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Heat Sterilization Times of Five Hardwood Species

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Abstract

Heat sterilization of lumber, timbers, and pallets is currently used to kill insects, thus preventing their transfer between countries in international trade. An important factor in this treatment is the time required for the center of any wood configuration to reach the temperature necessary to kill the insect. This study explored the effect of size (1-, 1.5-, and 2.0-in.-thick by 6-in.-wide boards, and 3- by 3-, 4- by 4-, and 6- by 6-in. timbers), hardwood species (red maple, sugar maple, red oak, basswood, and aspen), and two wet-bulb depressions (nominal 2°F and 8–10°F) at a nominal heating temperature of 160°F. Two analytical methods were examined for their ability to calculate estimated heating times. Heating times varied from about 15 min for 1- by 6-in. boards to 300 min for 6- by 6-in. timbers. Heating time was about 15% longer at the larger of the two wet-bulb depressions. Some species differences were significantly different statistically but were not different enough in practical terms to warrant heating separately. We found that the wet-bulb temperature could be used successfully in an analytical model as the heating temperature when evaporation of water cooled the surface below the nominal heating temperature.

Keywords: heat sterilization, lumber, timbers, dry kilns

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SI conversion factors

English unit		SI Unit
inch (in.)	× 25.4	millimeter (mm)
temperature (°F)	$[T_F - 32]/1.8$	temperature (°C)
temperature (°F) increment	× 0.556	temperature (°C) increment

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Heat Sterilization Times of Five Hardwood Species

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Introduction

Heat sterilization of lumber, timbers, and pallets is currently used to kill insects, thus preventing their transfer between countries in international trade. Current regulations for heat sterilization of these wood products require holding a center temperature of 133°F for 30 min. An important factor in heat sterilization is the additional time required for the center of any wood configuration to reach that temperature. This additional time can vary widely depending on a number of factors such as wood species, specific gravity, moisture content, cross-sectional dimensions, initial temperature, heating temperature, heating medium (wet or dry heat), and stacking method. The objective of this study was to quantify the effects of species, cross-sectional dimensions, and heating medium on the time required to heat the center of five hardwoods to 133°F. Heat sterilization is currently the most practical way to eliminate the transfer of insect infestations in international trade operations that use wood pallets and containers. This study has the important aim of optimizing kiln conditions to save energy and money.

Background

Several issues and observations can be summarized from background literature and past studies by Simpson (2001, 2002, 2003, 2004) and Simpson and others (2003). Size has a major influence on heating time—ranging from only a few minutes for thin boards to many hours for large timbers. Higher heating temperatures obviously shorten heating time, and heating medium has a significant effect. Heating in saturated steam (wet heat) results in the shortest heating times. As the heating medium changes from wet to dry heat, heating time increases. 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. 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 heat transfer. The background literature cited also reviews and tests the ability of analytical methods to provide calculated estimates of heating times and shows that under certain circumstances, the calculated heating times provide good estimates.

Experimental Methods

The experimental material was sawn from logs of five hardwood species: red maple (*Acer rubrum*), sugar maple (*A. saccharum*), northern red oak (*Quercus rubra*), basswood (*Tilia Americana*), and aspen (*Populus* spp.). Six sizes of each species were tested: 1-, 1.5-, and 2-in.-thick boards, all 6 in. wide; and 3-, 4-, and 6-in. squares. All heating was done at a nominal heating temperature of 160°F.

Two levels of wet-bulb depression were tested. One was essentially saturated steam attained by using steam spray alone in the experimental kiln, which in practice resulted in a wet-bulb depression of about 2°F. The other wet-bulb depression was a nominal 8°F to 10°F, chosen to represent situations in which a small wet-bulb depression was desirable but kilns in use might not be able to hold a smaller depression. Each of two kiln runs per species consisted of five replicates of all six sizes of one species at one wet-bulb depression.

Internal temperatures were measured with thermocouples inserted to the geometric center of each of 10 replicate (by size) boards or squares. Figure 1 shows a thermocouple wire inserted in a hole and the hole plugged with a round toothpick to prevent ambient kiln air from influencing the thermocouple reading at the center.

Surface temperature was measured on each replicate to provide surface temperature data to use in a finite difference analysis where the boundary condition changes as the wood surface temperature changes during heating. Figure 2 shows a thermocouple held in place on the surface with a plastic push pin. Specific gravity and moisture content samples were taken during board and square preparation. The cross-sectional dimensions of every board and square were measured.

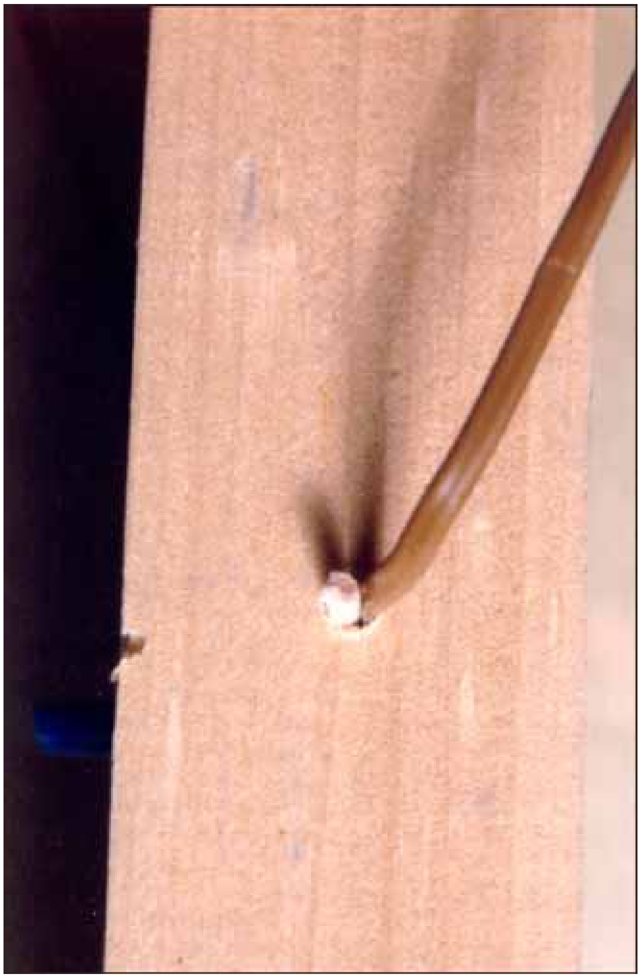

Figure 1—Interior thermocouple inserted to center of boards and timbers.

Figure 2—Surface thermocouple held in place by push pin.

With all thermocouples in place, the door to the already running and up-to-temperature kiln was opened, the kiln truck wheeled in, and the door closed as quickly as possible to minimize recovery time to the target kiln conditions. Both center and surface thermocouple readings were processed by a Keithly (Cleveland, Ohio) Model 2700 Multimeter/Data Acquisition System and read to a computer file at 1-min intervals. Runs were ended when the slowest squares (6- by 6-in.) reached the target center temperature of 133°F.

Analytical Methods

Two analytical methods have been applied as a means of calculating estimated heating times from heating temperature, size, specific gravity, and moisture content. These methods are described in detail in Simpson (2001, 2003, 2004). One method is based on heat conduction equations developed by MacClean (1932), and the other is a finite difference solution to the two-dimensional heat conduction equation solved with a variable surface temperature as the boundary condition. Past work has shown that these methods have some ability to provide estimates of heating time. We will use the experimental data of this study to further examine these methods.

Results

Experimental

One major objective of the study was to determine if the heating times of the five species are the same or different. This information would be useful if the different species were heat sterilized together. Direct comparison of experimental heating times of the five species is limited by several factors. It is not possible to saw every board or square of a nominal size to exactly the same actual size. Thus the board thicknesses and the cross-sectional dimensions of the squares varied. The initial temperature of the boards also differed. We conducted the 20 heating-time runs from early spring to mid-summer. No controlled temperature storage facilities were available, so the boards and squares were stored outside and initial temperatures ranged from about 45°F to 75°F.

Actual heating temperature also varied slightly from run to run. An adjustment in heating times for these three factors was made to improve the comparison of the heating times of the five species. The adjustment was made with the help of MacClean's heat conduction equation (Simpson 2001), where cross-sectional dimensions, initial temperature, and heating temperature are three of the variables. To make the adjustment, heating times were calculated at several intervals over the experimental range of each of the three variables. Then a multiple linear regression was developed relating the heating time to the linear combination of the three variables: $T_{133} = a + bT_\mathrm{i} + cT_\mathrm{h} + dS$, where T_{133} is time (min) for the center to reach 133°F; T_i is initial wood temperature at the center (*F*); T_h is heating temperature (*F*); *a*, *b*, *c*, and *d* are regression coefficients, and *S* is board thickness or the average cross-sectional square dimension. (With 6-in.-wide boards, thickness controls, heating time, and width are not factors.) The regression coefficients are shown in Table 1. These regression equations were then used to adjust heating times to a common initial temperature of 60°F, the overall actual average heating temperature of 157°F, and 1.0-, 1.5-, and 2.0-in. board thickness and 3- by 3-, 4- by 4-, and 6- by 6-in. square cross-sectional dimensions. This adjustment makes possible a better comparison of the heating time of the different species.

Table 2 summarizes heating times of the various experimental groups. The first three columns of heating times are unadjusted times; heating times adjusted to an initial temperature of 60°F, a heating temperature of 157°F, and the common sizes; and the 99% statistical confidence interval for the adjusted heating times. Adjusted heating times are also shown in Figure 3 for comparison of the relationship of heating times between species and wet-bulb depression.

Adjusted heating times were analyzed by a two-way analysis of variance (ANOVA) with species and wet-bulb depression as the two factors and an analysis conducted for each size. Details of the ANOVA are shown in Tables 3 to 8. As expected, size has a significant effect on heating time, ranging from about 15 min for 1-in.-thick boards to almost 300 min for 6- by 6-in. squares. Heating time was longer with the 10°F wet-bulb depression heating than with the 2°F wet-bulb depression heating. The overall average increase in heating time for all species and all sizes because of the greater wet-bulb depression was 15%. Overall, hardwood species had a statistically significant effect on heating time, but not all individual comparisons were statistically significant. The details of these significances can be found in Tables 3 to 8. However, the actual effect of species was not significant in the practical sense. This is apparent from Figure 3.

Table 1—Regression coefficients for adjusting heating times for initial temperature, heating temperature, and size to common values

$$T_{133} = \alpha + bT_\mathrm{i} + cT_\mathrm{h} = dS$$

(T_i, initial temp; T_h, heating temp; *S*, thickness or square dimension)

Run	*a*	*b*	*c*	*d*
Red maple – 1 in.	28.920	–0.086	–0.223	23.338
Red maple – 1.5 in.	71.319	–0.189	–0.503	30.638
Red maple – 2 in.	119.868	–0.349	–0.904	43.305
Red maple – 3 by 3 in.	127.770	–0.407	–1.043	40.855
Red maple – 4 by 4 in.	221.211	–0.707	–1.810	53.907
Red maple – 6 by 6 in.	502.467	–1.606	–4.112	81.256
Hard maple – 1 in.	28.843	–0.085	–0.228	23.927
Hard maple – 1.5 in.	65.021	–0.192	–0.513	35.823
Hard maple – 2 in.	121.354	–0.347	–0.921	46.445
Hard maple – 3 by 3 in.	128.825	–0.403	–1.062	41.927
Hard maple – 4 by 4 in.	223.489	–0.700	–1.844	55.258
Hard maple – 6 by 6 in.	507.474	–1.591	–4.189	83.308
Red oak – 1 in.	28.147	–0.084	–0.221	23.109
Red oak – 1.5 in.	63.362	–0.190	–0.497	34.568
Red oak – 2 in.	118.316	–0.343	–0.893	44.820
Red oak – 3 by 3 in.	125.813	–0.400	–1.030	40.465
Red oak – 4 by 4 in.	218.281	–0.695	–1.789	53.332
Red oak – 6 by 6 in.	495.709	–1.579	–4.064	80.402
Basswood – 1 in.	25.377	–0.081	–0.195	20.000
Basswood – 1.5 in.	57.193	–0.182	–0.439	29.944
Basswood – 2 in.	106.727	–0.328	–0.789	38.798
Basswood – 3 by 3 in.	114.017	–0.386	–0.910	35.053
Basswood – 4 by 4 in.	198.782	–0.672	–1.584	46.183
Basswood – 6 by 6 in.	451.262	–1.526	–3.598	69.630
Aspen – 1 in.	27.130	–0.085	–0.210	21.657
Aspen – 1.5 in.	61.182	–0.192	–0.473	32.491
Aspen – 2 in.	114.148	–0.345	–0.849	42.044
Aspen – 3 by 3 in.	124.210	–0.402	–0.990	37.614
Aspen – 4 by 4 in.	211.816	–0.703	–1.703	50.016
Aspen – 6 by 6 in.	482.343	–1.595	–3.869	75.156

Although some species differences were statistically significant, the differences have little practical significance. Table 7 illustrates this observation with the data for 4- by 4-in.-thick boards heated with a 2°F wet-bulb depression. Ten pair-wise comparisons of the five species are possible, and Table 7 shows a statistically significant difference between species in heating time in five of the ten pair-wise comparisons at 2°F wet-bulb depression. In the other five, the difference is not statistically significant. The actual adjusted heating times for 4- by 4-in. squares of the five species heated with a 2°F wet-bulb depression are as follows: red maple, 114.6 min; sugar maple, 107.4 min; red oak, 108.8 min; basswood, 100 min; and aspen, 112.7 min. Because the differences in heating time are so small, there is no practical reason to heat-treat these five species separately; the differences are of similar magnitude to the expected natural variability between individual boards and squares.

Table 2—Summary of heating times (min) for six sizes of five hardwood species heated at two wet-bulb depressions (WBDs)[a]

		1	2	3	4	5	6	7	8
WBD	Species and size	Unadjusted T_{133}	Adjusted (157°F) T_{133}	99% confidence interval	MacLean specific gravity—moisture content	Finite difference specific gravity—moisture content	MacLean wet-bulb temperature (°F)	Deviation from unadjusted (%)	99% confidence interval
	Red maple (Specific gravity (SG) = 0.531; MC = 65%)								
	1.0	13.2	13.5	12.5—14.5	11.8	13.4	12.9	−2.3	12.1—14.4*
0°F	1.5	29.3	28.8	27.2—30.5	27.5	29.4	29.1	−0.7	27.1—30.8*
	2.0	49.1	49.6	46.9—52.3	46.8	49.6	49.4	−0.6	46.0—52.1*
	3x3	53.9	59.4	54.9—63.9	56.5	59.6	59.0	9.5	49.9—57.9
	4x4	108.1	114.6	110.1—119.2	103.0	107.0	107.6	−0.5	104.5—111.7*
	6x6	254.9	264.6	246.0—283.3	237.3	245.5	247.1	−3.1	237.1—272.6*
10°F	1.0	16.7	16.5	15.4—17.6	12.3	17.1	18.3	9.6	15.3—18.2
	1.5	36.9	36.3	34.4—38.2	27.5	34.8	35.8	−3.0	34.9—38.8*
	2.0	58.4	58.8	55.7—62.0	46.8	57.2	58.3	−0.2	54.8—61.9*
	3x3	84.5	85.3	74.7—95.9	60.4	85.6	72.8	−13.8	72.8—96.3*
	4x4	133.7	136.7	130.2—143.1	106.1	122.5	126.6	−5.3	126.8—140.6
	6x6	294.4	294.4	284.7—304.1	245.4	280.7	294.1	−0.1	283.3—305.4*
	Sugar maple (SG = 0.582; MC = 50%)								
	1.0	12.2	12.9	11.8—13.9	11.7	13.4	12.3	0.8	11.3—13.0*
0°F	1.5	27.1	28.0	26.4—29.6	26.7	28.6	27.6	1.8	26.0—28.3*
	2.0	45.2	47.7	44.1—48.6	46.0	48.1	47.3	4.6	41.1—49.2*
	3x3	55.5	57.8	54.1—61.4	60.9	63.2	62.3	12.3	50.7—60.4
	4x4	103.9	107.4	101.7—113.1	108.9	110.6	111.4	7.2	97.0—110.8
	6x6	250.2	255.0	233.1—276.9	248.4	250.8	254.2	1.6	226.6—273.8*
10°F	1.0	13.9	13.8	13.1—14.6	12.3	15.3	15.7	12.9	12.6—15.1*
	1.5	32.8	31.1	28.6—33.6	29.5	35.7	35.4	7.9	30.6—34.9
	2.0	55.1	52.6	49.3— 55.9	50.9	61.0	60.6	10.0	50.5—59.8
	3x3	64.0	62.7	58.4—67.0	64.4	74.9	75.8	18.4	59.9—68.2
	4x4	124.4	120.7	114.2—127.2	115.9	133.1	135.6	9.0	116.7—132.1
	6x6	295.0	283.6	267 9—299.2	263.7	295.6	308.9	4.7	279.3—310.7*
	Red oak (SG = 0.551; MC = 75%)								
	1.0	13.9	14.0	13.3—14.7	11.8	13.7	12.7	−8.6	12.8—15.0
0°F	1.5	27.5	26.3	24.9—27 7	26.4	28.8	27.8	1.1	26.1—29.0*
	2.0	49.4	49.2	45.4—52.9	46.7	50.6	48.6	−1.6	44.9—53.9*
	3x3	56.0	56.9	53.4—60.4	60.7	63.2	62.6	11.8	52.9—59.1
	4x4	106.4	108.8	105.9—111.7	106.3	110.4	109.9	3.3	100.2—112.5*
	6x6	256.6	251.9	244.7—259.0	249.7	256.6	258.5	0.7	246.4—266.7*
10°F	1.0	14.5	15.2	14 .0—16.3	11.1	14.2	14.3	−1.4	12.6—16.4*
	1.5	31.6	31.7	30.1—33.3	26.3	32.5	32.1	1.6	27.7—35.4*
	2.0	56.0	56.3	53.5—59.1	46.1	56.0	55.2	−1.4	51.7—60.3*
	3x3	66.7	65.5	62.0—69.0	61.8	72.5	72.8	9.1	63.0—70.3
	4x4	126.0	124.0	118.5—129.4	109.7	127.0	128.3	1.8	117.8—134.3*
	6x6	294.7	283.6	269.6—297.6	253.5	288.6	296.9	0.7	274.5—314.9*
	Basswood (SG = 0.327; MC = 115%)								
	1.0	12.7	12.3	11.1—13.6	10.5	12.1	11.1	−12.6	10.6—14.7*
0°F	1.5	22.9	26.1	24.2—28.0	19.8	21.5	20.6	−10.0	20.6—25.1*
	2.0	43.6	45.6	42.8—48.3	38.3	40.7	39.6	−9.2	40.4—46.7
	3x3	45.8	51.3	44.8—57.7	47.2	49.5	48.7	6.3	38.6—53.1*
	4x4	92.3	100.0	92.2—107.7	85.8	89.2	88.8	−3.8	84.0—100.7*
	6x6	206.3	226.0	209.5—242.5	191.2	195.8	198.4	−3.8	188.8—223.7*
10°F	1.0	15.1	14.8	12.9—16.6	10.8	13.3	13.2	−12.6	12.7—17.5*
	1.5	27.9	29.2	27.0—31.4	21.9	26.6	26.5	−5.0	25.7—30.1*
	2.0	58.0	53.8	49.8—57.9	44.9	53.0	53.2	−8.3	53.9—62.1
	3x3	62.1	62.6	56.3—68.9	52.4	60.9	61.3	−1.3	57.2—67.1*
	4x4	113.7	113.9	108.3—119.6	94.0	108.1	109.7	−3.5	105.9—121.5*
	6x6	258.5	262.0	240.3—283.8	208.5	234.2	243.6	−5.8	233.8—283.2*
	Aspen (SG = 0.398; MC = 88%)								
	1.0	13.0	12.9	11.5—14.3	11.5	13.1	12.3	−5.4	11.5—14.6*
0°F	1.5	28.1	29.1	26.5—31.6	24.0	26.1	25.1	−10.7	23.9—32.2*
	2.0	48.8	50.2	46.8—53.6	41.5	44.2	43.3	−11.3	45.6—52.0
	3x3	60.0	61.4	59.0—63.9	55.6	58.3	57.5	−4.2	56.7—63.3*
	4x4	108.9	112.7	108.7—116.8	97.9	100.6	100.9	−7.3	104.6—113.2
	6x6	253.9	261.5	245.3—277.5	221.3	224.6	228.0	−10.2	236.2—271.5
10°F	1.0	14.6	15.1	14.1—16.2	10.7	13.2	13.5	−7.5	13.3—15.9*
	1.5	29.8	31.5	30.5—32.5	23.3	28.4	28.4	−4.7	28.9—30.7
	2.0	54.8	57.3	52.6—62.0	41.5	49.7	49.5	−9.7	49.0—60.7*
	3x3	66.8	69.2	64.7—73.7	54.5	63.4	63.8	−4.5	61.7—71.9*
	4x4	125.1	128.5	123.9—133.1	98.2	113.4	114.6	−8.4	120.3—130.0
	6x6	276.5	284.8	274.9—294.7	220.6	247.7	257.0	−7.1	267.3—285.8

[a]Calculated times in columns 4–6 are based on actual sizes, initial temperatures, and heating temperatures, and should be compared with unadjusted times. The * in column 8 indicates that the times calculated by MacClean's equations using the wet-bulb temperature as the heating temperature fall within the 99% confidence interval of the unadjusted times

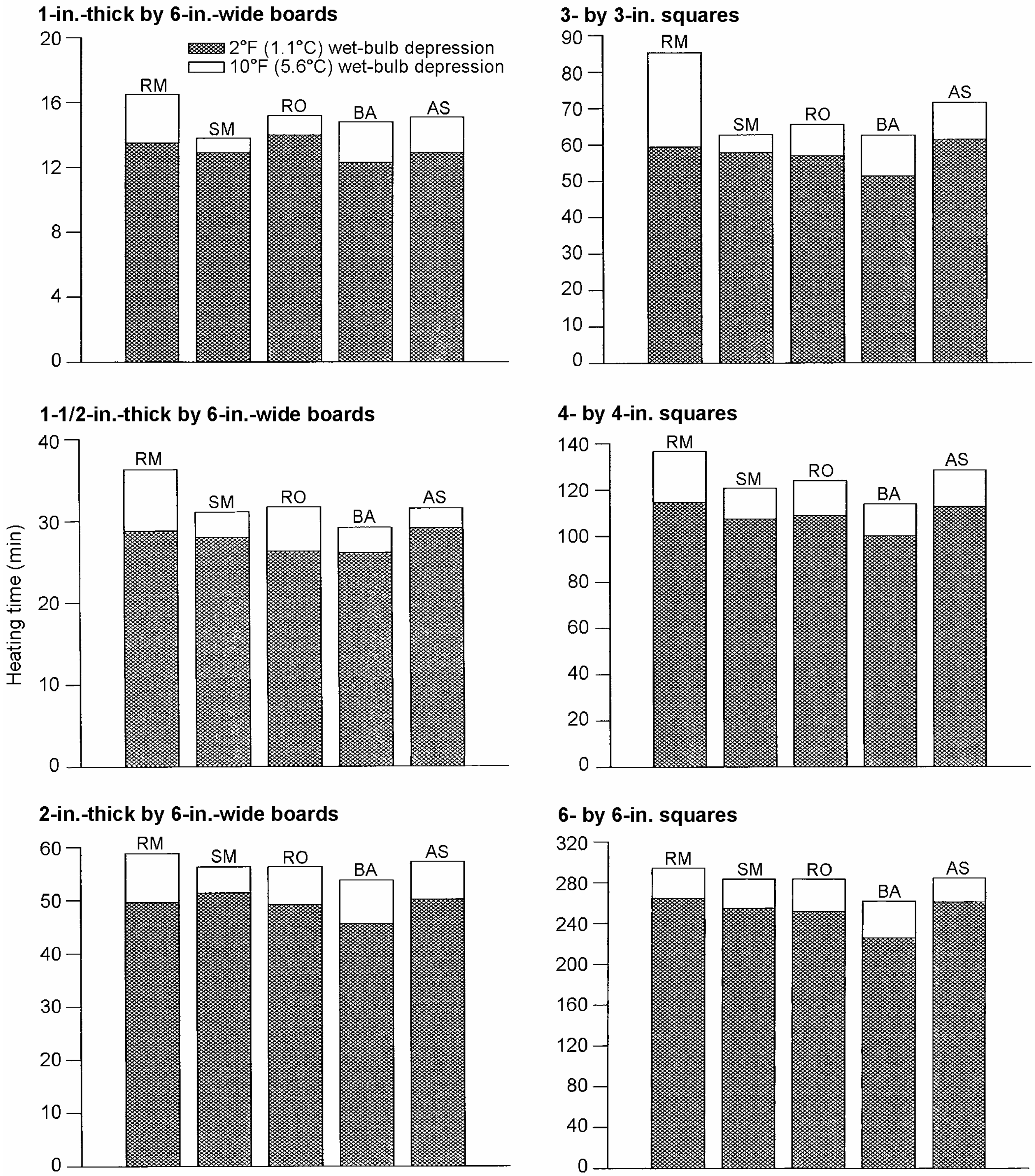

Figure 3—Effect of species and wet-bulb depression on heating times of boards and squares. RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 3—Results of two-way analysis of variance on heating times (min) for 1- by 6-in. boards[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	9.535	7.961	<0.0001
WBD	1	93.627	78.171	<0.0001
Species x WBD	4	3.901	3.257	<0.0001
Residual	88	1.198		
Total	97	2.612		

Pairwise multiple comparisons (Tukey test)

Comparison for species	***P***	***P* < 0.05**
RM vs. SM	0.0002	Yes
RM vs. BA	0.0010	Yes
RM vs. AS	0.0480	Yes
RM vs. RO	0.7920	No
RO vs. SM	0.0042	Yes
RO vs. BA	0.0309	Yes
RO vs. AS	0.4455	No
AS vs. SM	0.3230	No
AS vs. BA	0.7154	No
BA vs. SM	0.9706	No
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0551	No
WBD within RO	0.0225	Yes
WBD within BA	0.0001	Yes
WBD within AS	0.0001	Yes
Comparison for species within WBD = 2		
RO vs. BA (14.7 vs. 12.3)	0.0080	Yes
RO vs. SM (14.7 vs. 12.9)	0.1288	No
RO vs. AS (14.7 vs. 12.9)	0.1623	No
RO vs. RM (14.7 vs. 13.5)	0.7838	No
RM vs. BA (13.5 vs. 12.3)	0.1579	No
RM vs. SM (13.5 vs. 12.9)	0.7256	No
RM vs. AS (13.5 vs. 12.9)	0.7711	No
AS vs. BA (12.9 vs. 12.3)	0.8243	No
AS vs. SM (12.9 vs. 12.9)	1.0000	No
SM vs. BA (12.9 vs. 12.3)	0.8332	No
Comparison for species within WBD = 10		
RM vs. SM (16.5 vs. 13.8)	0.0001	Yes
RM vs. BA (16.5 vs. 14.8)	0.0073	Yes
RM vs. AS (16.5 vs. 15.1)	0.0459	Yes
RM vs. RO (16.5 vs. 15.2)	0.0568	No
RO vs. SM (15.2 vs. 13.8)	0.0525	No
RO vs. BA (15.2 vs. 14.8)	0.9296	No
RO vs. AS (15.2 vs. 15.1)	1.0000	No
AS vs. SM (15.1 vs. 13.8)	0.0648	No
AS vs. BA (15.1 vs. 14.8)	0.9515	No
BA vs. SM (14.8 vs. 13.8)	0.3297	No

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 4—Results of two-way analysis of variance on heating times (min) for 1.5- by 6-in. boards[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	66.399	19.730	<0.0001
WBD	1	462.723	137.498	<0.0001
Species x WBD	4	21.686	6.444	<0.0001
Residual	90	3.365		
Total	99	11.292		

Pairwise multiple comparisons (Tukey test)

Comparison for species	***P***	***P* < 0.05**
RM vs. SM	0.0002	Yes
RM vs. BA	0.0001	Yes
RM vs. AS	0.0017	Yes
RM vs. RO	0.0001	Yes
RO vs. SM	0.8670	No
RO vs. BA	0.1347	No
RO vs. AS	0.1818	No
AS vs. SM	0.7234	No
AS vs. BA	0.0002	Yes
BA vs. SM	0.0106	Yes
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0004	Yes
WBD within RO	0.0001	Yes
WBD within BA	0.0004	Yes
WBD within AS	0.0039	Yes
Comparison for species within WBD = 2		
RO vs. BA (26.3 vs. 26.1)	0.9990	No
RO vs. SM (26.3 vs. 28.0)	0.2339	No
RO vs. AS (26.3 vs. 29.1)	0.0093	Yes
RO vs. RM (26.3 vs. 28.8)	0.0205	Yes
RM vs. BA (28.8 vs. 26.1)	0.0095	Yes
RM vs. SM (28.8 vs. 28.0)	0.8438	No
RM vs. AS (28.8 vs. 29.1)	0.9989	No
AS vs. BA (29.1 vs. 26.1)	0.0041	Yes
AS vs. SM (29.1 vs. 28.0)	0.6961	No
SM vs. BA (28.0 vs. 26.1)	0.1391	No
Comparison for species within WBD = 10		
RM vs. SM (36.3 vs. 31.1)	0.0001	Yes
RM vs. BA (36.3 vs. 29.2)	0.0001	Yes
RM vs. AS (36.3 vs. 31.5)	0.0001	Yes
RM vs. RO (36.3 vs. 31.7)	0.0001	No
RO vs. SM (31.7 vs. 31.1)	0.9528	No
RO vs. BA (31.7 vs. 29.3)	0.0223	Yes
RO vs. AS (31.7 vs. 31.5)	0.9993	No
AS vs. SM (31.5 vs. 31.1)	0.9898	No
AS vs. BA (31.5 vs. 29.2)	0.0432	Yes
BA vs. SM (29.2 vs. 31.1)	0.1334	No

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 5—Results of two-way analysis of variance on heating times (min) for 2- by 6-in. boards[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	85.965	7.506	<0.0001
WBD	1	1336.268	116.674	<0.0001
Species x WBD	4	13.177	1.151	<0.3381
Residual	90	27.159		
Total	99	101.346		

Pairwise multiple comparisons (Tukey test)

Comparison for WBD	***P***	***P* < 0.05**
RM vs. SM	0.0024	Yes
RM vs. BA	0.0007	Yes
RM vs. AS	0.9926	No
RM vs. RO	0.6211	No
RO vs. SM	0.1243	No
RO vs. BA	0.0474	Yes
RO vs. AS	0.8638	No
AS vs. SM	0.0093	Yes
AS vs. BA	0.0026	Yes
BA vs. SM	0.9944	No
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0019	Yes
WBD within RO	0.0001	Yes
WBD within BA	0.0001	Yes
WBD within AS	0.0001	Yes
Comparison for species within WBD = 2		
RO vs. BA (49.4 vs. 45.6)	0.1363	No
RO vs. SM (49.4 vs. 51.4)	0.8756	No
RO vs. AS (49.4 vs. 50.2)	0.9520	No
RO vs. RM (49.4 vs. 49.6)	0.9979	No
RM vs. BA (49.6 vs. 45.6)	0.0660	No
RM vs. SM (49.6 vs. 51.4)	0.7122	No
RM vs. AS (49.6 vs. 50.2)	0.9944	No
AS vs. BA (50.2 vs. 45.6)	0.0227	Yes
AS vs. SM (50.2 vs. 51.4)	0.4578	No
SM vs. BA (51.4 vs. 45.6)	0.6246	No
Comparison for species within WBD = 10		
RM vs. SM (58.8 vs. 52.6)	0.0009	Yes
RM vs. BA (58.8 vs. 53.8)	0.0122	Yes
RM vs. AS (58.8 vs. 57.3)	0.8477	No
RM vs. RO (58.8 vs. 56.3)	0.4493	No
RO vs. SM (56.3 vs. 52.6)	0.1131	No
RO vs. BA (56.3 vs. 53.8)	0.4962	No
RO vs. AS (56.3 vs. 75.3)	0.9628	No
AS vs. SM (57.3 vs. 52.6)	0.0206	Yes
AS vs. BA (57.3 vs. 53.8)	0.1623	No
BA vs. SM (53.8 vs. 52.6)	0.9186	No

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 6—Results of two-way analysis of variance on heating times (min) for 3- by 3-in. squares[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	699.070	25.738	<0.0001
WBD	1	3432.437	126.382	<0.0001
Species x WBD	4	340.078	12.522	<0.0001
Residual	90	27.159		
Total	99	101.346		

Pairwise multiple comparisons (Tukey test)

Comparison for species	***P***	***P* < 0.05**
RM vs. SM	0.0001	Yes
RM vs. BA	0.0001	Yes
RM vs. AS	0.0006	Yes
RM vs. RO	0.0001	Yes
RO vs. SM	0.9779	No
RO vs. BA	0.0808	No
RO vs. AS	0.0982	No
AS vs. SM	0.0222	Yes
AS vs. BA	0.0001	Yes
BA vs. SM	0.2741	No
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0377	Yes
WBD within RO	0.0005	Yes
WBD within BA	0.0001	Yes
WBD within AS	0.0013	Yes
Comparison for species within WBD = 2		
RO vs. BA (56.9 vs. 51.3)	0.1207	No
RO vs. SM (56.9 vs. 57.8)	0.9954	No
RO vs. AS (56.9 vs. 61.4)	0.2997	No
RO vs. RM (56.9 vs. 59.4)	0.8199	No
RM vs. BA (59.4 vs. 51.3)	0.0067	Yes
RM vs. SM (59.4 vs. 57.8)	0.9584	No
RM vs. AS (59.4 vs. 61.4)	0.9052	No
AS vs. BA (61.4 vs. 51.3)	0.0004	Yes
AS vs. SM (61.4 vs. 57.8)	0.5327	No
SM vs. BA (57.8 vs. 51.3)	0.0482	Yes
Comparison for species within WBD = 10		
RM vs. SM (85.3 vs. 62.7)	0.0001	Yes
RM vs. BA (85.3 vs. 62.6)	0.0001	Yes
RM vs. AS (85.3 vs. 69.2)	0.0001	Yes
RM vs. RO (85.3 vs. 65.5)	0.0001	Yes
RO vs. SM (65.5 vs. 62.7)	0.7496	No
RO vs. BA (65.5 vs. 62.6)	0.7319	No
RO vs. AS (65.5 vs. 69.2)	0.5036	No
AS vs. SM (69.2 vs. 62.7)	0.0481	Yes
AS vs. BA (69.2 vs. 62.6)	0.0445	Yes
BA vs. SM (62.6 vs. 62.7)	1.0000	No

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 7—Results of two-way analysis of variance on heating times (min) for 4- by 4-in. squares heated with a 2°F wet-bulb depression[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	989.725	34.374	<0.0001
WBD	1	6447.126	223.917	<0.0001
Species x WBD	4	60.242	12.522	<0.0883
Residual	90	28.793		
Total	99	133.720		

Pairwise multiple comparisons (Tukey test)

Comparison for species	***P***	***P* < 0.05**
RM vs. SM	0.0001	Yes
RM vs. BA	0.0001	Yes
RM vs. AS	0.0307	Yes
RM vs. RO	0.0001	Yes
RO vs. SM	0.6430	No
RO vs. BA	0.0001	Yes
RO vs. AS	0.1018	No
AS vs. SM	0.0020	Yes
AS vs. BA	0.0001	Yes
BA vs. SM	0.0007	Yes
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0001	Yes
WBD within RO	0.0001	Yes
WBD within BA	0.0001	Yes
WBD within AS	0.0001	Yes
Comparison for species within WBD = 2		
RO vs. BA (108.8 vs. 100.0)	0.0035	Yes
RO vs. SM (108.8 vs. 107.4)	0.9753	No
RO vs. AS (108.8 vs. 112.7)	0.4769	No
RO vs. RM (108. 8vs. 114.6)	0.1166	No
RM vs. BA (114.6 vs. 100.0)	0.0001	Yes
RM vs. SM (114.6 vs. 107.4)	0.0261	Yes
RM vs. AS (114.6 vs. 112.7)	0.9324	No
AS vs. BA (112.7 vs. 100.0)	0.0001	Yes
AS vs. SM (112.7 vs. 107.4)	0.1763	No
SM vs. BA (107.4 vs. 100.0)	0.0216	Yes
Comparison for species within WBD = 10		
RM vs. SM (136.7 vs. 120.7)	0.0001	Yes
RM vs. BA (136.7 vs. 113.9)	0.0001	Yes
RM vs. AS (136.7 vs. 128.5)	0.0086	Yes
RM vs. RO (136.7 vs. 124.0)	0.0001	Yes
RO vs. SM (124.0 vs. 120.7)	0.6592	No
RO vs. BA (124.0 vs. 113.9)	0.0007	Yes
RO vs. AS (124.0 vs. 128.5)	0.3333	No
AS vs. SM (128.5 vs. 120.7)	0.0143	Yes
AS vs. BA (128.5 vs. 112.9)	0.0001	Yes
BA vs. SM (112.9 vs. 120.7)	0.0440	Yes

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Table 8—Results of two-way analysis of variance on heating times (min) for 6- by 6-in. squares[a]

Source of variation	Degrees of freedom	Mean square	*F*	*P*
Species	4	3631.283	15.3756	<0.0001
WBD	1	22432.251	94.987	<0.0001
Species x WBD	4	102.168	0.433	<0.7847
Residual	90	236.161		
Total	99	592.126		

Pairwise multiple comparisons (Tukey test)

Comparison for species	***P***	***P* < 0.05**
RM vs. SM	0.2273	No
RM vs. BA	0.0001	Yes
RM vs. AS	0.6704	No
RM vs. RO	0.1195	No
RO vs. SM	0.9979	No
RO vs. BA	0.0002	Yes
RO vs. AS	0.8139	No
AS vs. SM	0.9387	No
AS vs. BA	0.0001	Yes
BA vs. SM	0.0001	Yes
Comparison for WBD		
WBD 2 vs. WBD 10	0.0001	Yes
Comparison for WBD		
WBD within RM	0.0001	Yes
WBD within SM	0.0002	Yes
WBD within RO	0.0001	Yes
WBD within BA	0.0001	Yes
WBD within AS	0.0010	Yes
Comparison for species within WBD = 2		
RO vs. BA (251.9 vs. 226.0)	0.0028	Yes
RO vs. SM (251.9 vs. 255.0)	0.9916	No
RO vs. AS (251.9 vs. 261.5)	0.6585	No
RO vs. RM (251.98 vs. 264.6)	0.9916	No
RM vs. BA (264.6 vs. 226.0)	0.0001	Yes
RM vs. SM (264.6 vs. 255.0)	0.6264	No
RM vs. AS (264.6 vs. 261.5)	0.9874	No
AS vs. BA (261.5 vs. 226.0)	0.0001	Yes
AS vs. SM (261.5 vs. 255.0)	0.8939	No
SM vs. BA (255.0 vs. 226.0)	0.0007	Yes
Comparison for species within WBD = 10		
RM vs. SM (294.4 vs. 283.6)	0.5194	No
RM vs. BA (294.4 vs. 262.2)	0.0002	Yes
RM vs. AS (294.4 vs. 284.8)	0.6360	No
RM vs. RO (294.4 vs. 283.6)	0.5205	No
RO vs. SM (283.6 vs. 283.6)	1.0000	No
RO vs. BA (283.6 vs. 262.2)	0.0191	Yes
RO vs. AS (283.6 vs. 284.8)	0.9998	No
AS vs. SM (284.8 vs. 283.6)	0.9998	Yes
AS vs. BA (284.8 vs. 262.2)	0.0113	Yes
BA vs. SM (262.2 vs. 283.6)	0.0192	Yes

[a]WBD, wet-bulb depression; RM, red maple; SM, sugar maple; RO, red oak; BA, basswood; AS, aspen.

Although the effect of species on heating time is small, basswood generally had notably shorter heating times than the other species. This is consistent with predictions of the MacClean model, where basswood specific gravity was notably less than that of the other species, and the moisture content was notably higher (Table 2).

With the exception of the heating times for 2-in.-thick boards and 3- by 3-in. squares, size had such a clear effect on heating time that we did not include size in the ANOVA. However, the heating times of 2-in.-thick boards and 3- by 3-in. thick squares were close enough that a statistical analysis seemed desirable. We conducted a three-way ANOVA with size as the third factor to determine if heating time was different for those two sizes. The size factor had two levels: 2-in. boards and 3- by 3-in. squares. Results showed that heating times for 3- by 3-in. squares were significantly greater than for 2-in.-thick boards.

Analytical

MacClean Equations

The purpose of the analytical approach is to calculate estimates of heating times, which depend on various factors. One approach is the use of equations developed by MacClean (1932) and described and applied by Simpson (2001). One limitation of these equations is that they require the surface of the wood to immediately attain and thereafter maintain the temperature of the heating air. An advantage of these equations is that although the method is tedious, estimated heating times can be calculated relatively easily with a hand calculator or in a computer spreadsheet. Simpson (2001, 2002, 2003) found that these equations worked well when the heating medium was saturated steam—wet heat. When the heating air becomes dryer, the equations can severely underestimate heating time. Column 4 of Table 2 lists heating times calculated by MacClean's equations using heating temperature in the kiln and specific gravity and moisture content measured on the study material. Agreement between these calculated times and the unadjusted heating times (actual sizes, initial temperatures, and average heating temperatures were used in the calculations) is reasonably close at the nominal 2°F wet-bulb depression, but at the nominal 10°F wet-bulb depression, the calculated times underestimate the observed heating times.

The MacClean equations underestimate heating times at the nominal 10°F wet-bulb depression because drying occurs, and the evaporation of water from the wood surface cools the surface. The result is that the wood surface is at a lower temperature than the heating temperature (dry-bulb temperature), which reduces the surface-to-center temperature gradient from what it would be. Therefore, use of the dry-bulb temperature in the equations is not valid.

Two-Dimensional Finite Difference Equations

The surface cooling effect can be accommodated by using a different mathematical approach. Simpson (2004) showed a two-dimensional finite difference solution to the heat flow differential equation with a boundary condition allowing a time-dependent surface temperature. This equation worked well in calculating heating times in conditions where the wood was drying and thus the surface was below the heating temperature. This approach was applied to the data of this experiment, and the results are shown in column 5 of Table 2. The agreement between the unadjusted experimental heating times and those calculated by the two-dimensional finite difference approach is reasonably close with heating at both the nominal 2°F and 10°F heating conditions.

While the two-dimensional finite difference approach is successful in dry heating conditions, it is not really a practical approach in use. It requires measurement of surface temperatures, and the calculations are not easy and convenient for users. It was developed to help establish and define the mechanism by which surface cooling affects heating times.

Wet-Bulb Temperature Approach

When a wood surface is drying, the cooling effect may be similar to evaporation from a wet-bulb sensor. Therefore it is logical to evaluate an analytical method that assumes that the wood surface attains the wet-bulb temperature rather than the dry-bulb temperature. Because the MacClean equations are easier to use than the two-dimensional finite difference equations, they seem the most useful ones to test. The results of the test are shown in column 6 of Table 2, where estimated heating times are calculated by the MacClean equations with the average wet-bulb temperatures used as the heating temperature. The percentage deviation of the calculated times from the unadjusted experimental times is shown in column 7 of Table 2. The agreement is good, with an overall average deviation of 7.1% (sign ignored). Also, 67% of the heating times calculated this way fall within the 99% confidence interval of experimental times. This use of wet-bulb temperature as the heating temperature expands the utility of the heating-time tables published by Simpson (2001) beyond heating in the wet heat of saturated steam to additional use when there is a wet-bulb depression during the use of dry heat.

The surface cooling phenomenon is also illustrated in Figures 4 and 5 using sugar maple 2- by 6-in. boards as an example. In Figure 4, the center, surface, dry-bulb, and wet-bulb temperatures are graphed as a function of time for the nominal 0°F wet-bulb depression. After the initial time period during which the kiln conditions recover from opening the door to push in the kiln truck, the surface temperature of the boards attains the wet-bulb temperature, which in the

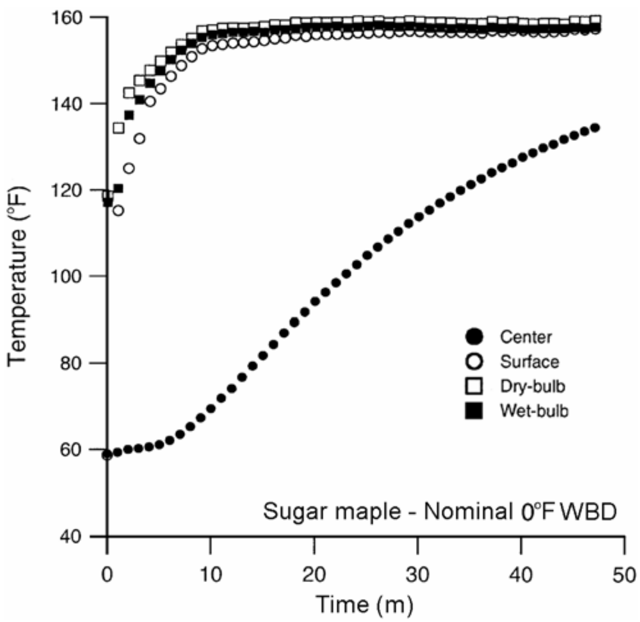

Figure 4—Dependence of center, surface, dry-bulb, and wet-bulb temperatures in heating sugar maple 2- by 6-in. boards in nominal 0°F wet-bulb depression conditions.

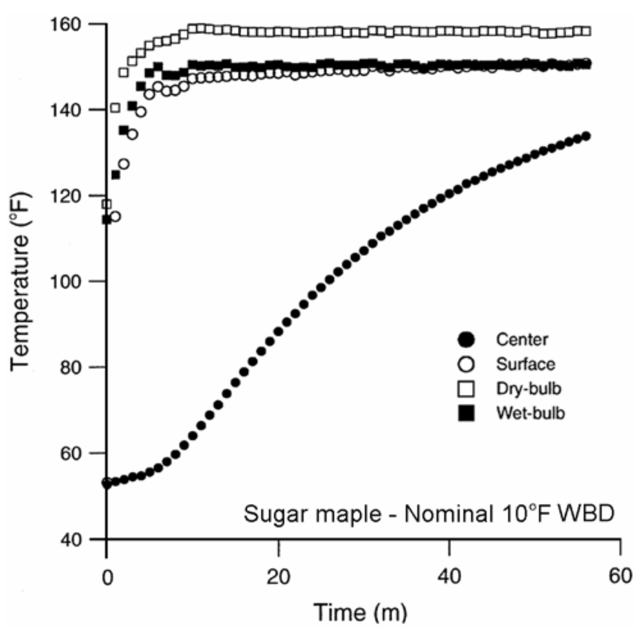

Figure 5—Dependence of center, surface, dry-bulb, and wet-bulb temperatures in heating sugar maple 2- by 6-in. boards in nominal 10°F wet-bulb depression conditions.

0°F degree wet-bulb condition is essentially the same as the dry-bulb temperature. In Figure 5, illustrating the nominal 10°F wet-bulb depression, the surface temperature also attains the wet-bulb temperature, but in this case it is approximately 10°F lower than the dry-bulb temperature.

Summary and Conclusions

The time required to heat the center of five hardwood species—red maple, sugar maple, red oak, basswood, and aspen—to 133°F was determined with a nominal heating temperature of 160°F and two nominal wet-bulb depressions of 2°F and 8–10°F. Two analytical methods were applied to determine their ability to calculate estimates of heating times. One method was the use of MacClean's (1932) equations. The other was a two-dimensional finite difference solution to the differential heat flow equation with the boundary condition of variable temperature (Simpson 2004), which is necessary during the use of dry heat where the surface of the wood is cooling from the evaporation of water during drying.

Size had the expected effect on heating time, with times as short as about 15 min for 1-in.-thick boards to almost 300 min for 6- by 6-in. square timbers. Heating time was about 15% longer with the larger wet-bulb depression. Some heating times between species were significantly different statistically, but differences were not great enough to warrant heating species separately.

The analytical methods for calculating estimates of heating times worked well within their limitations. The most significant result was that wet-bulb temperature can be used successfully with the MacClean equations as the heating temperature. This opens the use of Simpson's (2001) tables (based on MacClean equations) to applications other than heating in saturated steam.

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