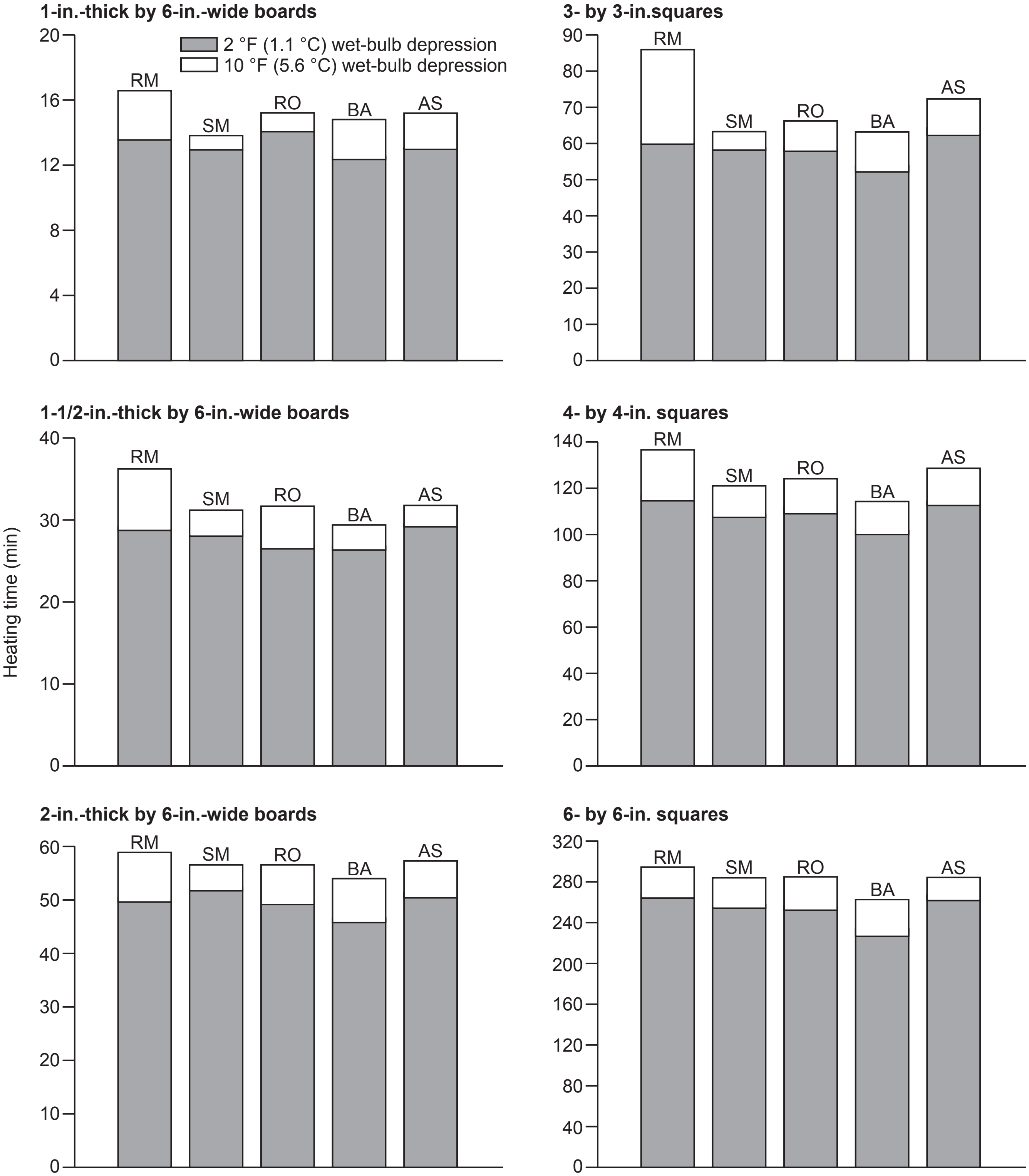
Size and Configuration of Wood

The heat treatment process is affected by wood configuration and size. Heating time increases with size and at a rate that is more than proportional to the cross-section configuration. For example, heating time can range from only a few minutes for thin boards to many hours for large timbers. The effect of wood configuration on heating time can be seen in Figure 20–1 for a series of web-bulb depressions.

Species

Studies of five hardwood species (red maple, sugar maple, red oak, basswood, and aspen) at the Forest Products Laboratory have indicated that the actual effect of species was not large (Simpson and others 2005). In fact, the differences in heating times of different species are of a similar magnitude to the expected natural variability between individual boards and square timbers. In heat treatment operation, there is no practical reason to heat-treat different hardwood species separately. Figure 20–2 illustrates the effects of species on heating times of boards and square timbers for five hardwood species.

No data are currently available to directly assess the effect of species in heat-treating softwood products. However, there are practical reasons to separate species in drying softwood lumber, and heat treatment for softwood products is often accomplished as part of the wood drying process. Detail information on heating times for softwood products are presented in the sections of stacking methods, heating times for wood in various forms, and methods for estimating heating times.



1-in.-thick by 6-in.-wide boards

3- by 3-in.squares

1-1/2-in.-thick by 6-in.-wide boards

4- by 4-in. squares

2-in.-thick by 6-in.-wide boards

6- by 6-in. squares

Figure 20–2. Effect of species on heating times of boards and squares (RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen).

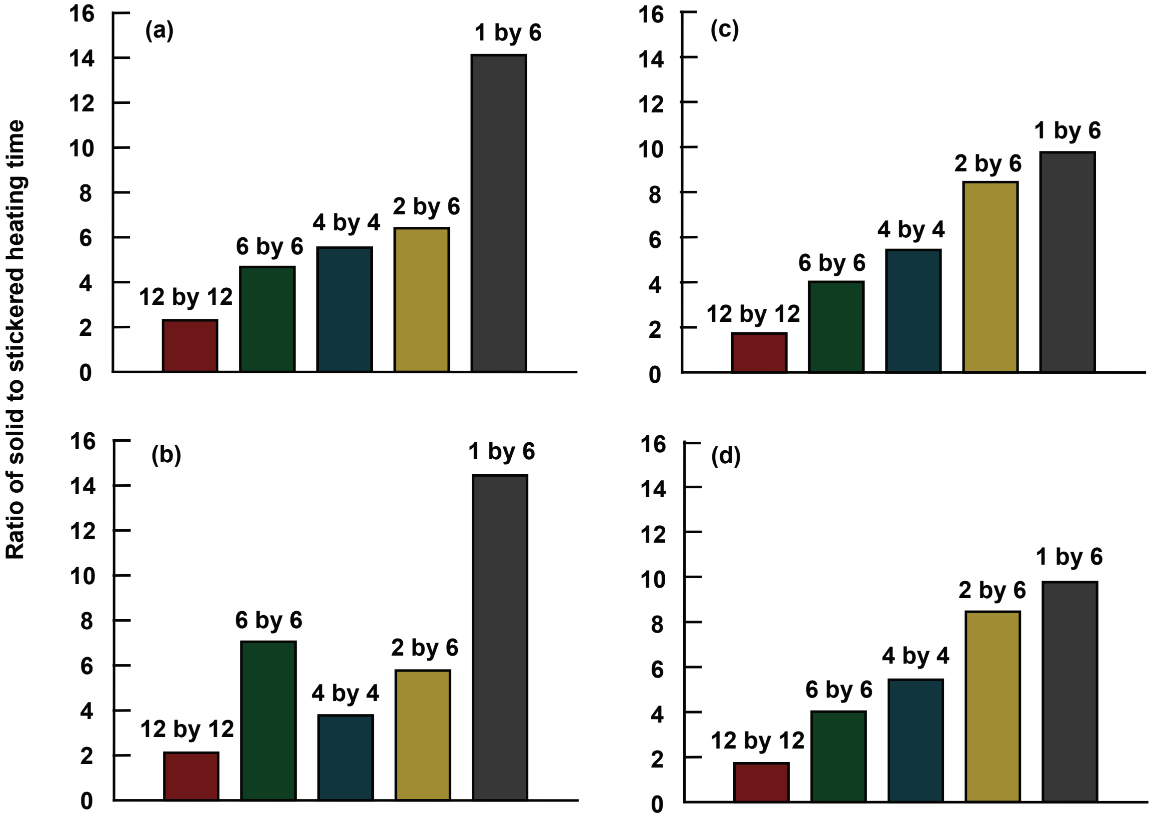


Figure 20–3. Ratio of heating times of solid-piled boards and timbers (4 by 3.2 ft) to stickered boards and timbers for (a) Douglas-fir, 1.5 °F/2.2 °F (0.8 °C/1.2 °C) wet-bulb depression; (b) Douglas-fir, 12.5 °F/13.8 °F 7.0 °C/7.7 °C) wet-bulb depression; (c) ponderosa pine, 2.5 °F/2.8 °F (1.4 °C/1.6 °C) wet-bulb depression; and (d) ponderosa pine, 12.0 °F/13.4 °F (6.7 °C/7.5 °C) wet-bulb depression.

Stacking Methods

Proper stacking of lumber or timbers is an essential aspect of the heat treatment process because it directly affects heat transfer and, consequently, heating times. If a heat treatment facility receives solid-piled bundles of lumber or timbers, it may be desirable to heat-treat in the solid-piled configuration. However, a solid bundle of lumber or timbers requires much longer heating times than a comparable quantity of stickered lumber or timbers. Figure 20–3 shows the ratio of heating times for equal quantities of lumber or timbers, one being heat treated as a solid bundle (4 by 3.2 ft) and the other treated after stickering. Note that a solid bundle of 1- by 6-in. lumber takes at least 10 times longer to heat than the same wood that has been stickered. In addition, a higher degree of variation in heating times for solid-piled materials than for stickered materials results from how closely the individual pieces fit together in a stacking bundle (Simpson and others 2003). Gaps between individual pieces allow hot air to penetrate and thus warm the surface more than where adjacent pieces fit tightly together. In commercial practice, this high variability would cause complications in estimating heating times.

Heating Times for Wood in Various Forms

A series of heating experiments were conducted at the Forest Products Laboratory to determine the time required to heat the center of various wood configurations to the kill temperature (Simpson 2001, 2002; Simpson and others 2003, 2005). Tables 20–2 and 20–3 summarize experimental heating times for ponderosa pine and Douglas-fir boards and square timbers to a center temperature of 56 °C (133 °F) in a heating environment of 71 °C (160 °F) dry-bulb temperature and various wet-bulb depressions. Table 20–4 summarizes average heating times required to reach 56 °C (133 °F) for six sizes of five hardwood species (red maple, sugar maple, red oak, basswood, and aspen) at two wet-bulb depressions (0 and 5.6 °C (0 and 10 °F)). Note that heating times in these tables are for wood in green condition and that these data were obtained through laboratory experiments in a small-scale dry kiln (approximately 3.5 m^3 (1,500 board foot) capacity) under well-controlled heating conditions. Although the experimental results have not been calibrated to commercial operation, they have served as the bases for developing heat treatment schedules for industrial applications (ALSC 2014).

Table 20–2. Summary of experimental heating times to heat ponderosa pine boards and square timbers to a center temperature of 133 °F (56 °C) in a heating environment of nominal 160 °F (71 °C) dry-bulb temperature and various wet-bulb depressions

Wet-bulb depression (°F (°C))	Experimental heating times (min)[a]				
	1 by 6[b]	2 by 6	4 by 4	6 by 6	12 by 12
			Stickered		
2.5 (1.4)	17 (8.1)	43 (13.1)	153 (8.9)	299 (17.7)	1,006 (15.5)
6.2 (3.4)	16 (5.9)	53 (2.4)	180 (6.0)	271 (6.2)	980 (12.1)
12.0 (6.6)	23 (3.1)	67 (15.0)	207 (17.3)	420 (28.3)	1,428 (8.2)
26.8 (14.9)	188 (45.2)	137 (12.5)	256 (19.0)	568 (7.2)	1,680 (13.9)
47.5 (26.4)	427 (18.1)	361 (30.7)	817 (53.9)	953 (38.1)	2,551 (22.2)
			Solid-piled[c]		
2.8 (1.6)	166 (70.3)	361 (64.9)	831 (14.0)	1,201 (30.1)	1,736 (26.4)
13.4 (7.4)	201 (22.7)	391 (23.4)	710 (48.1)	1,617 (26.7)	2,889 (22.4)

[a] Values in parentheses are coefficients of variation (%).
[b] Actual sizes are the same as nominal sizes.
[c] Solid pile 4 ft wide and 3.2 ft high.

Table 20–3. Summary of experimental heating times to heat Douglas-fir boards and square timbers to a center temperature of 133 °F (56 °C) in a heating environment of nominal 160 °F (71 °C) dry-bulb temperature and various wet-bulb depressions

Wet-bulb depression (°F (°C))	Experimental heating times (min)[a]				
	1 by 6[b]	2 by 6	4 by 4	6 by 6	12 by 12
			Stickered		
2.2 (1.2)	7 (22.2[c])	21 (21.3)	78 (12.5)	209 (8.9)	840 (8.8)
6.3 (3.5)	8 (10.3)	25 (21.9)	91 (10.5)	202 (11.6)	914 (13.9)
12.5 (6.9)	10 (6.7)	34 (22.3)	138 (17.8)	262 (7.7)	1,153 (7.0)
27.1 (15.0)	216 (39.9)	157 (23.1)	255 (25.1)	715 (22.8)	1,679 (3.1)
44.2 (24.6)	233 (62.8)	223 (20.3)	362 (28.0)	849 (6.1)	2,005 (23.3)
			Solid-piled[c]		
1.5 (0.8)	103 (45.2)	137 (46.9)	432 (27.2)	977 (9.3)	1,931 (13.5)
13.8 (7.7)	143 (69.1)	195 (77.4)	521 (54.7)	1,847 (25.7)	1,847 (25.7)

[a] Values in parentheses are coefficients of variation (%).
[b] Nominal sizes.
[c] Solid pile 4 ft wide and 3.2 ft high.

Methods for Estimating Heating Times

Many combinations of wood configurations, heating temperatures, wet-bulb depressions, and initial wood temperatures are possible. It is not possible to conduct an experiment of practical scope to be able to address them together. Therefore, analytical methods are needed to estimate the heating times for combinations not directly measured experimentally.

MacLean Equations

MacLean (1930, 1932, 1941) developed equations for estimating heating times in steam and showed experimentally that they worked well. The equations are for two-dimensional heat flow (heating is from all four cross-sectional faces) and apply only to heating in a saturated steam environment. Heat conduction is considered to be about 2.5 times faster in the longitudinal grain direction than across the grain. However, because the length of many typical timbers and rounds is much greater than the cross-sectional dimension, longitudinal conduction is ignored and the equations thus simplified.

Round Cross Section

The heat conduction equations for round cross sections are taken from MacLean (1930), further refined by Ingersoll and Zobel (1948). The temperature T at any point on radius r is given by

$$T = T_{\mathrm{s}} + 2\left(T_0 - T_{\mathrm{s}}\right)\sum_{n=1}^{\infty}\frac{J_0(z_n\, r/R)}{z_n J_1(z_n)}\exp\left(-\alpha t z_n^2 / R^2\right) \tag{20–1}$$

where

Table 20–4. Summary of experimental heating times to 133 °F (56 °C) for six sizes of five hardwood species heated at a nominal dry-bulb temperature of 160 °F (71 °C) and two wet-bulb depressions[a]

Wet-bulb depression (°F (°C))	Piece size (in.)[c]	Heating time (min)[b] Red maple	Sugar maple	Red oak	Basswood	Aspen
0 (0)	1 by 6	14 (15)	13 (14)	14 (15)	12 (14)	13 (14)
	1-1/2 by 6	29 (31)	28 (30)	26 (28)	26 (28)	29 (32)
	2 by 6	50 (52)	48 (49)	49 (53)	46 (48)	50 (54)
	3 by 3	59 (64)	58 (61)	57 (60)	51 (58)	61 (64)
	4 by 4	115 (119)	107 (113)	109 (112)	100 (108)	113 (117)
	6 by 6	265 (283)	255 (277)	252 (259)	226 (243)	262 (278)
10 (5.6)	1 by 6	17 (18)	14 (15)	15 (16)	15 (17)	15 (16)
	1-1/2 by 6	36 (38)	31 (34)	32 (33)	29 (31)	32 (33)
	2 by 6	59 (62)	53 (56)	56 (59)	54 (58)	57 (62)
	3 by 3	85 (96)	63 (67)	66 (69)	63 (69)	69 (74)
	4 by 4	137 (143)	121 (127)	124 (129)	114 (120)	129 (133)
	6 by 6	294 (304)	284 (299)	284 (298)	262 (284)	285 (195)

[a] Heating times were adjusted to a common initial temperature of 60 F (16 C) and the overall actual average heating temperature of 157 F (69 C).

[b] Values in parentheses are 99% upper confidence bounds of heating times.

[c] Actual sizes.

T_s is surface temperature (which must be attained immediately),
T_0 initial temperature,
J_0 zero-order Bessel function,
J_1 first-order Bessel function,
z_n nth root of $J_0(z_n) = 0$,
r any point on radius of cross section,
R radius of cross section,
α thermal diffusivity (dimension^2/time), and
t heating time.

To calculate the temperature at the center of the cross section, $r = 0$, Equation (20–1) becomes

$$T_c = T_s + 2\left(T_0 - T_s\right)\sum_{n=1}^{\infty}\frac{\exp(-\alpha t z_n^2 / R^2)}{z_n J_1(z_n)} \qquad (20\text{–}2)$$

Equations (20–1) and (20–2) converge quickly, so only the first few terms are necessary. The first few terms of Equation (20–2) are

$$T_c = T_s + 2(T_0 - T_s)\left[\frac{\exp(-\alpha t z_1^2 / R^2)}{z_1 J_1(z_1)} + \frac{\exp(-\alpha t z_2^2 / R^2)}{z_2 J_1(z_2)} + \frac{\exp(-\alpha t z_3^2 / R^2)}{z_3 J_1(z_3)} + \ldots\right] \qquad (20\text{–}3)$$

From Watson (1958), the first five roots of $J_0(z_n) = 0$ are

$$z_1 = 2.405$$
$$z_2 = 5.520$$
$$z_3 = 8.654$$
$$z_4 = 11.792$$
$$z_5 = 14.931$$

and the first five values of $J_1(z_n)$ are

$$J_1(2.405) = 0.5191$$
$$J_1(5.520) = -0.3403$$
$$J_1(8.654) = 0.2714$$
$$J_1(11.792) = -0.2325$$
$$J_1(14.931) = 0.2065$$

Rectangular Cross Section

The equation for rectangular cross sections is taken from MacLean (1932) and is the solution to the differential equation of heat conduction in the two dimensions of a rectangular cross section. The temperature T at any point x and y is given by

$$\begin{aligned} T = T_s + (T_0 - T_s)(16/\pi^2) \times \\ \{&\sin(\pi x/a)\sin(\pi y/b)\exp[-\pi^2 t(\alpha_x/a^2+\alpha_y/b^2)] \\ &+(1/3)\sin(3\pi x/a)\sin(\pi y/b)\exp[-\pi^2 t(9\alpha_x/a^2+\alpha_y/b^2] \\ &+(1/3)\sin(\pi x/a)\sin(3\pi y/b)\exp[-\pi^2 t(\alpha_x/a^2+9\alpha_y/b^2] \\ &+(1/5)\sin(5\pi x/a)\sin(\pi y/b)\exp[-\pi^2 t(25\alpha_x/a^2+\alpha_y/b^2] \\ &+(1/5)\sin(\pi x/a)\sin(5\pi y/b)\exp[-\pi^2 t(\alpha_x/a^2+25\alpha_y/b^2] \\ &+(1/7)\sin(7\pi x/a)\sin(\pi y/b)\exp[-\pi^2 t(49\alpha_x/a^2+\alpha_y/b^2] \\ &+(1/7)\sin(\pi x/a)\sin(7\pi y/b)\exp[-\pi^2 t(\alpha_x/a^2+49\alpha_y/b^2] \\ &+\ldots\} \end{aligned} \qquad (20\text{–}4)$$

where

T_s is surface temperature (which must be attained immediately),

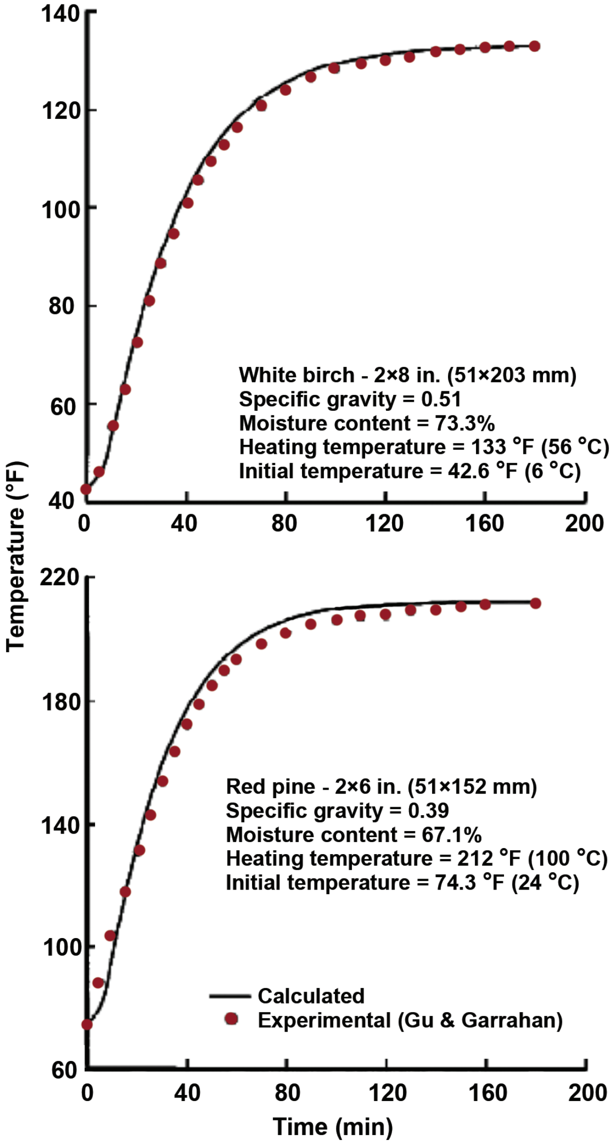


Figure 20–4. Comparison of experimental heating times of Gu and Garrahan (1984) with times calculated using MacLean equations for white birch and red pine.

T_0	initial temperature,
a	one cross-sectional dimension,
b	other cross-sectional dimension,
α_x	thermal diffusivity in the x direction (dimension^2/time),
α_y	thermal diffusivity in the y direction, and
t	heating time.

Equation (20–4) converges quickly, so only the first few terms are necessary. Because thermal conductivity and thermal diffusivity do not differ much in the radial and tangential directions of wood, in Equation (20–4) we can set $\alpha_x = \alpha_y$ (MacLean 1941). Equation (20–4) can easily be converted to calculate the temperature at the center of the cross section by setting $x = a/2$ and $y = b/2$.

Gu and Garrahan (1984) experimentally confirmed that MacLean's equations were valid for estimating heating times. Figure 20–4 shows close agreement of experimental heating times of Gu and Garrahan (1984) with times calculated using MacLean's heat conduction equation. Simpson (2001) further confirmed the validity of MacLean's equations and used them to develop a series of tables of heating times (to the center) of round and rectangular sections. Variables in the tables were wood specific gravity, moisture content, initial temperature, heating temperature, and target center temperature.

Specific gravity and moisture content values were chosen to represent several species that might be subjected to heat sterilization. Target center temperatures other than 56 °C (133 °F) were included because future heat sterilization requirements are not known and might include higher temperatures. As an example, Table 20–5 tabulates the estimated heating times to heat lumber of selected sizes to 56 °C (133 °F) for wood specific gravity of 0.35 (Cheung 2008). Tables for other combinations of variables are presented in Simpson (2001).

Heat experiments at the Forest Products Laboratory indicated that MacLean's equations are able to estimate heating times in steam to a degree of accuracy that is within about 5% to 15% of measured heating times. The equations offer a powerful way to include the effects of all the variables that affect heating time—specific gravity, moisture content, initial temperature, heating temperature, target center temperature, and cross-sectional dimensions.

MacLean's approach requires full access of all four faces to the heating medium. This might not be achieved in the close edge-to-edge contact of the stickered configuration or the solid-piled configuration. In practice, his approach will probably require some small level of gapping between adjacent boards or timbers.

Multiple Regressions

MacLean's equations apply only to heating in a saturated steam environment. When the heating medium is air that is not saturated with steam, there is a wet-bulb depression (the relative humidity is less than 100%), and drying occurs as water evaporates from the wood surface. The consequence is that heating time increases and MacLean's equations no longer apply. An alternative method to estimate the heating time when simultaneous drying occurs is to use a strictly empirical approach.

The following multiple regression model proved to have a good ability to predict heating time from size, wet-bulb depression, and initial wood temperature as long as the wet-bulb temperature in the heating chamber is greater than the target center temperature:

$$\ln T_{133} = \ln a + b\,(\ln t)^n + c \ln (\mathrm{WBD}) + d \ln (T_\mathrm{i}) \qquad (20\text{–}5)$$

where

T_{133}	is	time for the center to reach 56 °C (133 °F) (min),
t		thickness of boards or cross-sectional dimension

Table 20–5. Estimated heating times to heat lumber to 133 °F (56 °C) for wood with a specific gravity of 0.35

Thickness (*t*) and width (*w*) (in.)	Heat temp. (°F)	Estimated heating time (min) from four initial wood temperatures and four MC levels															
		30 °F				50 °F				70 °F				90 °F			
		25%	70%	100%	130%	25%	70%	100%	130%	25%	70%	100%	130%	25%	70%	100%	130%
t = 1.0 *w* = 4.0	140	21	21	20	19	19	19	18	17	17	17	16	15	15	14	13	12
	150	15	15	14	13	14	13	13	12	12	11	11	10	10	9	9	8
	160	13	12	12	11	11	11	10	9	10	9	9	8	8	7	7	6
	170	11	10	10	9	10	9	8	8	8	7	7	7	6	6	6	5
	180	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4
	190	9	8	8	7	7	7	7	6	6	6	5	5	5	4	4	4
	200	8	7	7	6	7	6	6	5	6	5	5	4	5	4	4	3
	210	7	7	6	6	6	6	5	5	5	5	4	4	4	4	3	3
t = 1.0 *w* = 6.0	140	21	21	20	19	19	19	18	17	17	17	16	15	15	14	13	12
	150	15	15	14	13	14	13	13	12	12	11	11	10	10	9	9	8
	160	13	12	12	11	11	11	10	9	10	9	9	8	8	7	7	6
	170	11	10	10	9	10	9	8	8	8	7	7	7	6	6	6	5
	180	9	9	9	8	8	8	7	7	7	6	6	6	6	5	5	4
	190	9	8	8	7	7	7	7	6	6	6	5	5	5	4	4	4
	200	8	7	7	6	7	6	6	5	6	5	5	4	5	4	4	3
	210	7	7	6	6	6	6	5	5	5	5	4	4	4	4	3	3
t = 2.0 *w* = 4.0	140	75	74	70	66	69	67	64	59	62	59	56	53	54	50	48	45
	150	56	55	52	49	51	49	46	43	45	42	40	38	38	35	33	31
	160	46	45	43	40	42	40	38	35	37	34	33	30	30	28	26	25
	170	41	39	37	35	36	34	33	30	32	29	28	26	26	24	22	21
	180	36	35	33	31	32	30	29	27	28	26	24	23	23	21	20	18
	190	33	31	30	28	29	27	26	24	25	23	22	20	21	18	17	16
	200	30	28	27	25	27	25	24	22	23	21	20	19	19	17	16	15
	210	28	26	25	23	25	23	22	20	22	19	18	17	18	15	15	14
t = 2.0 *w* = 8.0	140	86	85	81	76	79	77	73	68	71	67	64	60	61	57	54	50
	150	63	62	59	55	57	55	52	49	50	47	45	42	41	38	36	34
	160	52	50	48	45	46	44	42	39	40	37	35	33	32	30	28	26
	170	44	43	41	38	39	37	35	33	34	31	30	28	27	25	24	22
	180	39	37	36	33	35	32	31	29	30	27	26	24	24	21	20	19
	190	35	33	32	30	31	29	27	26	27	24	23	21	21	19	18	17
	200	32	30	29	27	29	26	25	23	24	22	21	19	19	17	16	15
	210	30	28	26	24	26	24	23	21	22	20	19	18	18	16	15	14
t = 4.0 w = 4.0	140	188	186	177	166	173	168	160	150	157	149	142	132	136	127	120	112
	150	141	138	131	123	128	123	117	110	114	107	102	95	96	89	85	79
	160	118	114	109	102	107	102	97	90	94	88	83	78	79	72	69	64
	170	103	99	94	88	93	88	83	78	82	76	72	67	68	62	59	55
	180	93	88	84	78	84	78	74	69	73	67	64	59	61	55	52	49
	190	85	80	76	71	76	71	67	63	67	61	58	54	56	50	47	44
	200	79	74	70	65	71	65	62	57	62	56	53	49	52	46	43	40
	210	74	68	65	60	66	60	57	53	58	52	49	46	48	43	40	37
t = 4.0 *w* = 12.0	140	335	332	316	296	309	300	286	267	278	265	252	235	239	224	213	198
	150	248	243	232	217	225	216	206	192	198	187	178	166	165	153	145	135
	160	205	199	190	177	184	175	167	156	160	150	142	133	131	120	114	106
	170	177	171	162	152	158	149	142	133	136	126	120	112	111	101	95	89
	180	158	150	143	133	140	131	124	116	120	110	105	98	97	87	83	77
	190	143	135	128	119	126	117	111	104	108	98	93	87	87	78	74	69
	200	131	122	116	108	115	106	101	94	98	89	84	78	79	70	67	62
	210	121	112	106	99	107	97	92	86	91	81	77	72	73	64	61	57

Table 20–6. Coefficients for multiple regression models (Eq. (20–5)) for estimating time required to heat stickered ponderosa pine and Douglas-fir boards and timbers to a 133 °F (56 °C) center temperature in a 160 °F (71 °C) heating medium[a]

	Coefficients				
Application	ln *a*	*b*	*c*	*d*	R^2
Ponderosa pine, 1- and 2-in. boards, WBD < 12 °F	5.04	1.55	0.257	0.627	0.978
Ponderosa pine, 4-, 6-, and 12-in. timbers, WBD < 12 °F	4.59	1.61	0.205	–0.521	0.967
Douglas-fir, 1- and 2-in. boards, WBD < 12 °F	8.04	1.63	0.265	–1.35	0.925
Douglas-fir, 4-, 6-, and 12-in. timbers, WBD < 12 °F	15.03	0.455	0.336	–2.70	0.984

[a] $T_{°C} = (T_{°F} - 32)/1.8$; C = F/1.8; 1 in. = 25.4 mm.

of timbers (in.),
WBD wet-bulb depression (°F),
T_i initial wood temperature (°F),
a,b,c,d regression coefficients,
n either 1 or 2.

Simpson and others (2003) developed a series of regression equations to estimate heating times for ponderosa pine and Douglas-fir boards and timbers. The regression coefficients (*a*, *b*, *c*, and *d*) and coefficients of determination (R^2) are shown in Table 20–6. The method worked well when the wet-bulb depression was less than or equal to about 6.7 °C (12 °F) and the boards or timbers were stickered. The heating time estimates for a series of sizes, wet-bulb depressions, and initial temperature generated using these equations are presented in Tables 20–7 to 20–10. The estimates for ponderosa pine cover initial temperatures from 4.4 to 26.7 °C (40 to 80 °F) (in 5.6 °C (10 °F) increments). The estimates for Douglas-fir cover only initial temperature ranging from15.6 to 26.7 °C (60 to 80 °F) because of the seasonal timing of the experiments.

The estimated heating times in Tables 20–7 to 20–10 are average times and give a reasonable general estimate of the time required to heat the center of wood to 56 °C (133 °F). In any group of lumber and timbers, the average time does not ensure that all pieces will achieve the target temperature because some will require more than the average time. Therefore, the upper statistical confidence levels for the heating times need to be considered. Equations for calculating the upper confidence levels of heating times for ponderosa pine and Douglas-fir boards and timbers are provided in Simpson and others (2003). In Tables 20–7 to 20–10, the heating time values of 99% upper confidence bounds are presented in parentheses.

American Lumber Standards Committee (ALSC) Enforcement Regulations

Heat treatment of wood is typically accomplished in a heat chamber. Heat chamber is defined as any enclosed equipment used to heat-treat lumber or wood packaging material and includes kiln, heat boxes, or any other appropriate apparatus. Depending on the treating schedules used, products from heat treatment processes are of two types:

1. Heat treated (HT)—lumber or used, previously assembled, or repaired wood packaging that has been placed in a closed chamber with artificial heat added until the lumber or packaging achieves a minimum core temperature of 56 °C (133 °F) for a minimum of 30 min. Note: 2013-13 CPM-8 adopted revised Annex 1 to ISPM 15 to include heat treatment using dielectric heating. When lumber or used, previously assembled, repaired, or remanufactured wood packaging material is heat-treated using dielectric heating (DH), the treatment code mark is DH.
2. Kiln-dried heat-treated (KD HT)—lumber or used, previously assembled, or repaired wood packaging that has been placed in a closed chamber with artificial heat added until the lumber or packaging achieves a minimum core temperature of 56 °C (133 °F) for a minimum of 30 min and that is dried to a maximum moisture content of 19% or less.

ALSC enforcement regulations require that a heat treatment facility should be inspected and verified by an accredited third-party agency for initial qualification. Agencies will verify the accuracy of temperature-measuring and recording devices in the heating chamber and require that thermocouples be located to accurately measure the temperature achieved in the heat chamber and that an appropriate number of thermocouples are utilized given the chamber configuration. A verification study is needed for heat treating chambers and heat treating schedules when any of the following conditions are being used: (1) both dry and wet heat (steam) with wet-bulb temperature of less than 60 °C (140 °F); (2) only dry heat of less than 71 °C (160 °F); or (3) no set schedule, but instead using thermocouples inserted directly into wood that do not maintain a core temperature of 60 °C (140 °F) or greater. In such a verification study, an appropriate number of thermocouples are used to accurately measure the temperature conditions of the chamber and the wood to ensure that time and temperature requirements for heat treating are met. Any equipment variance of more than ±2.8 °C (±5 °F) requires recalibration or replacement.

Table 20–7. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for ponderosa pine boards estimated by multiple regression models[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)[b]				
		1.00 in. thick	1.25 in. thick	1.50 in. thick	1.75 in. thick	2.00 in. thick
2	40	18 (39)	26 (53)	34 (67)	43 (82)	53 (98)
4	40	22 (45)	31 (60)	41 (76)	52 (93)	64 (112)
6	40	24 (48)	34 (65)	45 (83)	58 (101)	71 (121)
8	40	26 (51)	37 (69)	49 (87)	62 (107)	76 (128)
10	40	28 (54)	39 (72)	52 (92)	66 (112)	81 (134)
12	40	29 (56)	41 (75)	54 (95)	69 (117)	85 (139)
2	50	16 (28)	22 (37)	30 (47)	38 (58)	46 (70)
4	50	19 (31)	27 (42)	36 (54)	45 (66)	55 (80)
6	50	21 (34)	30 (46)	39 (59)	50 (72)	62 (87)
8	50	23 (36)	32 (49)	42 (62)	54 (77)	66 (92)
10	50	24 (38)	34 (51)	45 (65)	57 (80)	70 (97)
12	50	25 (39)	36 (53)	47 (68)	60 (84)	74 (101)
2	60	14 (21)	20 (28)	27 (36)	34 (45)	41 (55)
4	60	17 (24)	24 (33)	32 (42)	40 (52)	49 (63)
6	60	19 (26)	27 (35)	35 (46)	45 (57)	55 (70)
8	60	20 (28)	29 (38)	38 (49)	48 (61)	59 (75)
10	60	21 (29)	30 (40)	40 (52)	51 (65)	63 (79)
12	60	22 (30)	32 (42)	42 (54)	53 (68)	66 (83)
2	70	13 (17)	18 (24)	24 (31)	31 (39)	38 (48)
4	70	15 (20)	22 (27)	29 (36)	37 (46)	45 (57)
6	70	17 (22)	24 (30)	32 (40)	41 (51)	50 (64)
8	70	18 (23)	26 (33)	34 (43)	44 (56)	54 (70)
10	70	19 (25)	27 (35)	36 (46)	46 (59)	57 (74)
12	70	20 (26)	29 (36)	38 (45)	48 (63)	60 (78)
2	80	12 (15)	17 (21)	22 (29)	28 (37)	35 (46)
4	80	14 (18)	20 (26)	26 (35)	34 (45)	41 (56)
6	80	16 (20)	22 (29)	29 (39)	37 (51)	46 (64)
8	80	17 (22)	24 (31)	32 (42)	40 (55)	49 (70)
10	80	18 (23)	25 (33)	33 (45)	43 (59)	52 (75)
12	80	19 (24)	26 (35)	35 (48)	45 (63)	55 (79)

[a] $T_{°C} = (T_{°F} - 32)/1.8$; C = F/1.8; 1 in. = 25.4 mm.

[b] Values in parentheses are 99% upper confidence bounds of heating times.

Heat treatment facilities are also required to monitor temperatures throughout the heat treatment cycle by any of the following options:

1. Wet- and dry-bulb temperature
2. Dry bulb only—unless the specific schedule has been verified, required heating times shall be equal to or greater than the time specified for the applicable schedule assuming the maximum wet bulb depression as provided in either
    a. FPL–RP–607, *Heat sterilization time of ponderosa pine and Douglas-fir boards and square timbers* (Simpson and others 2003);
    b. FPL–RP–604, *Effect of wet-bulb depression on heat sterilization time of slash pine lumber* (Simpson 2002); or
    c. CFIA PI–07, *The technical heat treatment guidelines and operating conditions manual*, Option C (CFIA 2006).
3. Direct measurement of wood core temperature of the thickest piece(s) by use of thermocouple(s) properly sealed with non-conductive material

Heat treatment facilities are required to annually calibrate the temperature-monitoring and recording equipment for each facility heat-treating chamber and requalify a heat-treating chamber any time there is a major change in equipment or remodeling of the chamber. Except in the case of wood core temperature of the thickest piece(s) being directly measured by using thermocouples, when wood moisture content is not determined at the beginning of the heat treatment cycle, facilities are required to select and use appropriate time–temperature schedules assuming the lowest initial wood moisture content from one of the following publications:

a. FPL–GTR–130, *Heating times for round and rectangular cross sections of wood in steam* (Simpson 2001);

b. FPL–RP–607, *Heat sterilization time of ponderosa pine and Douglas-fir boards and square timbers* (Simpson and others 2003);

Table 20–8. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C)) for ponderosa pine square timbers estimated by multiple regression models[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)[b]				
		4 by 4	6 by 6	8 by 8	10 by 10	12 by 12
2	40	155 (225)	297 (429)	473 (682)	677 (980)	90 (1,321)
4	40	178 (259)	343 (492)	545 (782)	780 (1,123)	1,04 (1,512)
6	40	194 (282)	372 (535)	592 (850)	848 (1,220)	1,13 (1,643)
8	40	206 (299)	395 (569)	628 (903)	899 (1,296)	1,20 (1,745)
10	40	215 (314)	413 (597)	657 (947)	941 (1,359)	1,26 (1,830)
12	40	223 (327)	429 (621)	682 (986)	977 (1,414)	1,31 (1,904)
2	50	138 (200)	265 (382)	421 (609)	603 (878)	80 (1,185)
4	50	159 (229)	305 (437)	485 (697)	695 (1,003)	93 (1,354)
6	50	173 (249)	332 (475)	527 (756)	755 (1,088)	1,01 (1,468)
8	50	183 (264)	352 (504)	559 (802)	801 (1,155)	1,07 (1,558)
10	50	192 (277)	368 (529)	585 (841)	838 (1,210)	1,12 (1,633)
12	50	199 (288)	382 (550)	607 (875)	870 (1,258)	1,16 (1,697)
2	60	125 (182)	241 (350)	383 (559)	548 (807)	73 (1,091)
4	60	144 (208)	278 (400)	441 (638)	632 (921)	84 (1,245)
6	60	157 (226)	302 (433)	479 (692)	687 (998)	92 (1,349)
8	60	166 (240)	320 (460)	508 (734)	728 (1,058)	97 (1,430)
10	60	174 (251)	335 (482)	532 (769)	762 (1,108)	1,02 (1,497)
12	60	181 (261)	348 (501)	552 (799)	791 (1,151)	1,06 (1,555)
2	70	116 (169)	222 (326)	353 (523)	506 (755)	67 (1,022)
4	70	133 (193)	256 (372)	407 (596)	583 (860)	78 (1,164)
6	70	145 (210)	278 (403)	442 (645)	634 (932)	85 (1,260)
8	70	154 (222)	295 (427)	469 (684)	672 (987)	90 (1,335)
10	70	161 (233)	309 (448)	491 (716)	703 (1,033)	94 (1,398)
12	70	167 (242)	321 (465)	510 (743)	730 (1,073)	97 (1,451)
2	80	108 (160)	207 (308)	330 (494)	472 (715)	63 (968)
4	80	124 (182)	239 (351)	380 (563)	544 (814)	73 (1,102)
6	80	135 (197)	260 (380)	413 (609)	591 (880)	79 (1,192)
8	80	143 (209)	275 (403)	438 (645)	627 (932)	84 (1,262)
10	80	150 (219)	288 (421)	458 (675)	656 (975)	88 (1,321)
12	80	156 (227)	299 (438)	476 (701)	681 (1,013)	91 (1,371)

[a] $T_{°C} = (T_{°F} - 32)/1.8$; C = F/1.8; 1 in. = 25.4 mm.
[b] Values in parentheses are 99% upper confidence bounds of heating times.

c. FPL–RP–604, *Effect of wet-bulb depression on heat sterilization time of slash pine lumber* (Simpson 2002); or

d. CFIA PI–07, *The technical heat treatment guidelines and operating conditions manual, Option C* (CFIA 2006).

Quality Mark

ISPM 15 requires that treated packaging must be marked with an official stamp that includes an International Plant Protection Convention (IPPC) symbol, an International Standards Organization (ISO) two-letter country code, and abbreviation of the type of treatment used (heat treatment is indicated by the mark HT, dielectric heating is indicated by the mark DH), and a unique number assigned by the country's national plant protection organization to the producer of the wood packaging material, who is responsible for ensuring appropriate wood is used and properly marked (Figure 20–5). If wood packaging materials arrive in a member country without this quality mark, officials at the port of arrival have the right to refuse entry

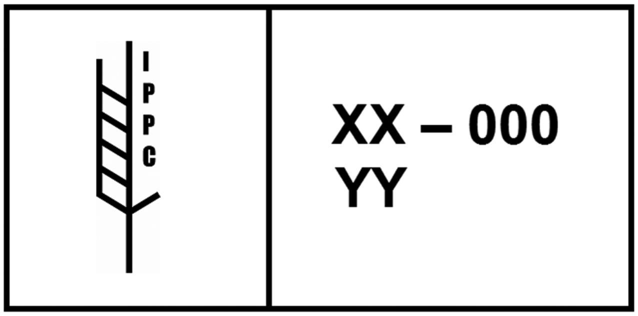


Figure 20–5. ISPM 15 requires the use of a quality mark on wood packaging materials to certify that proper treatment has occurred.

Table 20–9. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for Douglas-fir boards estimated by multiple regression models[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)[b]			
		0.75 in. thick	1.00 in. thick	1.25 in. thick	1.50 in. thick
2	60	9 (25)	14 (37)	21 (53)	28 (70)
4	60	11 (29)	17 (44)	25 (62)	34 (82)
6	60	12 (32)	19 (49)	28 (68)	38 (91)
8	60	13 (34)	21 (52)	30 (74)	41 (98)
10	60	14 (36)	22 (55)	32 (78)	43 (104)
12	60	15 (38)	23 (58)	34 (82)	45 (109)
2	70	7 (15)	12 (22)	17 (32)	23 (42)
4	70	9 (17)	14 (26)	20 (37)	27 (49)
6	70	10 (19)	16 (29)	23 (41)	31 (55)
8	70	11 (20)	17 (31)	24 (44)	33 (59)
10	70	11 (22)	18 (33)	26 (47)	35 (63)
12	70	12 (23)	19 (35)	27 (49)	37 (66)
2	80	6 (10)	10 (16)	14 (23)	19 (31)
4	80	7 (12)	12 (19)	17 (27)	23 (37)
6	80	8 (13)	13 (21)	19 (30)	25 (41)
8	80	9 (15)	14 (23)	20 (32)	28 (44)
10	80	9 (15)	15 (24)	22 (35)	29 (47)
12	80	10 (16)	16 (25)	23 (36)	31 (49)

[a] $T_{°C} = (T_{°F} - 32)/1.8$; C = F/1.8; 1 in. = 25.4 mm.

[b] Values in parentheses are 99% upper confidence bounds of heating times.

Table 20–10. Summary of heating times (at 160 °F (71 °C)) to 133 °F (56 °C) for Douglas-fir square timbers estimated by multiple regression models[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)[b]				
		4 by 4	6 by 6	8 by 8	10 by 10	12 by 12
2	60	159 (229)	285 (406)	473 (667)	738 (1,034)	1,098 (1,534)
4	60	200 (298)	360 (526)	597 (862)	932 (1,334)	1,386 (1,974)
6	60	229 (349)	412 (615)	684 (1,007)	1,068 (1,556)	1,588 (2,299)
8	60	253 (391)	454 (689)	754 (1,126)	1,176 (1,739)	1,749 (2,567)
10	60	272 (427)	489 (752)	812 (1,229)	1,267 (1,897)	1,885 (2,799)
12	60	289 (459)	520 (809)	863 (1,321)	1,347 (2,038)	2,004 (3,006)
2	70	105 (143)	188 (256)	312 (426)	487 (669)	724 (1,003)
4	70	132 (181)	237 (323)	394 (535)	614 (836)	914 (1,251)
6	70	151 (209)	272 (372)	451 (615)	704 (959)	1,047 (1,432)
8	70	167 (232)	299 (412)	497 (680)	775 (1,061)	1,153 (1,580)
10	70	179 (252)	323 (447)	535 (737)	835 (1,148)	1,243 (1,709)
12	70	191 (270)	343 (478)	569 (788)	888 (1,226)	1,321 (1,824)
2	80	73 (103)	131 (188)	217 (315)	339 (499)	505 (753)
4	80	92 (127)	165 (230)	274 (386)	428 (609)	637 (918)
6	80	105 (144)	189 (261)	314 (436)	491 (688)	730 (1,036)
8	80	116 (159)	209 (286)	346 (477)	540 (752)	804 (1,130)
10	80	125 (171)	225 (307)	373 (513)	582 (807)	866 (1,212)
12	80	133 (182)	239 (326)	397 (544)	619 (855)	921 (1,283)

[a] $T_{°C} = (T_{°F} - 32)/1.8$; C = F/1.8; 1 in. = 25.4 mm.

[b] Values in parentheses are 99% upper confidence bounds of heating times.

or require treatment (such as fumigation) at the port—a costly situation. Recycled, remanufactured, or repaired wood packing material should be recertified and remarked. All components of such material are required to be properly treated.

Other Considerations

Heating capacity—It is critical in heat sterilization that the heating and humidification system be designed to meet the production schedule. Typically, the heating capacity of a hardwood kiln ranges from 7,491 to 22,473 kJ h^{-1} per cubic meter of lumber (16,738 to 50,212 Btu h^{-1} per thousand board feet of lumber). To get the rapid heating needed, the boiler horsepower needs to be sized from 89,785 to 187,062 kJ h^{-1} per cubic meter (200,850 to 418,437 Btu h^{-1} per thousand board feet), depending on the lumber used and starting temperature (Denig and Bond 2003).

Structure damage—The environment used for heat sterilization of wood can be extremely corrosive and damaging to some structures. In addition to using the proper materials, a floor drain system should be used, especially when using the high-humidity schedules.

Mold prevention—Heat sterilization kills only mold, fungus, and insects that are present when the material is sterilized. In certain cases, mold and fungus have rapidly infested heat-sterilized lumber that was not dry (Denig and Bond 2003). It is critical for the pallet operator and user to keep their production facility free of waste wood, minimize inventory of heat-treated pallets, and ensure some air movement around green pallets that have been heat-treated.

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Wood Handbook

Wood as an Engineering Material

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

Abstract

Summarizes information on wood as an engineering material. Presents properties of wood and wood-based products of particular concern to the architect and engineer. Includes discussion of designing with wood and wood-based products along with some pertinent uses.

Keywords: wood structure, physical properties (wood), mechanical properties (wood), lumber, wood-based composites, plywood, panel products, design, fastenings, wood moisture, drying, gluing, fire resistance, finishing, decay, preservation, wood-based products, heat sterilization, sustainable use

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