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Heat Sterilization Time of Ponderosa Pine and Douglas-Fir Boards and Square Timbers

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Abstract

To prevent the unintentional transfer of insects and pathogens during world trade, wood products are often heat sterilized. The general requirement is that the center of the wood configuration be held at 133°F (56°C) for 30 min. However, many factors can affect the time required to reach this temperature. This study explored several of these factors, including thickness of boards or cross-sectional dimension of square timbers, wet-bulb depression, and stacking method (solid or stickered). The heating temperature used was 160°F (71°C). Heating time increased with increasing board thickness or increasing cross-sectional dimension. It also increased as wet-bulb depression increased because of surface cooling when simultaneous drying occurred at significant wet-bulb depressions. Solid piling increased heating time by a factor ranging from 2 to 10 compared with stickered piling, depending on species and size. This study also looked at developing an analytical method to predict heating time as a function of heating variables. Multiple regression was successful as a prediction tool as a function of wood size, wet-bulb depression, and initial wood temperature as long as the wet-bulb temperature in the heating chamber was higher than the target center temperature. The multiple regression results were used to create 99% upper confidence levels on estimated heating times.

Keywords: heat sterilization, lumber, dry kilns

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Introduction

Heat sterilization of lumber, timbers, and pallets is currently used to kill insects to prevent their transfer between countries in international trade. A typical requirement is that the center of any wood configuration be held at 133°F (56°C) for 30 min. However, the time required for the center to reach this temperature can vary widely depending on a number of factors such as wood species, wood specific gravity and moisture content, cross-sectional dimensions, initial temperature, heating temperature, heating medium (wet or dry heat), and stacking method. The broad objective of this study was to quantify the effects of cross-sectional dimensions, heating medium, and stacking method on the time required to heat the center of ponderosa pine and Douglas-fir lumber and timbers to 133°F at a heating temperature of 160°F (71°C). A more specific objective was to develop an analytical method to calculate estimates of heating times.

Background

The literature on heating times for lumber, timbers, and poles is mostly concerned with preparation for preservative treatment. 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, which means heating is from all four cross-sectional faces. Therefore, the equations are only applicable when these four faces all have access to the heating medium, except for wide boards where the width is much greater than the thickness. Gu and Garrahan (1984) also confirmed experimentally that MacLean's equations were valid for estimating heating times. 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 cross sections ranging from 4 to 16 in. (102 to 406 mm) in diameter (in 1-in. (25-mm) increments) and rectangular cross sections ranging from 0.75 in. (19 mm) (variable width) to 16- by 16-in. (406- by 406-mm) square timbers. Variables in the tables were wood specific gravity, moisture content, initial temperature, heating temperature, and target center temperature. Simpson (2001) also described MacLean's work and equations in detail.

MacLean's equations apply only to heating in a saturated steam environment. This means that little or no drying takes place during heating. In mathematical terms, it means a boundary condition where the surface immediately attains and holds the temperature of the heating medium. 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. When water evaporates from the wood surface, the latent heat of evaporation cools the surface. When this occurs, the surface is no longer at the dry-bulb temperature of the air. In other words, the wood is no longer being heated at the air temperature but at some lower temperature that depends on the rate of evaporation. The temperature difference between the surface and center is the driving force for heat conduction, and when that difference is reduced, heating time increases. The consequence is that when drying is occurring during heating, heating time is longer than if simultaneous drying were not occurring. A further consequence is that MacLean's equations no longer apply. They are derived from the solution to the differential equations of heat conduction, which requires the wood surface to immediately attain the temperature of the heating medium.

Simpson (2001, 2002) showed the effects of simultaneous drying on prolonging heating time for red maple, aspen, and slash pine. The slash pine study (Simpson 2002) went into more depth than the red maple and aspen study and clearly showed the increase in surface cooling as wet-bulb depression during heating was systematically increased. Heating times were shown to increase exponentially with wet-bulb depression increase. And when the wet-bulb depression was large enough that the wet-bulb temperature approached the target center temperature, the heating time increase became quite large. Under these conditions, the center temperature tended to remain at the wet-bulb temperature for an extended time period, which was probably related to the moisture content at the center, until the moisture content had decreased to below the fiber saturation point when evaporation rate slowed. Simpson (2002) also measured surface temperature during heating and incorporated the variation in surface temperature with time during heating into a one-dimensional (boards must be much wider than thick) finite difference solution to the heat conduction equation that included the boundary condition of changing surface temperature rather than the requirement of immediate attainment and retention of the dry-bulb temperature.

Experimental Methods

Freshly sawn ponderosa pine and Douglas-fir boards and square timbers in the following sizes were supplied by mills: nominal 1- by 6- and 2- by 6-in. (25- and 50- by 152-mm) boards and nominal 4- by 4-, 6- by 6-, and 12- by 12-in. (102- by 102-, 152- by 152-, and 305- by 305-mm) timbers. Actual sizes for the ponderosa pine were the same as nominal sizes. Actual sizes of Douglas-fir were 3/4 by 5-5/8, 1-1/2 by 5-5/8, 3-1/2 by 3-1/2 in. (19 by 143, 38 by 143, 89 by 89 mm) and approximately 5-3/4 by 5-3/4 and 11-3/4 by 11-3/4 in. (146 by 146 and 298 by 298 mm). The nominal 6 by 6 and 12 by 12 Douglas-fir varied from the 5-3/4 or 11-3/4 in. up to the full 6 or 12 in. The material arrived in Madison in late winter. For several months, during which experimental runs were started on the ponderosa pine, the material was stored in the shade and wrapped with sheet plastic. By the time the ponderosa pine experimental runs were completed, warm weather had arrived and the Douglas-fir was stored under water spray as the experimental runs progressed. This difference in outdoor storage temperature created different initial center temperatures—ranging from as low as 32°F (0°C) in the first 12- by 12-in. ponderosa pine run in March to as high as 80°F (27°C) for the last 1- by 6-in. Douglas-fir run in August. Heating time comparisons were thus complicated by these differing initial temperatures.

Two stacking methods were used. Most of the study was on stickered lumber or timbers, but several runs were made on solid-piled material. If a heat treating facility received solid-piled bundles of lumber or timber, it might be desirable to heat treat in the solid-piled configuration rather than unstacking, stickering for better access of all wood surfaces to the heating medium, and then restacking in solid-piled configuration.

All heating was done in a 1,500-board-foot (3.5-m^3) experimental dry kiln at the target dry-bulb temperature of 160°F. This is a temperature that strikes a balance between what most commercial dry kilns can easily reach and one that is high enough to result in reasonably short heating times. Exiting air velocity was approximately 600 ft/min (3 m/s).

Wet-bulb depression was chosen as another main experimental variable because of the previously discussed effect of simultaneous drying on heating time and the expected variation in the ability of commercial dry kilns to achieve low wet-bulb depressions. For the stickered material, the target experimental wet-bulb depressions were 2°F, 6°F, 12°F, 27°F, and 45°F to 50°F (1.1°C, 3.3°C, 6.7°C, 15.0°C, and 25.0°C to 27.8°C). Because of the limited amount of experimental material, only 2°F and 12°F were studied for solid-piled material. Five replicates of each size were included in each test run except for the 12 by 12's where only four replicates were tested. Dummy boards and timbers were included in each test stack so that all test boards were surrounded on all sides by other boards or timbers and thus all test boards responded as boards or timbers within the stack and not as edge boards or timbers.

Internal temperatures were measured with thermocouples inserted to the geometrical center of each of the five or four replicate boards or timbers. Figure 1 shows a hole being drilled for a thermocouple in one of the 12 by 12's. Figure 2 shows a round toothpick being inserted to seal the hole. Figure 3 shows a close-up of the thermocouple and toothpick. Surface temperatures were also measured on each of

Figure 1—Hole for thermocouple being drilled in 12- by 12-in. timber.

Figure 2—Toothpick being driven into 12- by 12-in. timber to seal thermocouple.

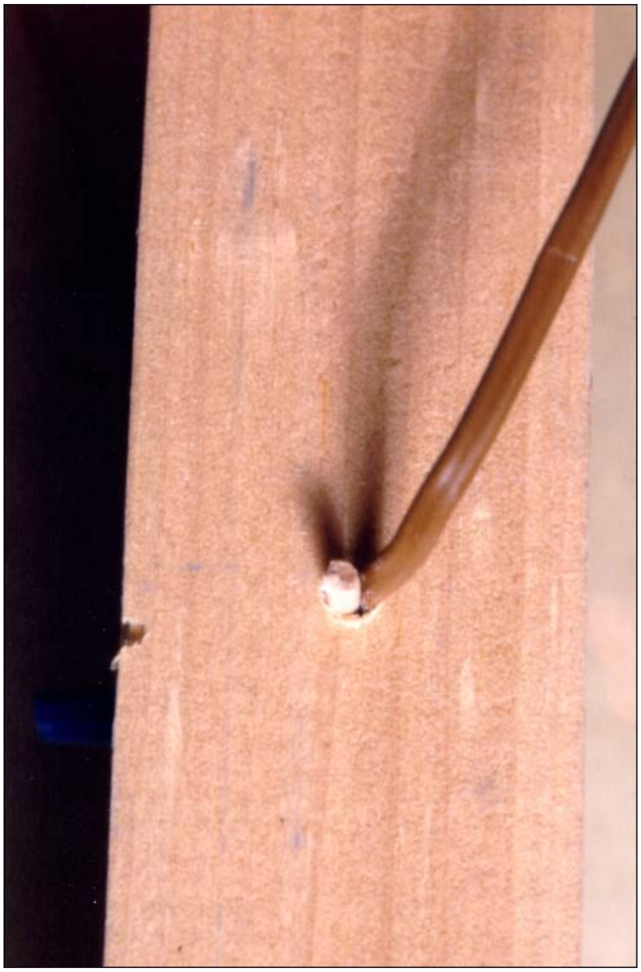

Figure 3—Interior thermocouple inserted to center of boards and timbers.

Figure 4—Surface thermocouple held in place by push pin.

the replicates so that the finite difference analysis (Simpson 2002) could be applied. Figure 4 shows a surface thermocouple in place. The surface thermocouples were held tightly to the board surfaces with plastic-headed (nonconducting) push pins. We then increased the contact with the surface by pressing down gently on the thermocouple junction. Figure 5 shows a stack of boards and timbers ready to be pushed into the kiln for heat treatment. The boards and timbers with the white markers are the ones fitted with center and surface thermocouples. The rest are dummies. Each test run thus consisted of all board and timber sizes of one species at one level of wet-bulb depression. Therefore, there was a total of five test runs of stickered material and two test runs of solid-piled material for each species, for a total of fourteen test runs. In each test run, the top layer of seven 1- by 6-in. boards and the bottom layer of seven 2- by 6-in. boards were weighed before heating, and then after the test, they were ovendried and reweighed for moisture content determination.

Figure 5—Stack of boards and timbers ready to be pushed into the kiln for heating. Pieces with white tags have thermocouples.

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 of the target kiln conditions. Recovery time to full target conditions was usually only 5 to 10 min. However, heating time of the nominal 1-in.-thick boards was so short (as short as 7 min in some cases) that full recovery was just barely made by the time the center had reached target temperature. This recovery time is probably longer in full-size commercial kilns and will be a factor in determining the time to be allowed for heating. Both center and surface thermocouple readings were processed by a Keithly (Cleveland, OH) Model 2700 Multimeter/Data Acquisition System and read to a computer file at intervals ranging from 0.5 min, to record the rapid heating of the nominal 1-in. boards especially early in their heating, to 10 min, for the last stages of the nominal 12- by 12-in. timbers. The center temperature at this point was taken as the initial temperature to be used later in the data analysis. Runs were terminated after the last of the slowest timbers (12 by 12 in.) reached the target center temperature of 133°F.

Analytical Methods

There are many possible combinations of material sizes, wet-bulb depressions, and initial temperatures. No one experiment of practical scope could cover them all. Therefore, developing an analytical method to calculate estimated heating times for combinations not directly measured experimentally would be very useful. As previously discussed, MacLean's method (Simpson 2001) and a finite difference approach (Simpson 2002) are possibilities. However, they have limitations that suggest they will not be fully successful in describing the experimental data of this study. 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 used in this study. In practice, his approach will probably require some small level of gapping between adjacent boards or timbers. It might also be successfully applied to timbers, where heat flow into all four faces occurs, as well as to wide boards where heat flow is important only through the wide faces, that is, as one-dimensional heat flow. His approach can also be successfully applied to round cross sections (Simpson 2001) but cannot be applied at some as yet unknown level of simultaneous surface drying. The finite difference solution can be adapted to the situation where simultaneous drying occurs (Simpson 2002), but it's use depends either on measurements of the surface temperature with time or the as yet undeveloped knowledge of how the surface transfer coefficient *h* (Simpson 2002) varies with temperature, wet-bulb depression, thickness, and species. And it requires extension to the two-dimensional solution to be applied to timbers.

The data of this study were analyzed using the two methods just mentioned, and the results of the analyses will be presented in the next section. However, with the exception of some applications of the finite difference method to boards, they were not very successful at predicting heating times. The detailed descriptions of how these two methods were applied will not be covered in this report but are available in Simpson (2001, 2002). However, the shortcomings of these two methods led to the development of a multiple regression analysis that was successful.

Results

The results of this study are summarized in Table 1 for ponderosa pine and Table 2 for Douglas-fir. Average experimental heating times are given, as well as times predicted by MacLean's method, the finite difference method, and the multiple regression analysis. The average green moisture content was 112% for ponderosa pine and 97% for Douglas-fir.

Experimental Heating Times

Experimental times to 133°F at the center were quite variable, ranging from 7 min for stickered nominal 1- by 6-in. (actual thickness 0.75 in.) Douglas-fir boards to 2,889 min (48.2 h) for solid-piled ponderosa pine 12 by 12's. Size had a significant effect, with 12 by 12's taking more than 100 times longer than 1-in.-thick boards in some cases. Wet-bulb depression also affected experimental heating times, with heating time increasing as wet-bulb depression increased. This was expected because drying rate, and thus the rate of surface evaporation and cooling, increases as wet-bulb depression increases. The increase in heating time became especially large in the 1- and 2-in.-thick boards when the wet-bulb temperature in the kiln approached the target center temperature. When the wet-bulb depression was 27°F, the wet-bulb temperature in the kiln was 133°F—the same as the target center temperature. As long as water is still evaporating from the wood, the limit on wood temperature will be approximately the wet-bulb temperature, and thus, the center temperature will approach 133°F slowly. If the wet-bulb temperature is above the target center temperature of 133°F, as is the case for wet-bulb depressions of 2°F, 6°F, and 12°F, the center temperature has no trouble exceeding 133°F. For example, for 1-in.-thick ponderosa pine heated in a 12°F wet-bulb depression environment, heating time was 22.5 min. But when the wet-bulb depression was increased to 26.8°F (14.9°C), heating time increased to 188 min.

This effect is much more noticeable on the 1- and 2-in.-thick boards than on the larger dimension timbers. This is because, in drying thin material as opposed to thick material, surface evaporation is a more important mechanism than internal moisture movement, and thus the surface cooling with its slowing effect on the rate of internal heating is more pronounced. The extreme example of this was the 427-min

Table 1—Summary of experimental and calculated times to heat ponderosa pine boards and square timbers to a center temperature of 133°F in a heating environment of nominal 160°F dry-bulb temperature and various wet-bulb temperatures[a]

Wet-bulb depr. (°F)	Nominal size (in.)	Experimental T_{133} Avg. (min)	Experimental T_{133} CV[b] (%)	MacLean T_{133} (min)	MacLean dev. (%)	Finite diff. T_{133} (min)	Finite diff. dev. (%)	Mult. reg. T_{133} (min)	Mult. reg. dev. (%)
				Stickered					
2.5	12 by 12	1,006	15.5	964	4.2	1,759	74.9	974[c]	3.2
	6 by 6	299	17.7	237	20.7	432	44.5	308[c]	3.0
	4 by 4	153	8.9	105	31.3	189	23.5	143[c]	6.5
	2 by 6	42.7	13.1	42.0	1.6	45.8	7.3	43.4[d]	1.6
	1 by 6	17.0	8.1	12.2	28.2	15.3	10.0	16.7[d]	1.8
6.2	12 by 12	980	12.1	867	11.5	1,728	76.3	961[c]	1.9
	6 by 6	271	6.2	207	23.6	407	50.2	297[c]	9.6
	4 by 4	180	6.0	107	40.6	211	17.2	180[c]	0.0
	2 by 6	52.7	2.4	38.2	27.5	46.0	12.7	49.5[d]	6.1
	1 by 6	16.0	5.9	10.8	32.5	14.8	7.5	16.6[d]	3.8
12.0	12 by 12	1,428	8.2	1,004	29.7	1,840	28.9	1,432[c]	0.3
	6 by 6	420	28.3	229	45.5	514	22.4	383[c]	8.8
	4 by 4	207	17.3	109	47.3	248	19.8	207[c]	0.0
	2 by 6	67.0	15.0	45.6	31.9	62.1	7.3	68.6[d]	2.4
	1 by 6	22.5	3.1	12.3	45.3	19.5	13.3	22.1[d]	1.8
26.8	12 by 12	1,680	13.9	881	47.6	1,870	11.3	1,463[e]	12.9
	6 by 6	568	7.2	209	63.2	580	2.1	525[e]	7.6
	4 by 4	256	19.0	95.1	62.9	219	14.5	303[e]	18.4
	2 by 6	137	12.5	39.9	70.9	83.8	38.8	139[f]	1.5
	1 by 6	188	45.2	9.6	94.9	37.3	80.2	171[f]	9.0
47.5	12 by 12	2,551	22.2	897	64.8	1,917	24.9	2,745[e]	7.6
	6 by 6	953	38.1	221	76.8	583	38.8	1098[e]	15.2
	4 by 4	817	53.9	96.1	88.2	294	64.0	593[e]	27.4
	2 by 6	361	30.7	40.0	88.9	101	72.0	345[f]	4.4
	1 by 6	427	18.1	10.1	97.6	98.3	77.0	422[f]	1.2
				Solid-piled					
2.8	12 by 12	1,736	26.4	871	49.8	2,590	49.2	2,007[g]	15.6
	6 by 6	1,201	30.1	217	81.9	1366	13.7	1231[g]	2.5
	4 by 4	831	14.0	101	87.8	528	36.5	675[g]	18.8
	2 by 6	361	64.9	38.5	89.3	423	17.2	300[h]	16.9
	1 by 6	166	70.3	9.9	94.0	128	22.9	141[h]	15.1
13.4	12 by 12	2,889	22.4	837	71.0	3,758	30.1	2,412[g]	16.5
	6 by 6	1,617	26.7	209	87.1	1522	5.9	1,441[g]	10.9
	4 by 4	710	48.1	92.9	86.9	674	5.1	810[g]	14.1
	2 by 6	391	23.4	37.3	90.5	355	9.2	387[h]	1.0
	1 by 6	201	22.7	9.7	95.2	197	2.0	195[h]	3.0

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.
[b]CV, coefficient of variation.
[c]Multiple regression is based on data for wet-bulb depressions of 2.5°F, 6.2°F, and 12.0°F; 4- by 4-, 6- by 6-, and 12- by 12-in. stickered timbers; R^2 = 0.967.
[d]Multiple regression is based on data for wet-bulb depressions of 2.5°F, 6.2°F, and 12.0°F; 1- and 2-in.-thick stickered boards; R^2 = 0.978.
[e]Multiple regression is based on data for wet-bulb depressions of 26.8°F and 47.5°F; 4- by 4-, 6- by 6-, and 12- by 12-in. stickered timbers; R^2 = 0.848.
[f]Multiple regression is based on data for wet-bulb depressions of 26.8°F and 47.5°F; 1- and 2-in.-thick stickered boards; R^2 = 0.739.
[g]Multiple regression is based on data for wet-bulb depressions of 2.8°F and 13.4°F; 4- by 4-, 6- by 6-, and 12- by 12-in. solid-piled timbers; R^2 = 0.672.
[h]Multiple regression is based on data for wet-bulb depressions of 2.8°F and 13.4°F; 1- and 2-in.-thick solid-piled boards; R^2 = 0.434.

Table 2—Summary of experimental and calculated times to heat Douglas-fir boards and square timbers to a center temperature of 133°F in a heating environment of nominal 160°F dry-bulb temperature and various wet-bulb temperatures[a]

Wet-bulb depr. (°F)	Nominal size (in.)	Experimental T_{133} Avg. (min)	Experimental T_{133} CV[b] (%)	MacLean T_{133} (min)	MacLean dev. (%)	Finite diff. T_{133} (min)	Finite diff. dev. (%)	Mult. reg T_{133} (min)	Mult. reg dev. (%)
				Stickered					
2.2	12 by 12	840	8.8	837	0.4	1,429	70.1	865[c]	3.0
	6 by 6	209	8.9	198	5.3	348	66.5	203[c]	2.9
	4 by 4	78.1	12.5	70.9	9.2	125	60.1	82.0[c]	5.0
	2 by 6	21.4	21.3	22.6	5.6	24.8	15.9	21.1[d]	1.4
	1 by 6	7.3	22.2	6.4	12.3	7.5	2.7	7.3[d]	0.0
6.3	12 by 12	914	13.9	765	16.3	1,446	58.2	918[c]	0.4
	6 by 6	202	11.6	183	10.4	325	60.9	204[c]	1.0
	4 by 4	91.3	10.5	64.1	29.8	128	40.2	92.2[c]	1.0
	2 by 6	24.9	21.9	20.4	18.1	25.3	1.6	25.3[d]	1.6
	1 by 6	7.9	10.3	5.5	30.4	7.0	11.4	7.5[d]	5.1
12.5	12 by 12	1,153	7.0	779	32.4	1,524	32.3	1,156[c]	0.3
	6 by 6	262	7.7	189	27.9	439	67.6	282[c]	7.6
	4 by 4	138	17.8	70.5	48.9	163	18.1	131[c]	5.1
	2 by 6	33.8	22.3	23.0	32.0	32.5	3.8	32.6[d]	3.6
	1 by 6	9.9	6.7	6.1	38.4	10.0	1.0	10.1[d]	2.0
27.1	12 by 12	1,679	3.1	858	48.9	1,769	5.4	1,877[e]	11.8
	6 by 6	715	22.8	212	70.3	653	8.7	574[e]	19.7
	4 by 4	255	25.1	86.7	66.0	241	5.5	279[e]	9.4
	2 by 6	157	23.1	24.9	84.1	53.0	66.2	181[f]	15.3
	1 by 6	216	39.9	5.9	97.7	97.3	55.0	136[f]	37.0
44.2	12 by 12	2,005	23.3	796	60.3	1,581	21.1	1,930[e]	3.7
	6 by 6	849	6.1	193	77.3	591	30.4	858[e]	1.2
	4 by 4	362	28.0	68.9	81.0	237	34.2	353[e]	2.5
	2 by 6	223	20.3	21.0	90.6	64.0	71.3	252[f]	13.0
	1 by 6	233	62.8	5.2	97.8	49.5	78.8	163[f]	30.0
				Solid-piled					
1.5	12 by 12	1,931	13.5	817	57.7	2,661	37.8	1,973[g]	2.2
	6 by 6	977	9.3	197	79.8	1,245	27.4	1,096[g]	12.2
	4 by 4	432	27.2	70.2	83.8	514	19.0	364[g]	15.7
	2 by 6	137	46.9	21.7	84.2	99.3	27.5	123[h]	10.2
	1 by 6	103	45.2	5.4	94.8	107	3.9	89.9[h]	12.7
13.8	12 by 12	2,437	28.6	806	66.9	3,085	26.6	2,500[g]	2.6
	6 by 6	1,847	25.7	200	89.2	2,813	52.3	1,368[g]	25.9
	4 by 4	521	54.7	66.9	87.2	861	65.3	562[g]	7.9
	2 by 6	195	77.4	21.0	89.2	260	33.3	160[h]	17.9
	1 by 6	143	69.1	5.2	96.4	189	32.2	121[h]	15.4

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.
[b]CV, coefficient of variation.
[c]Multiple regression is based on data for wet-bulb depressions of 2.2°F, 6.3°F, and 12.5°F; 4- by 4-, 6- by 6-, and 12- by 12-in. stickered timbers; R^2 = 0.977.
[d]Multiple regression is based on data for wet-bulb depressions of 2.2°F, 6.3°F, and 12.5°F; 1- and 2-in.-thick stickered boards; R^2 = 0.925.
[e]Multiple regression is based on data for wet-bulb depressions of 27.1°F and 44.2°F; 4- by 4-, 6- by 6-, and 12- by 12-in. stickered timbers; R^2 = 0.935.
[f]Multiple regression is based on data for wet-bulb depressions of 27.1°F and 44.2°F; 1- and 2-in.-thick stickered boards; R^2 = 0.784.
[g]Multiple regression is based on data for wet-bulb depressions of 1.5°F and 13.8°F; 4- by 4-, 6- by 6-, and 12- by 12-in. solid-piled timbers; R^2 = 0.784.
[h]Multiple regression is based on data for wet-bulb depressions of 1.5°F and 13.48°F; 1- and 2-in.-thick solid-piled boards; R^2 = 0.118.

heating time of 1-in.-thick ponderosa pine at a wet-bulb depression of 47.4°F (26.3°C), which was substantially longer than what a 6- by 6-in. timber requires at wet-bulb depressions of either 2.5°F or 6.2°F (1.4°C or 3.4°C).

Solid piling had a large effect on increasing heating time compared with that of stickered material. Figure 6 shows the ratio of heating time for solid-piled material to the heating time for stickered material at the target wet-bulb depression of 2°F. The ratio increased as size decreased and ranged from about 2 for 12- by 12-in. timbers to more than 14 for 1- by 6-in. boards. Another observation on the comparison of solid-piled to stickered material was the variability among the replicates in heating times. For ponderosa pine, the average coefficient of variation of heating times was 17.1% for stickered material and 34.9% for solid-piled material. For Douglas-fir, they were 18.3% and 39.8%. This is a logical outcome of the high degree of variability in how closely together wood pieces can be fit in solid stacking. In places where there was a gap, the kiln air could penetrate and thus warm the surface more than where adjacent pieces fitted tightly together. Thus, in commercial practice, this high variability would cause complications in estimating heating times.

MacLean Estimates of Heating Times

Estimates of heating times by MacLean's equations are also given in Tables 1 and 2. For stickered material heated at the target wet-bulb depression of 2°F, the agreement between experimental and calculated times was quite good for Douglas-fir, averaging about 5% for all sizes. The agreement for ponderosa pine was not as good, averaging about 17%. There is no obvious reason for the difference between the two species. As discussed previously, MacLean's equation cannot account for surface cooling during heating, and this is reflected in the increase in deviation between experimental and calculated times as wet-bulb depression increased. The small difference in heating time calculations by MacLean's equations for different wet-bulb depression groups is due to the slight differences in dimensions, moisture content, and specific gravity between groups.

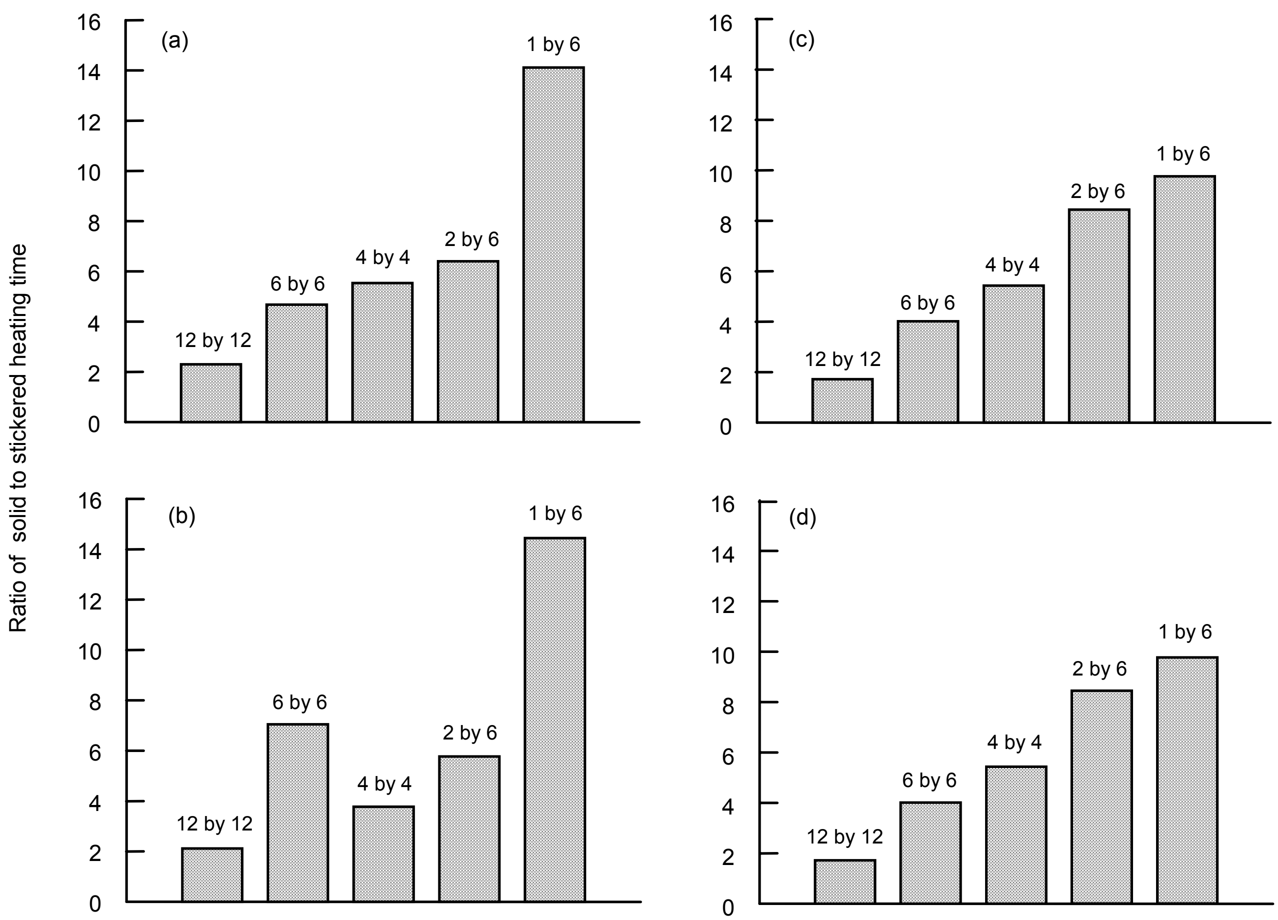

Figure 6—Ratio of heating times of solid-piled boards and timbers to stickered boards and timbers for (a) Douglas-fir, 1.5°F/2.2°F (–16.9°C/–16.6°C) wet-bulb depression; (b) Douglas-fir, 12.5°F/13.8°F (–10.8°C/–10.1°C) wet-bulb depression; (c) ponderosa pine, 2.5°F/2.8°F (–16.4°C/–16.2°C) wet-bulb depression; and (d) ponderosa pine, 12.0°F/13.4°F (–11.1°C/–10.3°C) wet-bulb depression.

Finite Difference Estimates of Heating Times

As developed to this point, the finite difference solution to the heat conduction equations is for one-dimensional heating only; that is, heat flow occurs only through two opposite faces and not through the edges. Thus, this solution only applies to boards much wider than they are thick. The effect of edge heating gradually declines as the width-to-thickness ratio increases (Fig. 7), and when it is above the 3 to 4 range, the one-dimensional solution is a good approximation.

The one-dimensional finite difference solution has two possible applications in this study. First, it might apply to the 1- and 2-in.-thick boards because the width-to-thickness ratio is high. Second, it was possible that it would apply to the stickered timbers because of the way they were stacked. The edge-to-edge stacking might have resulted in the width of the whole stack (instead of the individual piece width) acting as the controlling width, thus making a large width-to-thickness ratio even for the larger timbers. Examination of the data in Tables 1 and 2, however, shows that this was not the case. Deviation between experimental and calculated times was quite large for the timbers. However, agreement for the 1- and 2-in.-thick boards was good for the target wet-bulb depressions of 2°F, 6°F, and 12°F, with average deviations of 9.7% and 6.1% for ponderosa pine and Douglas-fir, respectively. Deviation was large with target wet-bulb depressions of 27°F and 45°F for the same reasons discussed previously—wet-bulb temperature limits the possible internal temperature, which is a different mechanism than surface cooling. Application of the finite difference solution requires a functional relationship between time and surface temperature. The method for accomplishing this is detailed in Simpson (2002), and the results from this study are shown in Table 3.

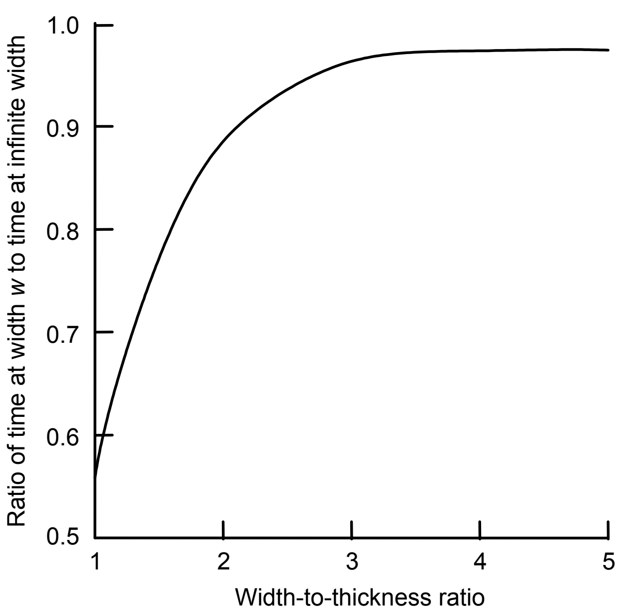

Figure 7—Effect of board width-to-thickness ratio on the ratio of the heating time at various widths to the heating time at infinite width, as calculated by MacLean's equation for two-dimensional heat flow (MacLean 1932, Simpson 2001).

Multiple Regression

The MacLean method and the finite difference approach were not successful in providing a way to calculate heating times. They could not provide accurate estimates for the sizes, wet-bulb depressions, and initial temperatures used in this study and therefore are of no use in calculating estimates for other combinations of the three variables. It would have been desirable to base an analytical estimation method on the theory of heat conduction, but we do not yet have the capability to do that. Therefore, it seemed necessary to turn to the strictly empirical approach of multiple regression.

The following multiple regression model proved to have a good ability to predict heating time from size, wet-bulb depression, and initial temperature:

$$\ln T_{133} = \ln a + b\,(\ln(x))^n + c \ln(\text{wbd}) + d \ln(T_i)$$

where T_{133} is time for the center to reach 133°F (min); x, thickness of boards or cross-sectional dimension 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.

Separate regressions were developed for the following groupings:

Ponderosa pine and Douglas-fir

1- to 2-in. boards, stickered, wet-bulb depression <12°F

4- to 12-in. timbers, stickered, wet-bulb depression <12°F

1- to 2-in. boards, stickered, 12°F < wet-bulb depression <50°F

4- to 12-in. timbers, stickered, 12°F < wet-bulb depression <50°F

1- to 2-in. boards, solid-piled, wet-bulb depression <14°F (–10°C)

4- to 12-in. timbers, solid-piled, wet-bulb depression <14°F

In Equation (1), $n = 1$ was best for all groupings except Douglas-fir timbers with wet-bulb depression <12°F, where $n = 2$ worked best. The regression coefficients (*a,b,c,d*) and coefficients of determination (R^2) are shown in Table 4. The R^2 values for the groups of stickered material range from 0.739 to 0.984 and average 0.893. The values for solid-piled material are not as high, ranging from 0.118 to 0.757 and

Table 3—Least squares coefficients for relationships between surface temperature and time[a] (Surface temperature = $a + b(\ln t) + c(\ln t)^2 + d(\ln t)^3 + e(\ln t)^4$)

Board dimension (in.)	Coefficients					Standard error of estimate
	a	*b*	*c*	*d*	*e*	
			Ponderosa pine – wet-bulb depression = 2.5°F			
1 by 6	129	4.32	–2.15	2.90	–0.485	0.231
2 by 6	133	4.58	–4.03	4.21	–0.797	1.162
			Ponderosa pine – wet-bulb depression = 6.2°F			
1 by 6	119	20.43	–16.08	10.13	–1.957	0.955
2 by 6	110	41.20	–21.07	5.78	–0.611	2.177
			Ponderosa pine – wet-bulb depression = 12.0°F			
1 by 6	109	12.70	3.68	–1.96	0.218	1.311
2 by 6	110	16.24	1.45	–1.70	0.220	1.307
			Douglas-fir – wet-bulb depression = 2.2°F			
1 by 6	132	15.19	–2.25	0.0164	0.0115	1.193
2 by 6	128	16.02	–2.10	–0.0454	0.0162	1.137
			Douglas-fir – wet-bulb depression = 6.3°F			
1 by 6	137	11.41	–3.02	0.366	–0.0149	0.919
2 by 6	135	11.23	–2.77	0.320	–0.0122	0.906
			Douglas-fir – wet-bulb depression = 12.5°F			
1 by 6	119	17.06	–3.65	0.290	0.00406	1.067
2 by 6	121	16.92	–4.79	0.689	–0.0339	1.071

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

averaging 0.495, which is not surprising given the higher variability in the solid-piled heating times.

The ability of the multiple regression equations to predict experimental heating times is shown in Tables 1 and 2. The agreement was good for stickered boards and timbers when the target wet-bulb depression was 2°F, 6°F, or 12°F. The deviations between the experimental and calculated heating times ranged from 0% to 9.6% and averaged 3.4% for ponderosa pine and 5.4% for Douglas-fir. The predictions for stickered boards and timbers when the target wet-bulb depression was 27°F or 50°F was not very good, with deviations as high as 37%. For solid-piled material, the deviations ranged from 1.0% to 25.9% and averaged 11.4% and 12.3% for ponderosa pine and Douglas-fir, respectively. However, the R^2 values for solid-piled material were low enough that the usefulness of the regression results is questionable.

Predicted Heating Times

One of the main objectives of the study was to develop an analytical method to estimate heating times from some of the variables involved, and the multiple regression equation provided such a method. The method worked well when the wet-bulb depression was less than or equal to about 12°F and the boards or timbers were stickered, so it seemed possible to use the multiple regression equation to generate heating time estimates for a series of sizes, wet-bulb depressions, and initial temperatures. Results can be seen in Figure 8 and Tables 5 to 8. The estimates for ponderosa pine cover initial temperatures from 40°F (4.4°C) to 80°F (in 10°F increments). The estimates for Douglas-fir only cover initial temperatures of 60°F (15.6°C) to 80°F. The reason for this difference was because of the timing of the experiments. The lumber and timbers were received in the winter. The ponderosa pine was tested first and therefore some was cold. By the time the Douglas-fir boards and timbers were tested, their temperatures ranged from about 58°F (14.4°C) to about 80°F, and therefore, it is not valid to extend the multiple regression estimates beyond the range of the experimental data. The regression results for stickered material at target wet-bulb depressions of 27°F and 50°F and for solid-piled material were not considered reliable enough to generate estimated times of the type in Figure 8 and Tables 5 to 8.

Table 4—Coefficients for multiple regression equation for estimating time required to heat ponderosa pine and Douglas-fir boards and timbers to a 133°F center temperature in a 160°F heating medium[a]

$$\ln T_{133} = \ln a + b\,(\ln t)^n + c \ln w + d \ln T_i$$

where T_{133} is time for the center to reach 133°F, t thickness of boards or cross-sectional dimensions of timbers (in.), w wet-bulb depression (WBD) (°F), T_i initial wood temperature (°F), a,b,c,d are regression coefficients, n = 2 for Douglas-fir timbers when WBD <12°F, n = 1 for all others.

Application	Coefficients				
	ln *a*	*b*	*c*	*d*	R^2
Stickered					
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
Ponderosa pine, 1- and 2-in. boards, 12 <WBD <50°F	0.322	–0.294	1.57	–0.0715	0.739
Ponderosa pine, 4-, 6-, and 12-in. timbers, 12 <WBD <50°F	4.94	1.25	0.919	–0.944	0.848
Douglas-fir, 1- and 2-in. boards, 12 <WBD <50°F	30.43	0.538	2.95	–8.35	0.769
Douglas-fir, 4-, 6-, and 12-in. timbers, 12 <WBD <50°F	18.64	1.33	2.03	–5.13	0.935
Solid-piled					
Ponderosa pine, 1- and 2-in. boards, WBD <14°F	9.18	0.958	0.271	–1.06	0.434
Ponderosa pine, 4-, 6-, and 12-in. timbers, WBD <14°F	17.15	0.572	0.574	3.01	0.672
Douglas-fir, 1- and 2-in. boards, WBD <14°F	13.31	0.415	0.211	–2.05	0.118
Douglas-fir, 4-, 6-, and 12-in. timbers, WBD <14°F	154.3	–0.588	1.67	–35.1	0.757

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

The estimated heating times in Figure 8 and Tables 5 to 8 are average times and give a reasonable general estimate of the time required. However, since the objective of heat sterilization is to be reasonably certain all insects are killed, the average heating time is not really good enough. In any group of boards and timbers, there will always be some that require more than the average time. With this in mind, it seems necessary to determine the upper statistical confidence levels for the heating times. The equations for these are given in the Appendix. Tables 9 to 12 list the experimental heating times, the heating times predicted by multiple regression (Eq. (1)), and the 99% upper confidence levels for the experimental heating times for ponderosa pine boards and timbers and for Douglas-fir boards and timbers.

While Tables 5 to 8 and Figure 8 show the average heating times for a number of typical combinations of size, wet-bulb depression, and initial wood temperature, to be fully useful, this information should also be shown as upper confidence levels (Tables 13–16, Fig. 9). Figure 9 shows the average and upper confidence levels of heating times, and Tables 13 to 16 are similar to Tables 5 to 8 except that they show 99% upper confidence level heating times instead of average heating times.

Conclusions

This study explored the effects of wood cross-sectional dimensions, wet-bulb depression, initial wood temperature, and stacking method on the time required to heat the center of ponderosa pine and Douglas-fir boards and timbers to 133°F when heated at 160°F dry-bulb temperature. As expected, heating time increased as size and wet-bulb depression increased and as initial temperature decreased. Also, heating time is significantly increased by solid-piling compared with stickered piling. This study also examined the possibility of predicting heating times using an analytical method. We determined that multiple regression can be used successfully to develop prediction equations to estimate heating time as a function of either board thickness or the cross-sectional dimension of square timbers, 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.

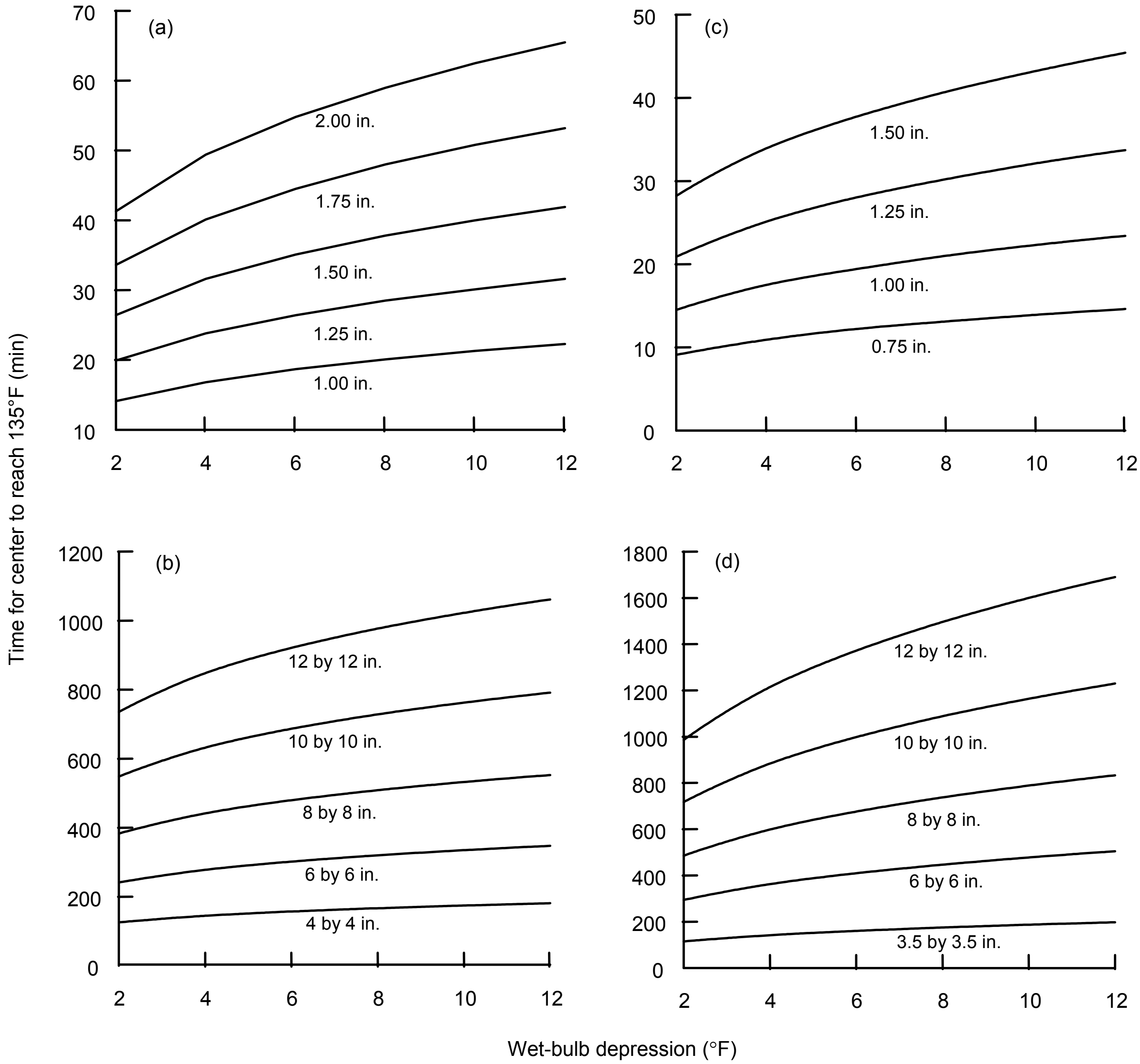

Figure 8—Dependence of heating time on wet-bulb depression for (a) 1- to 2-in.-thick ponderosa pine boards, (b) 4- to 12-in. ponderosa pine timbers, (c) 3/4- to 1-1/2-in.-thick Douglas-fir boards, and (d) 3-1/2- by 3-1/2-in. Douglas-fir timbers (initial temperature for all experiments was 60°F) (°C = (°F – 32)/1.8; 1 in. = 25.4 mm).

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Table 5—Summary of average heating times (at 160°F) to 133°F for ponderosa pine boards estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)				
		1.00 in. thick	1.25 in. thick	1.50 in. thick	1.75 in. thick	2.00 in. thick
2	40	18	26	34	43	53
4	40	22	31	41	52	64
6	40	24	34	45	58	71
8	40	26	37	49	62	76
10	40	28	39	52	66	81
12	40	29	41	54	69	85
2	50	16	22	30	38	46
4	50	19	27	36	45	55
6	50	21	30	39	50	62
8	50	23	32	42	54	66
10	50	24	34	45	57	70
12	50	25	36	47	60	74
2	60	14	20	27	34	41
4	60	17	24	32	40	49
6	60	19	27	35	45	55
8	60	20	29	38	48	59
10	60	21	30	40	51	63
12	60	22	32	42	53	66
2	70	13	18	24	31	38
4	70	15	22	29	37	45
6	70	17	24	32	41	50
8	70	18	26	34	44	54
10	70	19	27	36	46	57
12	70	20	29	38	48	60
2	80	12	17	22	28	35
4	80	14	20	26	34	41
6	80	16	22	29	37	46
8	80	17	24	32	40	49
10	80	18	25	33	43	52
12	80	19	26	35	45	55

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 6—Summary of average heating times (at 160°F) to 133°F for ponderosa pine square timbers estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)								
		4 by 4	5 by 5	6 by 6	7 by 7	8 by 8	9 by 9	10 by 10	11 by 11	12 by 12
2	40	155	222	297	381	473	571	677	789	908
4	40	178	256	343	439	545	659	780	910	1,047
6	40	194	278	372	477	592	716	848	989	1,137
8	40	206	295	395	506	628	759	899	1,048	1,206
10	40	215	308	413	530	657	794	941	1,097	1,263
12	40	223	320	429	550	682	825	977	1,139	1,311
2	50	138	197	265	339	421	509	603	703	809
4	50	159	228	305	391	485	586	695	810	932
6	50	173	247	332	425	527	637	755	880	1,013
8	50	183	262	352	451	559	676	801	934	1,074
10	50	192	274	368	472	585	707	838	977	1,124
12	50	199	285	382	490	607	734	870	1,014	1,167
2	60	125	180	241	309	383	463	548	639	735
4	60	144	207	278	356	441	533	632	737	848
6	60	157	225	302	387	479	579	687	800	921
8	60	166	238	320	410	508	615	728	849	977
10	60	174	250	335	429	532	643	762	889	1,022
12	60	181	259	348	445	552	668	791	922	1,061
2	70	116	166	222	285	353	427	506	590	679
4	70	133	191	256	328	407	492	583	680	782
6	70	145	207	278	357	442	535	634	739	850
8	70	154	220	295	378	469	567	672	784	901
10	70	161	230	309	396	491	594	703	820	943
12	70	167	239	321	411	510	616	730	851	979
2	80	108	155	207	266	330	398	472	550	633
4	80	124	178	239	306	380	459	544	634	730
6	80	135	194	260	333	413	499	591	689	793
8	80	143	205	275	353	438	529	627	731	841
10	80	150	215	288	369	458	554	656	765	880
12	80	156	223	299	384	476	575	681	794	914

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 7—Summary of average heating times (at 160°F) to 133°F for Douglas-fir boards estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)			
		0.75 in. thick	1.00 in. thick	1.25 in. thick	1.50 in. thick
2	60	9	14	21	28
4	60	11	17	25	34
6	60	12	19	28	38
8	60	13	21	30	41
10	60	14	22	32	43
12	60	15	23	34	45
2	70	7	12	17	23
4	70	9	14	20	27
6	70	10	16	23	31
8	70	11	17	24	33
10	70	11	18	26	35
12	70	12	19	27	37
2	80	6	10	14	19
4	80	7	12	17	23
6	80	8	13	19	25
8	80	9	14	20	28
10	80	9	15	22	29
12	80	10	16	23	31

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 8—Summary of average heating times (at 160°F) to 133°F for Douglas-fir square timbers estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)									
		3.5 by 3.5	4 by 4	5 by 5	6 by 6	7 by 7	8 by 8	9 by 9	10 by 10	11 by 11	12 by 12
2	60	135	159	215	285	371	473	595	738	905	1,098
4	60	171	200	271	360	468	597	751	932	1,142	1,386
6	60	195	229	311	412	536	684	860	1,068	1,309	1,588
8	60	215	253	342	454	590	754	948	1,176	1,442	1,749
10	60	232	272	369	489	636	812	1,021	1,267	1,554	1,885
12	60	247	289	392	520	676	863	1,086	1,347	1,652	2,004
2	70	89	105	142	188	244	312	392	487	597	724
4	70	112	132	179	237	308	394	495	614	753	914
6	70	129	151	205	272	353	451	567	704	863	1,047
8	70	142	167	226	299	389	497	625	775	950	1,153
10	70	153	179	243	323	419	535	673	835	1,024	1,243
12	70	163	191	259	343	446	569	716	888	1,089	1,321
2	80	62	73	99	131	170	217	273	339	416	505
4	80	78	92	125	165	215	274	345	428	525	637
6	80	90	105	143	189	246	314	395	491	601	730
8	80	99	116	157	209	271	346	435	540	662	804
10	80	107	125	170	225	292	373	469	582	714	866
12	80	113	133	180	239	311	397	499	619	759	921

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 9—Times for the center of ponderosa pine boards to reach 133°F: experimental times, times estimated by multiple regression (MR), and the upper 99% confidence limit on the experimental time[a]

Exp. T_{133} (min)	Thickness (in.)	Wet-bulb depression (°F)	T_i (°F)	MR T_{133} (min)	99% T_{133} (min)
19.1	1.2	3.9	76.3	17.9	22.6
15.4	1.1	3.9	75.0	15.7	19.9
16.4	1.1	3.9	75.3	16.8	21.3
17.2	1.1	3.9	74.0	17.0	21.5
16.9	1.1	3.9	72.3	16.3	20.8
48.6	2.0	2.8	66.5	42.0	53.3
48.6	2.0	2.8	65.2	44.2	56.2
41.2	2.1	2.8	66.4	44.7	56.8
38.6	2.1	2.8	66.7	45.3	57.5
36.7	2.0	2.8	66.9	40.6	51.5
16.4	1.0	6.0	76.2	17.1	21.6
16.7	1.0	6.0	76.4	16.1	20.3
15.4	1.0	6.0	76.4	15.9	20.0
16.8	1.0	6.0	74.5	17.4	21.9
14.6	1.0	6.0	76.1	16.4	20.7
53.3	1.8	6.1	64.4	46.3	58.3
53.9	1.9	6.1	66.4	49.3	62.3
51.8	2.1	6.1	64.6	55.1	69.6
53.4	1.9	6.1	65.4	48.3	60.8
50.9	2.0	6.1	69.3	48.8	62.3
23.7	1.1	11.1	70.8	22.3	28.2
22.0	1.0	11.1	68.8	20.8	26.5
22.3	1.1	11.1	69.5	22.2	28.2
22.5	1.1	11.1	73.1	22.8	28.9
22.0	1.1	11.1	75.1	22.4	28.6
70.7	2.1	11.8	58.9	69.7	88.6
59.7	2.1	11.8	55.4	73.5	94.9
81.4	2.2	11.8	55.5	77.8	100.2
66.1	1.9	11.8	62.1	61.0	77.3
56.5	2.0	11.8	67.3	62.2	80.5

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 10—Times for the center of ponderosa pine timbers to reach 133°F: experimental times, times estimated by multiple regression (MR), and the upper 99% confidence limit on the experimental time[a]

Exp. T_{133} (min)	Thickness (in.)	Wet-bulb depression (°F)	T_i (°F)	MR T_{133} (min)	99% T_{133} (min)
132	4.2	2.1	49.6	153	223
166	4.1	2.1	43.1	159	232
159	4.2	2.1	54.0	145	211
160	4.2	2.1	60.8	136	199
147	4.2	2.1	66.5	130	191
346	5.9	2.0	32.2	327	479
328	6.1	2.0	33.7	329	482
329	6.1	2.0	35.1	322	471
277	5.9	2.0	36.8	304	444
216	6.1	2.0	50.7	266	387
1,061	12.1	1.7	34.7	956	1,404
952	12.0	1.7	34.2	955	1,402
823	11.9	1.7	31.3	992	1,459
1,190	11.9	1.7	31.4	991	1,457
177	4.2	6.4	42.5	205	299
185	4.2	6.4	54.7	180	260
185	4.1	6.4	52.1	180	261
188	4.2	6.4	59.4	174	253
162	4.2	6.4	67.5	161	235
254	5.9	6.4	62.8	289	419
270	6.1	6.4	61.7	312	452
285	5.9	6.4	60.6	297	430
256	6.1	6.4	63.2	308	447
292	5.9	6.4	67.3	279	406
1,092	12.1	6.2	50.7	1,024	1,498
1,064	12.0	6.2	53.0	986	1,444
924	11.9	6.2	58.0	936	1,378
840	12.0	6.2	63.6	896	1,328
238	4.2	12.2	58.0	198	287
204	4.2	12.2	44.4	226	331
242	4.1	12.2	45.3	217	318
196	4.2	12.2	48.4	216	315
154	4.1	12.2	65.9	179	261
356	5.9	12.4	54.9	355	514
322	6.1	12.4	41.5	440	641
551	6.0	12.4	44.9	404	586
545	5.9	12.4	54.0	361	523
326	6.1	12.4	60.5	357	518
1,589	12.0	12.6	33.9	1,442	2,123
1,375	12.1	12.6	35.1	1,428	2,099
1,430	12.1	12.6	35.4	1,428	2,099
1,316	11.9	12.6	34.1	1,427	2,100

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 11—Times for the center of Douglas-fir boards to reach 133°F: experimental times, times estimated by multiple regression (MR), and the upper 99% confidence limit on the experimental time[a]

Exp. T_{133} (min)	Thickness (in.)	Wet-bulb depression (°F)	T_i (°F)	MR T_{133} (min)	99% T_{133} (min)
8.5	0.76	4.4	82.5	7.4	11.8
4.7	0.75	4.4	82.9	7.2	11.6
8.0	0.76	4.4	82.1	7.4	11.8
8.6	0.74	4.4	82.2	7.2	11.5
6.9	0.75	4.4	81.9	7.3	11.7
26.7	1.53	2.2	78.8	20.7	33.7
17.5	1.54	2.2	77.3	21.5	35.2
18.2	1.54	2.2	77.9	21.2	34.7
26.0	1.53	2.2	77.5	21.1	34.7
18.5	1.52	2.2	78.7	20.4	33.3
7.3	0.75	6.1	86.1	7.4	12.0
8.5	0.76	6.1	85.8	7.6	12.2
7.8	0.75	6.1	85.6	7.6	12.2
6.9	0.75	6.1	85.1	7.6	12.3
8.9	0.75	6.1	85.8	7.4	12.0
21.3	1.51	6.6	84.4	24.5	40.0
22.3	1.50	6.6	83.2	24.8	40.0
32.4	1.52	6.6	82.9	25.4	41.0
29.0	1.52	6.6	82.7	25.6	41.2
19.7	1.53	6.6	83.8	25.4	41.2
10.7	0.75	12.4	80.8	9.8	15.7
10.5	0.76	12.4	79.9	10.3	16.6
9.5	0.75	12.4	79.3	10.0	16.2
9.4	0.75	12.4	79.0	10.1	16.5
9.3	0.75	12.4	77.5	10.4	17.2
41.9	1.53	12.0	78.7	32.4	52.5
29.3	1.51	12.0	78.8	31.7	51.3
29.5	1.53	12.0	78.7	32.4	52.5
42.1	1.53	12.0	77.0	33.3	54.2
26.4	1.52	12.0	79.2	31.8	51.4

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 12—Times for the center of Douglas-fir timbers to reach 133°F: experimental times, times estimated by multiple regression (MR), and the upper 99% confidence limit on the experimental time[a]

Exp. T_{133} (min)	Thickness (in.)	Wet-bulb depression (°F)	T_i (°F)	MR T_{133} (min)	99% T_{133} (min)
95	3.6	1.5	72.6	75	105
72	3.6	1.5	71.7	78	108
77	3.6	1.5	69.3	86	118
76	3.6	1.5	69.3	86	118
70	3.6	1.5	71.5	79	109
217	5.8	1.5	66.6	184	258
223	5.9	1.5	63.8	212	301
226	5.9	1.5	63.4	214	304
194	5.9	1.5	64.5	204	288
185	5.8	1.5	66.8	183	255
745	11.9	1.4	64.4	785	1,145
902	12.0	1.4	63.9	816	1,193
819	12.0	1.4	61.0	925	1,375
896	12.1	1.4	62.7	879	1,294
88	3.5	6.4	81.0	89	123
106	3.5	6.4	79.3	94	129
96	3.5	6.4	79.3	94	129
84	3.5	6.4	79.7	93	128
83	3.5	6.4	82.7	84	117
186	5.9	6.1	77.5	201	279
243	5.8	6.1	76.3	204	283
199	5.8	6.1	76.9	200	277
189	5.8	6.1	76.4	207	287
193	5.8	6.1	78.0	191	265
847	11.7	6.3	73.3	889	1,280
823	11.8	6.3	72.8	927	1,338
1,101	11.8	6.3	72.9	908	1,308
887	11.8	6.3	73.6	884	1,273
136	3.6	12.2	77.4	127	176
199	3.6	12.2	75.5	136	189
144	3.6	12.2	76.4	132	183
110	3.6	12.2	76.7	130	180
102	3.6	12.2	78.9	121	166
241	5.8	12.3	73.9	286	402
261	5.8	12.3	74.5	275	386
252	5.8	12.3	74.1	279	392
264	5.7	12.3	74.2	271	380
294	5.8	12.3	74.5	277	389
1,183	11.7	13.4	74.9	1,083	1,573
1,033	12.1	13.4	74.4	1,191	1,738
1,200	11.8	13.4	74.7	1,111	1,615
1,195	12.0	13.4	74.5	1,159	1,689

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 13—Summary of 99% upper confidence level of heating times (at 160°F) to 133°F for ponderosa pine boards estimated by multiple regression[a]

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

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 14—Summary of 99% upper confidence levels of heating times (at 160°F) to 133°F for ponderosa pine square timbers estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)								
		4 by 4	5 by 5	6 by 6	7 by 7	8 by 8	9 by 9	10 by 10	11 by 11	12 by 12
2	40	225	321	429	550	682	825	980	1,145	1,321
4	40	259	368	492	630	782	946	1,123	1,312	1,512
6	40	282	401	535	685	850	1,028	1,220	1,425	1,643
8	40	299	426	569	728	903	1,092	1,296	1,514	1,745
10	40	314	447	597	764	947	1,146	1,359	1,587	1,830
12	40	327	465	621	795	986	1,192	1,414	1,651	1,904
2	50	200	285	382	490	609	738	878	1,026	1,185
4	50	229	326	437	561	697	844	1,003	1,173	1,354
6	50	249	354	475	609	756	916	1,088	1,272	1,468
8	50	264	376	504	646	802	972	1,155	1,350	1,558
10	50	277	395	529	678	841	1,019	1,210	1,415	1,633
12	50	288	411	550	705	875	1,059	1,258	1,471	1,697
2	60	182	261	350	450	559	679	807	945	1,091
4	60	208	298	400	513	638	774	921	1,078	1245
6	60	226	323	433	557	692	839	998	1,168	1,349
8	60	240	343	460	590	734	890	1,058	1,238	1,430
10	60	251	359	482	618	769	932	1,108	1,297	1,497
12	60	261	373	501	643	799	969	1,151	1,347	1,555
2	70	169	243	326	420	523	634	755	884	1,022
4	70	193	277	372	479	596	723	860	1,008	1,164
6	70	210	300	403	518	645	783	932	1,091	1,260
8	70	222	318	427	549	684	830	987	1,156	1,335
10	70	233	333	448	575	716	868	1,033	1,210	1,398
12	70	242	346	465	598	743	902	1,073	1,256	1,451
2	80	160	229	308	397	494	600	715	837	968
4	80	182	261	351	452	563	683	814	953	1,102
6	80	197	282	380	489	609	739	880	1,031	1,192
8	80	209	299	403	518	645	783	932	1,092	1,262
10	80	219	313	421	542	675	819	975	1,143	1,321
12	80	227	325	438	563	701	851	1,013	1,186	1,371

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 15—Summary of 99% upper confidence levels of heating times (at 160°F) to 133°F for Douglas-fir boards estimated by multiple regression[a]

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

[a]°C = (°F – 32)/1.8; 1 in. = 25.4 mm.

Table 16—Summary of 99% upper confidence levels of heating times (at 160°F) to 133°F for Douglas-fir square timbers estimated by multiple regression[a]

Wet-bulb depression (°F)	Initial temperature (°F)	Heating time (min)									
		3.5 by 3.5	4 by 4	5 by 5	6 by 6	7 by 7	8 by 8	9 by 9	10 by 10	11 by 11	12 by 12
2	60	196	229	308	406	524	667	835	1,034	1,266	1,534
4	60	255	298	400	526	679	862	1,079	1,334	1,631	1,974
6	60	299	349	468	615	794	1,007	1,260	1,556	1,901	2,299
8	60	335	391	524	689	888	1,126	1,408	1,739	2,123	2,567
10	60	366	427	573	752	969	1,229	1,537	1,897	2,315	2,799
12	60	394	459	616	809	1,042	1,321	1,651	2,038	2,487	3,006
2	70	122	143	193	256	333	426	537	669	823	1,003
4	70	154	181	244	323	419	535	673	836	1,028	1,251
6	70	178	209	281	372	482	615	773	959	1,178	1,432
8	70	198	232	312	412	534	680	855	1,061	1,301	1,580
10	70	215	252	339	447	579	737	926	1,148	1,408	1,709
12	70	231	270	363	478	619	788	989	1,226	1,503	1,824
2	80	88	103	141	188	245	315	399	499	616	753
4	80	108	127	173	230	301	386	488	609	752	918
6	80	123	144	196	261	340	436	552	688	849	1,036
8	80	135	159	215	286	372	477	603	752	927	1,130
10	80	145	171	231	307	400	513	647	807	994	1,212
12	80	155	182	246	326	425	544	686	855	1,053	1,283

[a] °C = (°F – 32)/1.8; 1 in. = 25.4 mm.

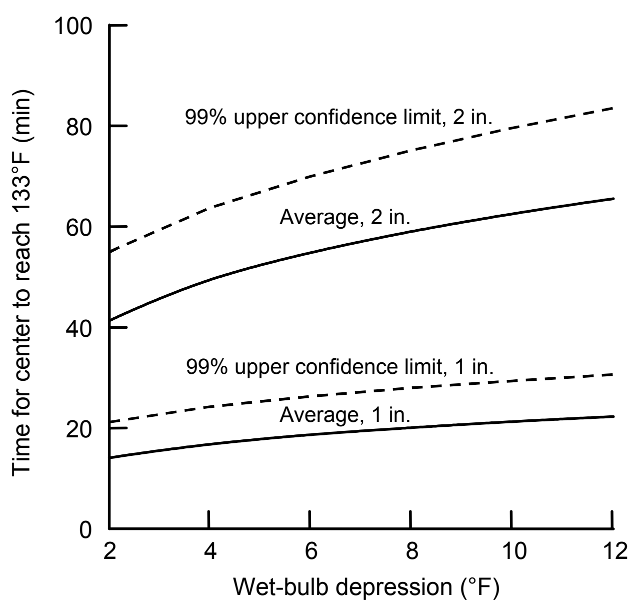

Figure 9—Dependence of average and upper 99% confidence limits of heating time for ponderosa pine boards at 60°F initial temperature (°C = (°F – 32)/1.8; 1 in. = 25.4 mm).

Appendix—Equations for Calculating Upper Confidence Levels of Heating Times

The general form of the equation for calculating the upper confidence level for heating time is

$$\exp(f(\ln(x), \ln(\text{wbd}), \ln(T_\text{i}), \alpha))$$

where x is thickness of boards or one cross-sectional dimension of timbers; wbd, wet-bulb depression in °F; T_i, initial temperature in °F; α, confidence level.

Ponderosa Pine Boards

$$f(\ln(x), \ln(\text{wbd}), \ln(T_\text{i}), \alpha) = 5.0390 + 1.5489 \ln(x) + 0.25739 \ln(\text{wbd}) - 0.62726 \ln(T_\text{i}) + t_{26} (V)^{0.5}$$

where t_{26} is the Student's t critical value for 26 degrees of freedom and confidence level $100(1 - \alpha)$. For 99% confidence level, $t_{26} = 2.479$.

$$V = 0.0080659 + 3.4245 + 0.012576 (\ln(x))^2 + 0.0016782 (\ln(\text{wbd}))^2 + 0.17411 (\ln(T_\text{i}))^2 - 2.0 (0.18580) \ln(x) - 2.0 (0.049441) \ln(\text{wbd}) - 2.0 (0.77169) \ln(T_\text{i}) + 2.0 (0.0026822) \ln(x) \ln(\text{wbd}) + 2.0 (0.041650) \ln(x) \ln(T_\text{i}) + 2.0 (0.01073) \ln(\text{wbd}) \ln(T_\text{i})$$

Ponderosa Pine Timbers

$$f(\ln(x), \ln(\text{wbd}), \ln(T_\text{i}), \alpha) = 4.5880 + 1.6105 \ln(x) + 0.20466 \ln(\text{wbd}) - 0.52056 \ln(T_\text{i}) + t_{38} (V)^{0.5}$$

where t_{38} is the Student's t critical value for 38 degrees of freedom and confidence level $100(1 - \alpha)$. For 99% confidence level, $t_{38} = 2.429$.

$$V = 0.021308 + 0.21943 + 0.0036715 (\ln(x))^2 + 0.00095297 (\ln(\text{wbd}))^2 + 0.011565 (\ln(T_\text{i}))^2 - 2.0 (0.018617) \ln(x) + 2.0 (0.0027247) \ln(\text{wbd}) - 2.0 (0.048852) \ln(T_\text{i}) - 2.0 (0.00021215) \ln(x) \ln(\text{wbd}) + 2.0 (0.0031414) \ln(x) \ln(T_\text{i}) - 2.0 (0.0010160) \ln(\text{wbd}) \ln(T_\text{i})$$

Douglas-Fir Boards

$$f(\ln(x), \ln(\text{wbd}), \ln(T_\text{i}), \alpha) = 8.0391 + 1.6341 \ln(x) + 0.26546 \ln(\text{wbd}) - 1.3553 \ln(T_\text{i}) + t_{26} (V)^{0.5}$$

where t_{26} is the Student's t critical value for 26 degrees of freedom and confidence level $100(1 - \alpha)$. For 99% confidence level, $t_{26} = 2.479$.

$$V = 0.033215 + 21.429 + 0.011386 (\ln(x))^2 + 0.0033429 (\ln(\text{wbd}))^2 + 1.1006 (\ln(T_\text{i}))^2 - 2.0 (0.22181) \ln(x) - 2.0 (0.037172) \ln(\text{wbd}) - 2.0 (4.8550) \ln(T_\text{i}) + 2.0 (0.0013054) \ln(x) \ln(\text{wbd}) + 2.0 (0.049734) \ln(x) \ln(T_\text{i}) + 2.0 (0.0070447) \ln(\text{wbd}) \ln(T_\text{i})$$

Douglas-Fir Timbers

$$f(\ln(x), \ln(\text{wbd}), \ln(T_\text{i}), \alpha) = 15.026 + 0.45495 (\ln(x))^2 + 0.33554 \ln(\text{wbd}) - 2.7028 \ln(T_\text{i}) + t_{38} (V)^{0.5}$$

where t_{38} is the Student's t critical value for 38 degrees of freedom and confidence level $100(1 - \alpha)$. For 99% confidence level, $t_{38} = 2.429$. Note the $(\ln(x))^2$ term instead of $\ln(x)$.

$$V = 0.015284 + 4.6343 + 0.00018312 (\ln(x))^4 + 0.0015549 (\ln(\text{wbd}))^2 + 0.25738 (\ln(T_\text{i}))^2 - 2.0 (0.018841) (\ln(x))^2 + 2.0 (0.070693) \ln(\text{wbd}) - 2.0 (1.0918) \ln(T_\text{i}) - 2.0 (0.00028182) (\ln(x))^2 \ln(\text{wbd}) + 2.0 (0.0043519) (\ln(x))^2 \ln(T_\text{i}) - 2.0 (0.016836) \ln(\text{wbd}) \ln(T_\text{i})$$

Note the $(\ln(x))^4$ and $(\ln(x))^2$ terms instead of $(\ln(x))^2$ and $\ln(x)$.