Heat sterilization times of red pine boards

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Abstract

The objective of this study was to determine the time required to heat the center of red pine boards to various temperatures for sterilization. This information will serve as a guideline for those concerned with heat sterilizing wood pallets and other wood shipping containers to meet heat treatment requirements for protection against invasive pests. Red pine boards, 4 inches (102 mm) wide and 1, 2, and 4 inches (25, 51, and 102 mm) thick, were heated in several combinations of heating temperature and relative humidity. The time required to heat the boards increased exponentially with target center temperature and linearly with board thickness. Heating was fastest in saturated steam; dry air required more heating time. Upper 99 percent confidence levels for heating times were determined to offer practical estimates of heating times that have a high probability of ensuring the center of each board reaches target temperature. Heat conduction theory was successful in calculating estimated heating times when the heating medium was saturated steam.

The Asian longhorned beetle, *Anoplophora glabripennis* (Motsch.), was introduced into the United States via wood packing material imported from Asia, resulting in significant tree mortality (APHIS 1996, 2000; Forest Service 2001a, 2001b). Heat sterilization of wood packing material is one way to prevent further beetle infestation. Two issues are involved in the application of heat sterilization. One is the temperature-time regime required to kill the beetle; the second is the time required to heat any wood species and geometrical configuration to the kill temperature.

A study was initiated to address these two heat sterilization issues. A surrogate beetle species, *Monochamus carolenesis*, was used in place of the Asian longhorned beetle because of its availability in the Midwest, its similarity in size and life cycle to the Asian longhorned beetle, and its willingness to attack red pine (*Pinus resinosa*). One objective of the study (to be reported in a separate paper) was to determine the effect of several holding (30 min.) temperatures on beetle larvae mortality. The second objective was to determine the time for several sizes of red pine boards to reach these holding temperatures. This paper describes the portion of the study and results related to the second objective.

Background

Several studies on heating times of wood have been conducted (Simpson 2001, 2002, 2003; Simpson and Wang 2003), and several general observations have been made. All of these studies showed, as would be expected, that the larger the size of the wood configuration the longer the heating time. They also showed that the nature of the heating medium has a significant effect on heating time. Use of "wet" heat, as accomplished by heating with live steam only, results in the minimum possible heating time. As the heating medium becomes progressively dryer, that is, as the relative humidity (RH) decreases from near 100 percent in the case of live steam, heating time becomes longer. This phenomenon occurs because as the heating medium becomes drier, the wood is drying at the same time it is heating. This evaporation of water from the wood cools the surface, which in turn reduces the temperature gradient between the surface and the center of the wood. Since this temperature gradient is the driving force for heat conduction, its reduction slows heat conduction. The lower the RH the greater the drying rate and degree of surface cooling, and therefore the longer the heating time. When

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the RH is low enough that the wet-bulb temperature in the heating/drying chamber is below the desired temperature inside the wood, heating time will be greatly extended, because the drying wood will not heat to a temperature above the wet-bulb temperature until it has dried to a low enough moisture content (MC) that the rate of evaporation has slowed substantially.

Another result of the previous studies is some degree of success in mathematically modeling the heating process to both increase our understanding of the importance of the various factors that affect heating time and to offer a way to calculate estimated heating times as a function of these factors. When heating in saturated steam, it is possible to successfully estimate heating times of round and rectangular wood cross sections using a relatively straightforward solution to heat flow equations (Simpson 2001). These equations do not apply when simultaneous drying occurs in dry heat. The surface cooling that occurs when heating in dry heat can be dealt with in a finite difference solution to the heat flow equations using a boundary condition that incorporates a time-dependent change in surface temperature (Simpson 2002, 2003). Multiple regression has also been successfully used to estimate heating times and to set statistical confidence levels that are useful in selecting heating times that have a high probability of being long enough to reach target center temperature (Simpson and Wang 2003).

Experimental methods

Red pine trees were obtained from the Chequamegon National Forest in Wisconsin. Three board thicknesses were studied: 1, 2, and 4 inches (25, 51, and 102 mm). (Note: thickness dimensions will hereafter be referred to in English units of measurement.) All boards were 4 feet (1.22 m) long and 4 inches (102 mm) wide. These sizes are typical of pallet parts and other wood packing material. The boards were maintained in the green condition, and representative boards were sampled for MC. The thickness of each board was measured. A total of 12 heating experiments were conducted; the conditions for each experiment are shown in **Table 1**. The target center temperatures were 133°F, 140°F, 158°F, and 176°F (56°C, 60°C, 70°C, and 80°C). (Note: target center temperatures will hereafter be referred to in °F.)

Table 1. — Experimental conditions for 12 heating time experiments on red pine.[a]

Heating temperature	Wet-bulb temperature	Relative humidity	Thickness	Replicates
- - - - (°F) - - - -		(%)	(in.)	(no.)
140	110	30.0	1.0	12
185	135	27.3	1.0	24
185	135	27.3	2.0	24
185	135	27.3	4.0	24
185	185	100	1.0	12
185	185	100	2.0	12
212	165	34.3	1.0	12
212	165	34.3	2.0	12
212	165	34.3	4.0	12

[a] $T_C = [T_F - 32]/1.8$.

The center temperature of 133°F is of particular interest because several current regulations aimed at preventing insect infestation require that temperature. The three higher center temperatures were requested by a cooperator in this study, USDA Animal and Plant Health Inspection Service (APHIS), to represent potential target temperatures when further research clarifies the kill temperatures of other insect and fungal pests. Several heating temperatures (140°F, 185°F, and 212°F [60°C, 85°C, and 100°C]) were included (**Table 1**) to cover a range of typical heating temperatures. Initial board center temperatures ranged from 72° to 80°F (22° to 27°C).

The heating experiments were conducted in a 1,500 board foot (3.5 m^3) experimental dry kiln. One thermocouple was inserted into the geometric center of each of the 12 boards per run by drilling a slightly oversized hole into the edge of the board. After the thermocouple was inserted, each hole was plugged with a round toothpick to minimize the influence of the outside kiln temperature on the measured center temperature. The boards were stickered so that all faces and edges were exposed to the kiln conditions. When all the thermocouples were in place, the kiln door (kiln already running and up to set point) was opened, the kiln truck holding the boards was quickly wheeled in, and the door was closed as quickly as possible to minimize recovery time of the kiln conditions. Center temperatures were read and processed by a computer every one to two minutes, depending on the test run.

Results

The average initial MC of the red pine boards was 90 percent. **Table 2** summarizes the results of the heating time experiments, listing the average times to reach the target center temperatures and the upper 99 percent confidence levels for those heating times. **Figures 1 to 3** show the relationship between time for the center of each board to reach target temperature and target center temperature for 1-, 2-, and 4-inch-thick boards at three heating conditions of dry- and wet-bulb temperatures – 185°F/185°F, 185°F/135°F, and 212°F/165°F. **Figures 4 and 5** show the relationship between the time for the center to reach target temperature and board thickness for two combinations of dry- and wet-bulb temperatures, 185°F/135°F and 212°F/165°F. **Figures 1 to 5** include regression equations for calculating estimates of heating times at intermediate levels of either target center temperature or board thickness. The upper 99 percent confidence levels were included to offer heating time estimates that were very close to ensure that the target center temperatures were attained.

Several observations can be made from **Table 2** and **Figures 1 to 5**. Heating time increased as the target center temperature increased and followed approximately exponential relationships (**Figs. 1 to 3**), which make it possible to calculate intermediate heating times relative to experimentally observed heating times. Another observation is that heating was fastest in saturated steam. The heating times at the 185°F/185°F dry/wet bulb conditions were the shortest. For example, at 185°F/185°F, 23.2 minutes were required for 2-inch-thick boards to reach a center temperature of 133°F. But at the higher dry-bulb temperature of 212°F, with a wet-bulb temperature of 165°F, heating time was 29.0

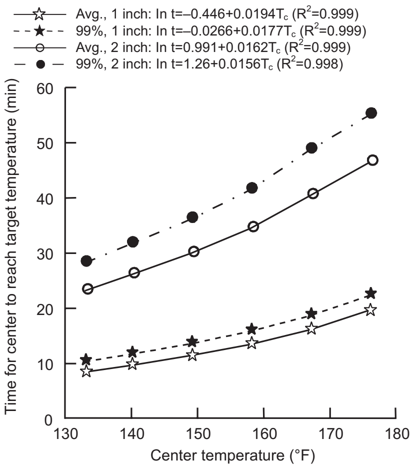

Figure 1. — Dependence of time for center of 1- by 4-inch (25- by 102-mm) and 2- by 4-inch (51- by 102-mm) red pine boards to reach target temperature at a dry-bulb temperature of 185°F (85°C) and a wet-bulb temperature of 185°F.

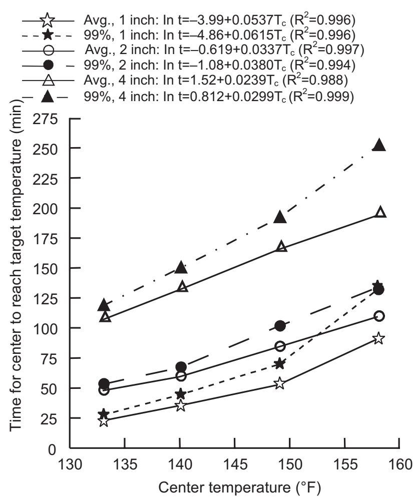

Figure 2. — Dependence of time for center of 1- by 4-inch (25- by 102-mm), 2- by 4-inch (51- by 102-mm), and 4- by 4-inch (102- by 102-mm) red pine boards to reach target temperature at a dry-bulb temperature of 185°F (85°C) and a wet-bulb temperature of 135°F (57°C).

Table 2. — Average and upper 99 percent confidence level times to heat 4-inch-wide red pine boards.

Temperature				Time		99% level	
Heating	Wet-bulb	Center	Thickness	Average	99% level	above average	MacClean estimate
(°F)			(in.)	(min.)		(%)	(min.)
140	110	133	1.0	660	907	37.4	NA
185	135	135	1.0	22.8	27.4	20.2	NA
			2.0	47.8	53.1	11.1	NA
			4.0	107	118	10.3	NA
		140	1.0	35.4	44.4	25.4	NA
			2.0	59.5	67.0	12.6	NA
			4.0	132	150	13.6	NA
		149	1.0	52.8	69.7	32.0	NA
			2.0	84.3	101	19.8	NA
			4.0	165	192	16.4	NA
		158	1.0	90.0	132	46.7	NA
			2.0	109	134	22.9	NA
			4.0	194	252	29.9	NA
185	185	133	1.0	8.5	10.3	21.2	7.4
			2.0	23.2	28.2	21.6	24.5
		140	1.0	9.7	11.7	20.6	8.4
			2.0	26.1	31.7	21.5	27.6
		149	1.0	11.4	13.6	19.3	10.1
			2.0	29.9	36.2	21.1	32.4
		158	1.0	13.5	15.9	17.8	12.1
			2.0	34.5	41.5	20.9	38.4
		167	1.0	16.1	18.7	16.1	15.1
			2.0	40.4	48.7	20.5	46.8
		176	1.0	19.7	22.3	13.2	20.1
			2.0	46.5	55.0	18.3	61.0
212	165	133	1.0	10.9	13.1	20.2	NA
			2.0	29.0	33.6	15.9	NA
			4.0	60.2	68.7	14.1	NA
		140	1.0	12.7	15.1	18.9	NA
			2.0	32.9	39.0	15.5	NA
			4.0	68.0	78.1	14.9	NA
		149	1.0	15.6	18.4	17.9	NA
			2.0	39.4	46.5	18.0	NA
			4.0	80.7	93.2	15.5	NA
		158	1.0	20.5	24.7	20.5	NA
			2.0	49.9	60.3	20.8	NA
			4.0	97.5	114	16.9	NA
		167	1.0	37.8	49.7	31.5	NA
			2.0	68.6	88.3	28.7	NA
			4.0	123	150	22.0	NA
		176	1.0	85.8	129	50.3	NA
			2.0	97.3	129	32.6	NA
			4.0	167	219	31.1	NA

minutes. At the same (185°F) dry-bulb temperature, but a lower wet-bulb temperature of only 135°F, heating time was even longer – 47.8 minutes. These observations illustrate the effect of surface cooling on heating time when heating is done in a dry environment where drying can occur during heating. The effect of surface cooling on heating time is discussed in more detail in Simpson (2002), where the effect of wet-bulb depressions ranging from small to large, not just large, was studied. Similarly, the time required to reach a center temperature of 133°F at the dry-bulb/wet-bulb combination of 140°F/110°F (660 min.) was much longer than any other heating conditions. This illustrates the consequences of using the combination of a low heating temperature and dry heat.

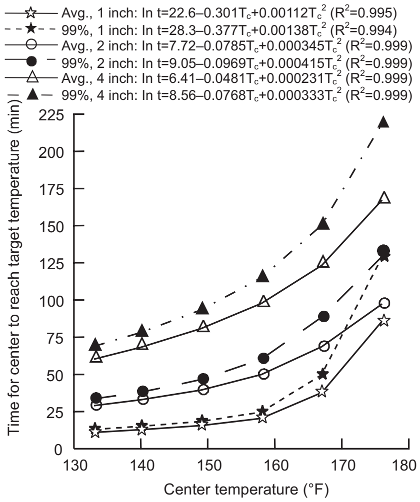

Figure 3. — Dependence of time for center of 1- by 4-inch (25- by 102-mm), 2- by 4-inch (51- by 102-mm), and 4- by 4-inch (102- by 102-mm) red pine boards to reach target temperature at a dry-bulb temperature of 212°F (100°C) and a wet-bulb temperature of 165°F (74°C).

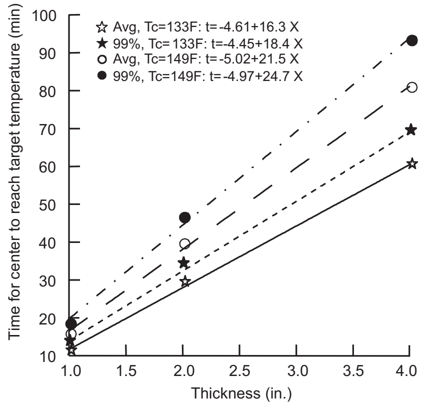

Figure 5. — Dependence of time for center of 4-inch- (102-mm-) wide red pine boards to reach target temperature at a dry-bulb temperature of 212°F (100°C) and a wet-bulb temperature of 165°F (74°C).

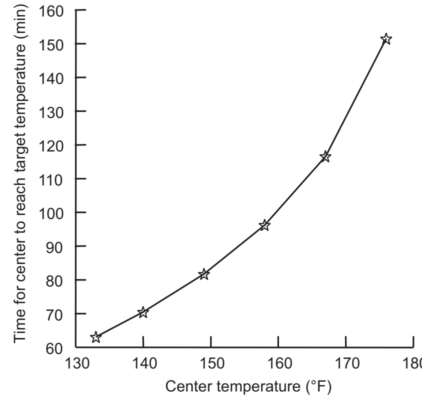

Figure 7. — Calculated estimates of heating times for 4- by 4-inch (102- by 102-mm) red pine boards at a heating and wet-bulb temperature of 185°F (85°C).

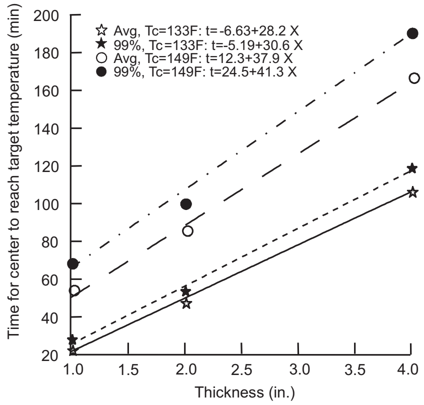

Figure 4. — Dependence of time for center of 4-inch- (102-mm-) wide red pine boards to reach target temperature at a dry-bulb temperature of 185°F (85°C) and a wet-bulb temperature of 135°F (57°C).

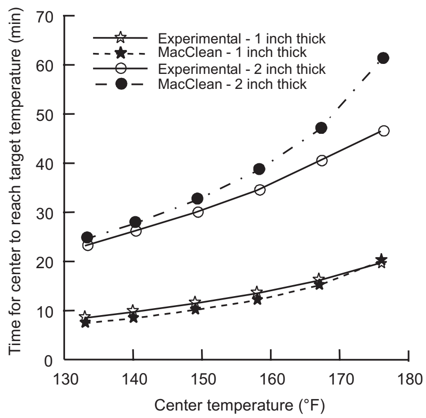

Figure 6. — Comparison of experimental heating times of 1- by 4-inch (25- by 102-mm) and 2- by 4-inch (51- by 102-mm) red pine boards with heating times estimated by MacClean's equations at a heating and wet-bulb temperature of 185°F (85°C)

Three factors combined to cause this slow heating. One was the small difference between the heating temperature of 140°F and the target center temperature of 133°F. Another was the substantial surface cooling caused by the low RH (30%, **Table 1**). Probably the most important factor was the relationship between the wet-bulb temperature of 110°F and the target center temperature of 133°F. The high rate of evaporation lowered the wet-bulb temperature of the wood to below 133°F, and therefore the wood could not reach 133°F until it had dried to a low enough MC to slow evaporation enough to allow the wet-bulb temperature to increase to that level. As a result, it may not be practical to heat-treat wood in conditions where the wet-bulb temperature in the heating chamber is below the target center temperature.

The effect of thickness on heating time is approximately linear (**Figs. 4 and 5**). Even though in heat conduction the heating time is expected to increase with the square of thickness (double thickness and increase heating time by four times), such a large effect was not seen. The reason is that as the 4-inch-wide boards in this study increased in thickness from 1 to 4 inches, heating from the edges became a more important factor in heat conduction. This relationship would not be the same if the boards were wider than 4 inches.

Figure 6 compares experimental heating times for 1- and 2-inch-thick boards heated at both dry- and wet-bulb temperatures of 185°F (85°C), with heating times calculated by the heat flow equations utilized by Simpson (2001). Calculated heating times were less than experimental times for 1-inch-thick boards and greater for 2-inch-thick boards, with average deviations between experimental and calculated times of about 10 percent for both thicknesses. There were no experimental data for 4-inch-thick boards at these heating conditions; **Figure 7** shows calculated estimates.

Summary and conclusions

Heating time experiments were conducted on red pine boards 4 inches wide and ranging from 1 to 4 inches thick, which are typical sizes for wood pallet parts and other wood packing components used in international trade where invasive pests are a problem. Several regimes of heating temperature and RH were included in the experiments to cover a range of heating capabilities that might be available to users engaged in heat sterilization. The time required to heat the experimental configurations to several target center temperatures increased exponentially with the target center temperature and linearly with board thickness. The upper 99 percent confidence levels for heating times were about 22 percent higher than the average heating times. When heating was done in a saturated steam environment, estimated heating times could be calculated within about 10 percent using equations based on heat conduction theory. Heating in saturated steam also resulted in heating times shorter than when the heating environment contained dryer air.

Literature cited

APHIS. 1996. New pest advisory group report. Sept. 25, 1996. USDA, Animal, Plant Protection and Quarantine. Riverdale, MD.

__________. 2000. Introductions and warehouse detections of longhorned beetles from cargo origination in China. July 14, 2000. USDA, Animal, Plant Protection and Quarantine. Riverdale, MD. www.aphis.usda.gov/lpa/issues/alb/albmap.html.

Forest Service. 2001a. Asian longhorned beetle infestation data, New York. USDA, Forest Serv., Northeastern Area. www.na.fs.fed.us/spfo/alb/data/nyinfest.htm.

___________. 2001b. Asian longhorned beetle infestation data, Illinois. USDA, Forest Service, Northeastern Area. www.na.fs.fed.us/spfo/alb/data/ilinfest.htm.

Simpson, W.T. 2003. Mechanism responsible for the effect of wet bulb depression on heat sterilization time of slash pine lumber. Accepted for publication in Wood and Fiber Sci.

__________. 2002. Effect of wet bulb depression on heat sterilization time of slash pine lumber. Res. Pap. FPL-RP-604. USDA, Forest Serv., Forest Prod. Lab., Madison, WI.

__________. 2001. Heating times for round and rectangular cross sections of wood in steam. Gen. Tech. Rept. FPL-GTR-130. USDA Forest Serv., Forest Prod. Lab., Madison, WI.

__________ and X. Wang. 2003. Effect of wet bulb depression on the heat sterilization time of ponderosa pine and Douglas fir boards and square timbers. Forest Products Laboratory Research Paper. In press.