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Effect of Wet Bulb Depression on Heat Sterilization Time of Slash Pine Lumber

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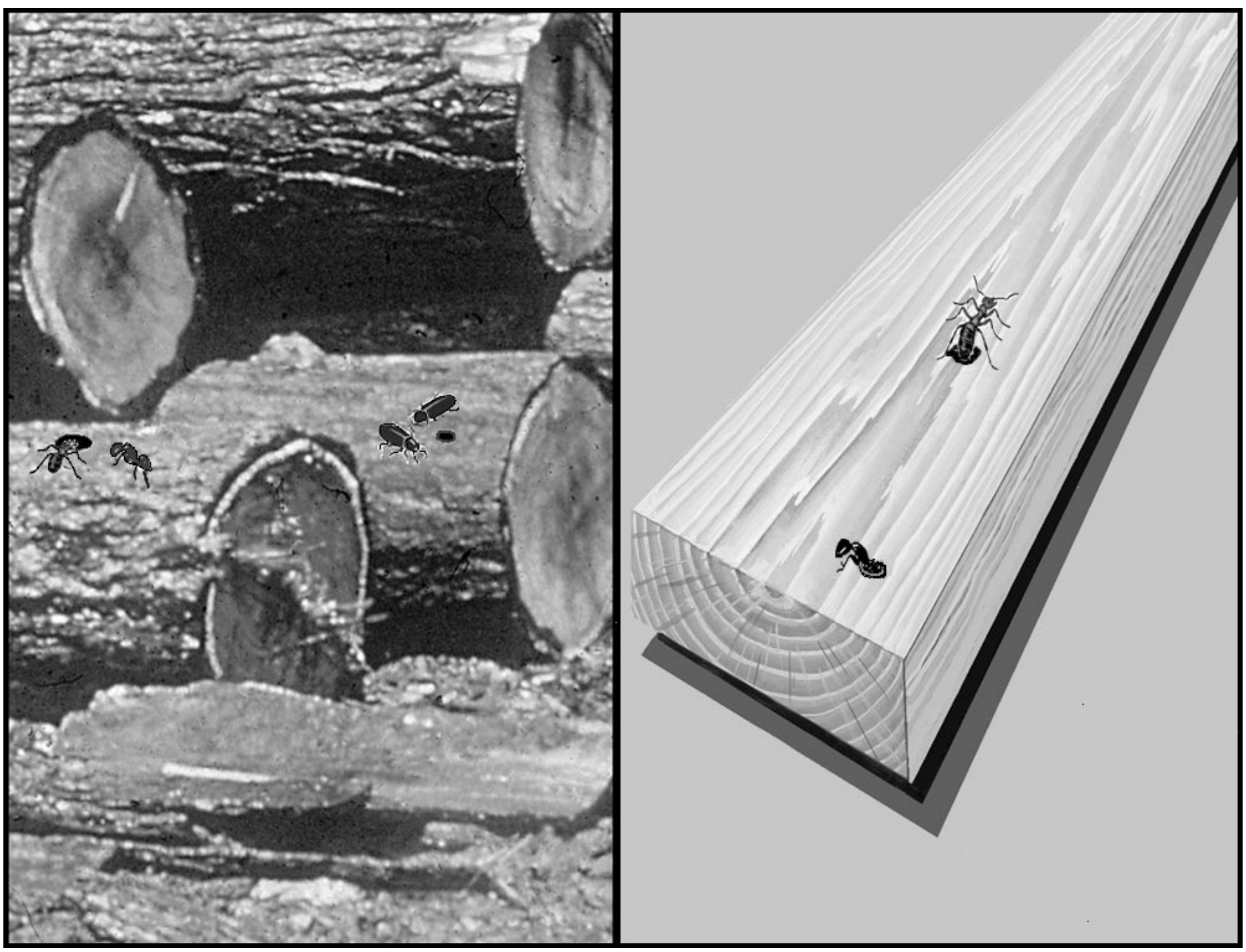

Abstract

For international trade, heat sterilization of wood products is often required to prevent the spread of insects and pathogens. Application of heat sterilization requires estimates of the time necessary to heat the center of the wood configuration to the temperature required to kill the insect or other pest. The nature of the heating medium was found to have a significant effect on heating time of slash pine lumber. The heating time increased exponentially with wet bulb depression. When the wet bulb temperature in the heating chamber was below the desired center temperature, heating times were extended far beyond the times when target center temperature was greater than the wet bulb temperature. This effect was less in air-dried lumber than in green lumber.

Keywords: heat sterilization, international trade, kiln drying

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Effect of Wet Bulb Depression on Heat Sterilization Time of Slash Pine Lumber

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Introduction

Heat sterilization of wood in various forms is currently receiving attention as a means of killing insects and pathogens to prevent their transfer from one region of the world to another as a side effect of international trade. One issue of concern is the time required to heat wood of various species and sizes to a temperature that will kill the insect or pathogen. Recent research (Simpson 2001) has shown that the heating medium has a large effect on heating time. In the nondrying medium of saturated steam, heating proceeds rapidly. But when the drying air is not saturated, the wood also dries during heat treatment. This drying causes the surface to cool below the air temperature, which in turn reduces the center-to-surface temperature gradient. The temperature gradient is the driving force for heat conduction; when it is reduced, heat conduction is slowed. We would expect that as drying conditions become more severe, the surface cooling will increase and the time required for the center to reach some temperature will also increase. Previous work showed heating times of green lumber in severe drying conditions were in some cases extended to more than five times that in a saturated steam environment. Heat sterilization therefore should ideally be done in saturated steam, which can sometimes be accomplished in a tight dry kiln by heating with just the steam spray. However, some dry kilns are not capable of maintaining saturated conditions, and furthermore, some specially constructed heat sterilization chambers may have no provision for introducing steam.

The purpose of this study was to further define the effect of simultaneous drying on heating times. The previous study (Simpson 2001) looked only at the two extremes—nondrying saturated steam and a very severe drying condition of 55°F (30.6°C) wet bulb depression (the difference between dry bulb temperature, that is, the air temperature, and wet bulb temperature)—but did not examine drying conditions of intermediate severity. This study includes the effect of several levels of wet bulb depression on heating times of slash pine lumber 1.0 and 1.8 in. thick (25 and 46 mm thick) heated at green moisture content and 1.0 in. (25 mm) thick heated at air-dried moisture content.

Experimental Methods

The slash pine lumber was obtained from a plantation in northern Florida and was received in the form of 8-ft- (2.4-m-) long nominal 2- by 4-in. (nominal 51- by 102-mm) lumber freshly sawn and undried. Some lumber for the study was used in the thickness as received (1.8 in. (46 mm)), and the rest was surfaced to 1.0 in. (25 mm) thick for the study. Board width averaged about 3.85 in. (98 mm).

The experimental heating runs were conducted in a 1,500 board foot (3.5 m^3) laboratory dry kiln. Most of them were run at a dry bulb temperature of 160°F (71°C). The target levels of wet bulb depression for both 1.0- and 1.8-in.- (25- and 46-mm-) thick lumber were 0, 5, 10, 15, 20, 30, and 50°F (0, 2.8, 5.6, 8.3, 11.1, 16.7, and 27.8°C), with corresponding equilibrium moisture content levels of +20%, 15.2%, 11.5%, 9.4%, 7.9%, 5.8%, and 3.2%. Because there was an excess of experimental material, several additional heating runs were conducted. With the 1.8-in.- (46-mm-) thick lumber, we missed some target wet bulb depressions by an undesirably wide margin; so two additional runs were conducted to fill in the large gaps between depression levels. Because high temperature dry kilns are common in the Southern Pine lumber industry, we also included several heating runs at a target dry bulb temperature of 240°F (116°C). For the 1.0-in- (25-mm-) thick lumber, we included target wet bulb depressions of 60°F (15.6°C) and 110°F (43.3°C), resulting in target wet bulb temperatures of 180°F (82.2°C) and 130°F (54.4°C). For the 1.8-in.- (46-mm-) thick lumber, the target wet bulb depression was 60°F (15.6°C). Air velocity was about 600 ft/min (3 m/s). All these tests were conducted at green moisture contents. Because of the anticipated effect that surface cooling during drying would extend heating times, the question arose of whether or not heating times would also be extended if the drying during heating were reduced. With that question in mind, we air-dried enough of the 1.0-in.- (25-mm-) thick boards before heat treatment for six levels of wet bulb depression. Table 1 summarizes the experimental conditions.

Table 1—Experimental heating conditions used in study. Temperatures listed are target temperatures and differ slightly from actual temperatures attained

1.0 in. (25 mm) thick		1.8 in. (46 mm) thick	
Heating temperature °F (°C)	Target wet bulb depression °F (°C)	Heating temperature °F (°C)	Target wet bulb depression °F (°C)
Heated at green moisture content			
160 (71)	0	160 (71)	0
	5 (2.8)		5 (2.8)
	10 (5.6)		10 (5.6)
	15 (8.3)		15 (8.3)
	20 (11.1)		20 (11.1)
	30 (16.7)		30 (16.7)
	50 (27.8)		50 (27.8)
240 (116)	60 (33.3)		—[a]
	110 (61.1)	240 (116)	60 (33.3)
Heated at air-dried moisture content			
160 (71)	0		
	10 (5.6)		
	15 (8.3)		
	20 (11.1)		
	30 (16.7)		
	50 (27.8)		

[a]Two additional runs at 160°F (70°C) were included with excess experimental material. Target wet bulb depressions were 15°F (8.3°C) and 20°F (11.1°C). See Table 2 for actual temperatures.

The center temperature of interest was 133°F (56°C) because at the time of this study, import–export regulations required that temperature to be reached and held for 30 min.

The choice of experimental wet bulb temperatures brackets this required center temperature, and the results will show that the relationship between the wet bulb temperature and the required center temperature has a pronounced effect on heating time.

Each heating run included 33 boards arranged in three layers of 11 boards each. Temperature measurements were made on the center nine boards in the center layer. The layer above and the layer below were present so that the study boards were flanked by wet boards and thus more closely simulated boards in a large kiln filled with lumber.

The lumber was stacked on a kiln truck outside the kiln, which was already running at the target conditions, and thermocouples were inserted into the nine study boards. Each of these nine boards was fitted with two thermocouples, one inserted to the center and one placed on the surface (Fig. 1a and b). The center thermocouple was inserted in a slightly oversized hole drilled into the edge of the board, and the hole was plugged with a round toothpick to minimize the influence of the outside kiln temperature on the measured center temperature. The surface thermocouples were held tightly to the board surfaces with plastic-headed (nonconducting) push pins and were brought into even closer contact

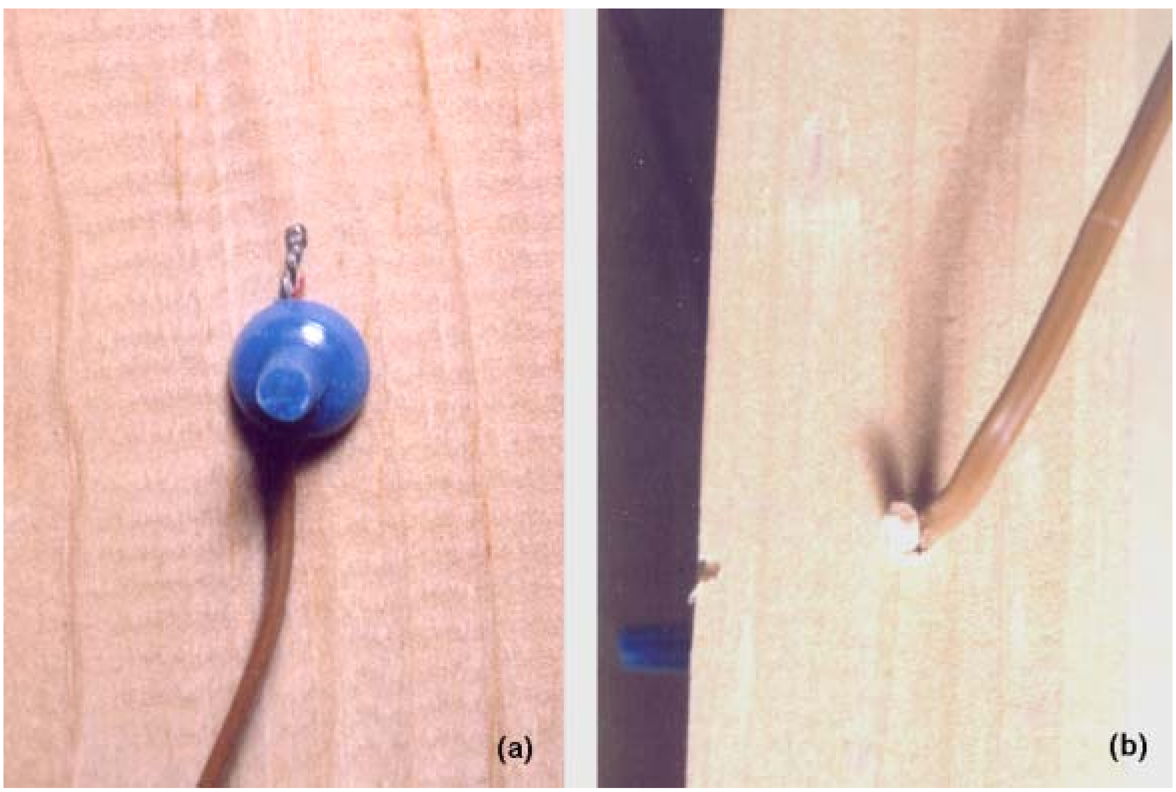

Figure 1—Thermocouples placed (a) on the surface and (b) in the center of board.

with the surface by pressing down gently on the thermocouple junction. The nine boards were stacked edge-to-edge with the surface thermocouple on the underside of the board.

With all thermocouples in place, the kiln door was opened, the kiln truck wheeled in, and the door closed as quickly as possible to minimize recovery time of the desired kiln conditions. Because of this required recovery time and the inherent difficulty of attaining precise control of kiln conditions (especially in a kiln loaded to only a small fraction of its capacity), the exact target wet and dry bulb temperatures were not always attained to a high degree of precision. However, they were attained to a level fully sufficient to satisfy the objectives of the study. Both center and surface temperatures were read to a computer file at intervals ranging from 0.5 to 2 min, depending on the expected rate of temperature rise. Runs were terminated after the last of the nine center temperatures reached 133°F (56°C). Each of the nine boards was weighed before and after heat treatment and then ovendried for moisture content determination.

Results and Discussion

As the wet bulb depression increased during heating, the rate of drying was expected to increase. One consequence of the increased drying rate was cooling of the surface below the heating temperature of 160°F (71°C). This cooling is shown in Figure 2 for 1.0-in.- (25-mm-) thick boards heated at green moisture content, in Figure 3 for 1.8-in.- (46-mm-) thick boards heated at green moisture content, and in Figure 4 for 1.0-in.- (25-mm-) thick boards heated at air-dried moisture content. In Figures 2 to 4, the average surface temperature of the nine boards in each heating run is plotted against wet bulb depression at several times during heating. All figures clearly show that as wet bulb depression increased, surface temperature decreased. For example, with 1.0-in.- (25-mm-) thick boards heated at green moisture content (Fig. 2), surface temperature was about 157°F (69.4°C) after 20 min when the average wet bulb depression during the run was 3.5°F (1.9°C). When wet bulb depression was 49°F (27.2°C), the surface temperature after 20 min was only about 112°F (44.4°C), indicating surface cooling due to the evaporation of water from the surface during drying. Figure 4 shows that even after 1.0-in.- (25-mm-) thick boards were air-dried to approximately 15% moisture content, surface cooling was still taking place, although as expected, not as much as when the boards were heated at green moisture contents. Even though the air-dried boards were at 15% moisture content, the equilibrium moisture content in the kiln was below that level (except for the minimum wet bulb depression level; Table 2) and evaporation from the surface could still occur.

The results of the heating time experiments are summarized in Table 2, and the effect of wet bulb depression on the time required to heat the center of the boards to 133°F (56°C) is shown in Figure 5 for boards heated at green moisture

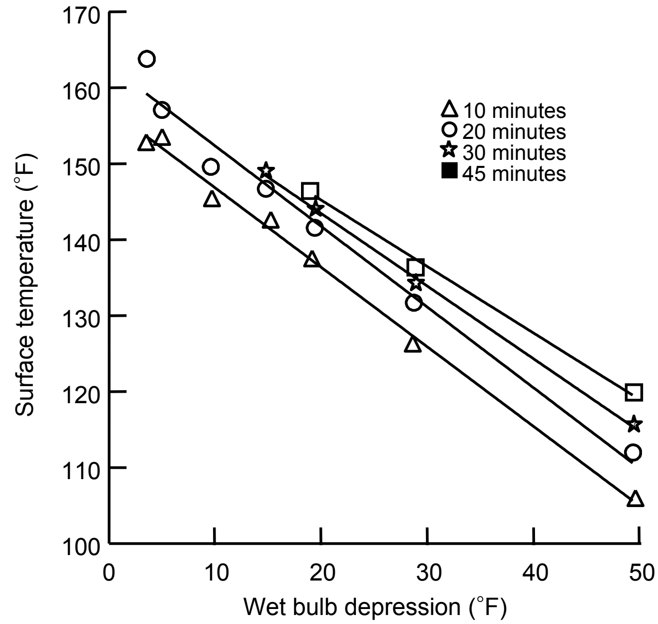

Figure 2—Dependence of surface temperature on wet bulb depression at several times during the heating of green 1.0-in.- (25-mm-) thick slash pine at 160°F (71°C) dry bulb temperature (°C = (°F – 32)/1.8).

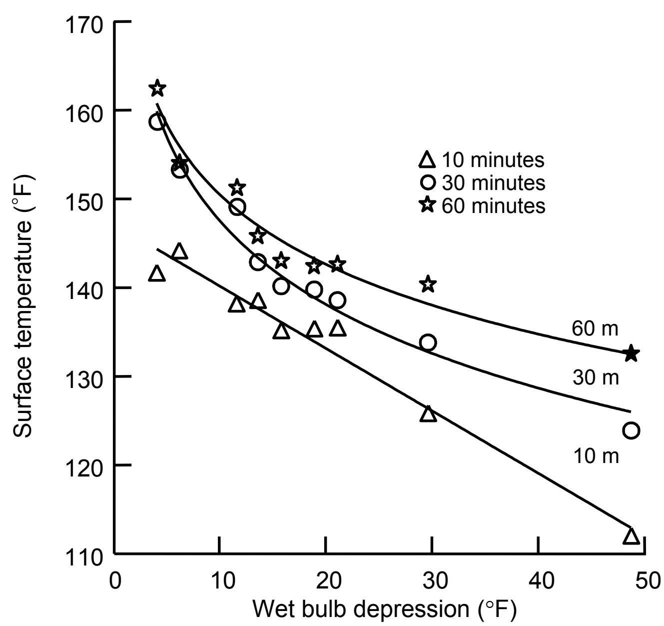

Figure 3—Dependence of surface temperature on wet bulb depression at several times during the heating of green 1.8-in.- (46-mm-) thick slash pine at 160°F (71°C) dry bulb temperature (°C = (°F – 32)/1.8).

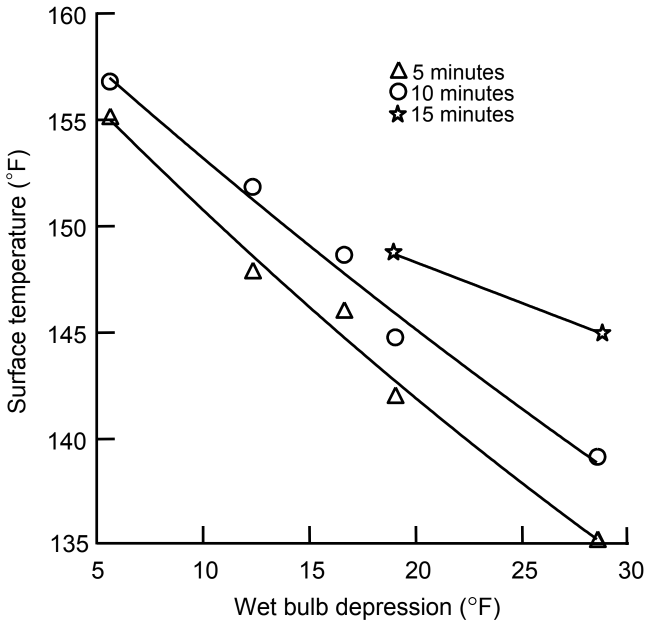

Figure 4—Dependence of surface temperature on wet bulb depression at several times during the heating of air-dried 1.0-in.- (25-mm-) thick slash pine at 160°F (71°C) dry bulb temperature (°C = (°F – 32)/1.8).

content and in Figure 6 for boards heated at air-dried moisture content. It is clear that as wet bulb depression increased, heating time also increased. For 1-in.- (25-mm-) thick boards heated at green moisture content, with a dry bulb temperature of 160°F (71°C), heating time increased from about 15 min at a wet bulb depression of 3.5°F (1.9°C) to 438 min at a wet bulb depression of 49.2°F (27.3°C), a factor of 29. For 1.8-in.- (46-mm-) thick boards heated at green moisture content, heating time increased from 38 min at a wet bulb depression of 4.0°F (2.2°C) to 198 min at a wet bulb depression of 48.6°F (27.0°C), a factor of 5.2. For 1.0-in.- (25-mm-) thick boards heated at 160°F (71°C) at air-dried moisture content, heating time increased from 8.7 to 23 min, a factor of only 2.6.

As Figure 5 shows, the increase in heating time with increase in wet bulb depression is relatively small at the lower values of wet bulb depression. But at the larger values of wet bulb depression, the increase is quite large and follows an exponential relationship. The point at which the heating time begins to increase sharply with wet bulb depression is when the wet bulb temperature in the kiln is about equal to the desired center temperature. In the heating runs listed in Table 2, the runs where the wet bulb temperature was below 133°F (56°C) (wet bulb temperatures targeted for either 110°F or 130°F) (43.4°C or 54.5°C) showed sharply longer heating times than runs where the wet bulb temperature was greater than 133°F (56°C).

Table 2—Results of heating time experiments with 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine heated at target temperatures of 160°F (71°C) and 240°F (116°C)[a]

Wet bulb depression (°F)	Average dry bulb temp. (°F)	Average wet bulb temp. (°F)	Average green moisture content (%)	Average moisture content after heating (%)	Average time for center to reach 133°F (min)
Heated at green moisture contents					
1.0 in. (25 mm) thick					
3.5	160.3	156.8	111	109	15.1
5.0	158.9	153.9	109	111	15.4
9.5	158.4	148.9	116	114	18.7
14.7	159.6	144.9	120	117	20.9
19.3	160.0	140.7	109	106	26.2
28.6	159.8	131.2	106	75	109
49.2	160.0	110.8	106	34	438
68.5	241.2	172.7	113	110	9.9
105.5	238.7	132.6	118	95	48.0
1.8 in. (46 mm) thick					
4.0	160.6	156.6	100	98	38
6.1	159.7	153.6	112	110	43
11.5	159.0	147.5	90	90	47
13.5	159.2	145.7	93	93	52
15.7	159.7	144.0	81	79	57
18.8	159.3	140.5	88	84	60
21.0	161.4	140.4	80	79	64
29.5	161.0	131.5	68	62	102
48.6	160.1	111.5	76	57	198
57.4	232.7	175.3	109	104	25
Heated at air-dried moisture contents					
1.0 in. (25 mm) thick					
5.6	157.4	151.8	15.3	15.3[b]	8.7
12.3	158.6	146.3	14.4	10.9[b]	10.2
16.6	159.1	142.5	15.4	9.3[b]	11.3
19.0	157.3	138.2	15.2	8.6[b]	14.2
28.5	158.4	129.8	15.6	6.6[b]	18.1
48.8	160.5	111.6	15.5	3.6[b]	23.0

[a]°C = (°F – 32)/1.8.
[b]Equilibrium moisture content conditions in kiln.

Figure 7 illustrates the progression of surface and center temperatures when the wet bulb temperature is less than the desired center temperature (heated at green moisture content). In this example, dry bulb temperature was 160°F (71°C), wet bulb depression was 49.2°F (27.3°C), wet bulb temperature was 110.8°F (43.8°C), and 1.0-in.- (25-mm-) thick boards were used. The center temperature rose to the wet bulb temperature relatively quickly (about 50 min), then gradually increased, but even after 800 min, it was only about 140°F (60°C). The surface temperature rose relatively quickly to about 125°F (51.7°C) and then gradually rose to

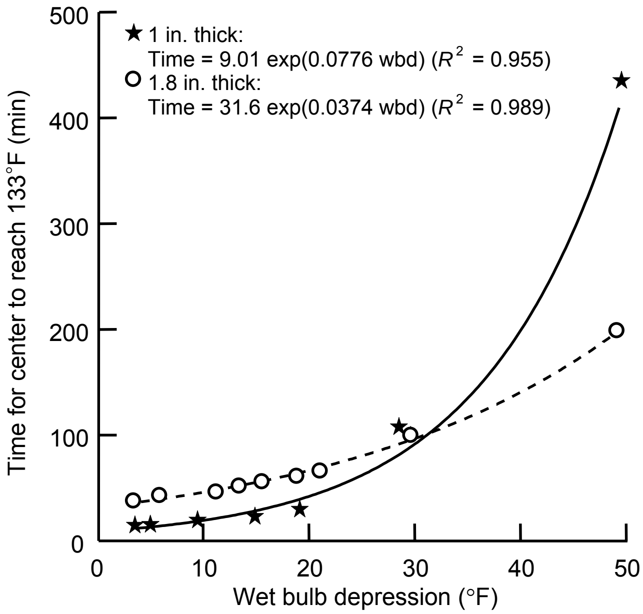

Figure 5—Dependence of the time required for the center of green slash pine boards to reach 133°F (56°C) on wet bulb depression (wbd) when heated at 160°F (71°C) dry bulb temperature (°C = (°F – 32)/1.8).

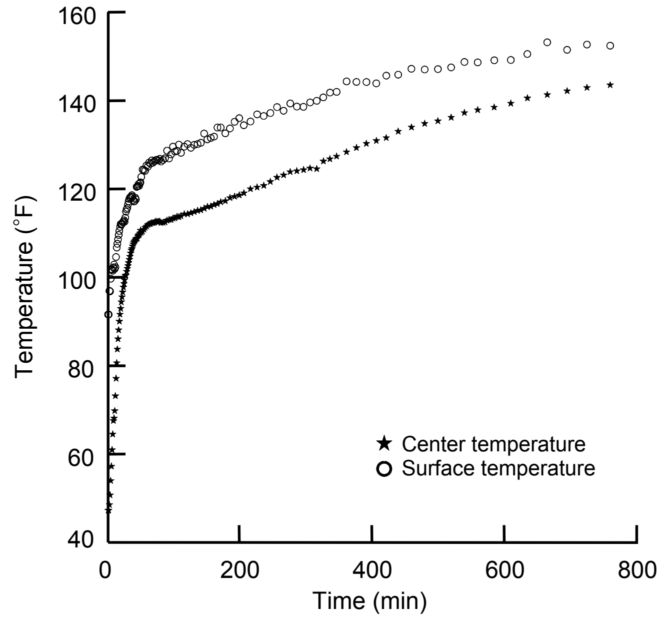

Figure 7—Increase in surface and center temperatures when green 1.0-in.- (25-mm-) thick slash pine boards were heated at 160°F (71°C) dry bulb temperature with a 49.2°F (27.3°C) wet bulb depression (°C = (°F – 32)/1.8).

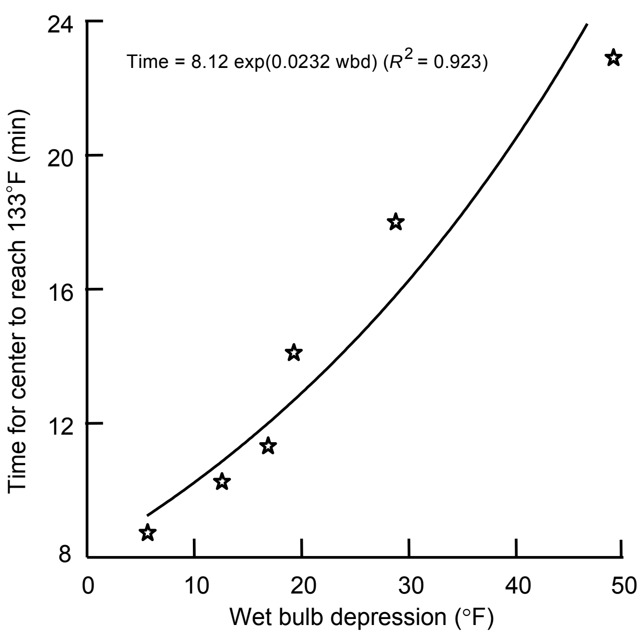

Figure 6—Dependence of the time required for the center of air-dried slash pine boards to reach 133°F (56°C) on wet bulb depression (wbd) when heated at 160°F (71°C) dry bulb temperature (°C = (°F – 32)/1.8).

about 150°F (65.6°C) after 800 min. In contrast, when the wet bulb depression was only 3.5°F (1.9°C), the center reached 110.8°F (43.8°C) in about 11 min and 133°F (56°C) in about 15 min. In addition, the surface temperature reached 160°F (71°C) in about 12 min.

The results suggest that there are two causes that extend heating times beyond those for heating in a saturated steam environment. The first is the surface cooling effect that results from the increased drying when wet bulb depression is increased. This reduces the center-to-surface temperature gradient, and because this temperature gradient is the driving force for heat conduction, heating time increases. Secondly, if the wet bulb temperature is less than the desired center temperature, the heating time may be increased because of evaporative cooling in the center during drying. Heating time to 133°F (56°C) (at 160°F (71°C) dry bulb temperature) increased by a factor of 29 from a wet bulb depression of 3.5°F (1.9°C) to a wet bulb depression of 49.2°F (27.3°C) for green 1.0-in- (25-mm-) thick boards. But the increase between those two extremes was only a factor of 5.2 for the 1.8-in.- (46-mm-) thick boards. The reason for this is that as thickness increases, internal transfer mechanisms play a more important role compared with surface heat and mass transfer mechanisms (Fleischer 1953).

The moisture content data in Table 2 show the extent of drying when the wet bulb depression is large. When the green 1.0-in.- (25-mm-) thick boards were heated with wet bulb temperatures above 133°F (56°C), there was little decrease in moisture content during heating. Moisture contents were reduced by only a few percent during drying. In contrast, with the two wet bulb temperatures below 133°F (56°C), moisture contents were reduced from slightly more than 100% to 75% and 34% for wet bulb temperatures of 131.2°F (55.1°C) and 110.8°F (43.8°C), respectively.

The results in Table 2 also show that heating times were extended at a wet bulb temperature below 133°F (56°C) even when the heating temperature was 240°F (116°C). With green 1.0-in.- (25-mm-) thick boards and a wet bulb temperature of 172.7°F (78.2°C), heating time was 9.9 min. But when the wet bulb temperature was 132.6°F (56°C), the heating time was 48 min.

Concluding Remarks

This study investigated the effect of wet bulb depression at constant dry bulb temperature on the time required to heat the center of green 1.0- and 1.8-in.- (25- and 46-mm-) thick slash pine boards to 133°F (56°C). The expectation was that as wet bulb depression increased, drying rate would increase and result in a cooling effect that would slow heating relative to conditions where little or no drying occurred. Measurements showed that surface cooling increased as wet bulb depression increased. The time required for the center to reach 133°F (56°C) increased exponentially with wet bulb depression at a constant dry bulb temperature of 160°F (71°C). The increase was greater for the 1.0-in.- (25-mm-) thick boards than for the 1.8-in.- (46-mm-) thick boards. When the wet bulb temperature was less than the desired center temperature, the time required for the center to reach the desired temperature was greatly extended far beyond the time required when the wet bulb temperature was greater than the desired center temperature. Boards that had been air-dried to 15% moisture content before heating also showed these effects but to a lesser degree than boards heated at green moisture content.

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