

Steam and Vacuum Treatment of Large Timber in Solid Wood Skids

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Forest pests are commonly transported along with wood packaging materials. Ports in the United States continue to intercept invasive pests in cross-section timbers that are packaged with steel or heavy consignments. The large cross-section timbers present a greater risk because the fumigation and kiln treatments that are currently used in treating wood packaging materials are not effective on large cross-section materials. The objective of this study is to determine the effectiveness of steam and vacuum for heat-treating large cross-section timbers in wood skids and crates, according to the heat-treating requirements of ISPM 15 (IPPC 2013) specifying 56 °C for a minimum of 30 minutes throughout the profile of the wood. Three wood species of large dimension timbers were tested. The timbers were partially air-dried to moisture contents for poplar at 39.1% MC, pine 38.3% MC, and oak 60.6% MC. Larvae of the pinewood sawyer beetles (*Monochamus* spp.) were used as a representative surrogate for invasive cerambycids. The initial vacuum pressure was 100 mm Hg and the test chamber temperature was set for 90 °C. The treatment cycle was continued until the core temperature of the large timber reached the required 56 °C for 30 min. To measure the temperature profiles within the timbers, thermocouples were placed at various locations. After each test, the larvae were recovered and assessed for mortality.

Keywords: Steam treatment; Vacuum treatment format; Larvae; Wood packaging

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INTRODUCTION

Heat has been used to kill insects, fungi, and nematodes that dwell in wood (Allen *et al.* 2017). Asians have used this method for thousands of years. There are early publications about the use of heat treatment to kill insects and fungi (Craighead 1921; Snyder 1923). Heat sterilization of wood, in various forms, is currently used for killing insects or pathogens to prevent their transfer from one geographical region to another (Allen *et al.* 2017). One important concern is the amount of time required to heat wood of various cross-sectional sizes to a required temperature.

Treatments for logs and other wood commodities were reviewed by the US Forest Service in the early 1990s as the international movement of wood products was seen as a major risk to the importation of exotic forest pests (USDA 1991). Heat treatment is an effective method for killing pests that affect the growth of specific trees. This paper reviews the history of heat as a wood treatment, the scientific basis for its effect on wood pests (including insects, fungi, nematodes, and bacteria), the industrial processes by which

wood is heat-treated, and how heat treatment can be incorporated into phytosanitary measures to control forest pests. Heat can be from steam, hot air, water, or generated using microwave energy.

Wood packaging has been recognized as a pathway for invasive forest pests (Allen and Humble 2002). The Asian long-horned beetle, *Anoplophora glabripennis* Motschulsky, migrated into North America in infested packaging materials (Liebhold *et al.* 1995). A preshipment treatment of 56 °C for 30 min has been adopted by many countries as a method of controlling the migration (Allen *et al.* 2017).

The ports of Baltimore and Philadelphia continue to intercept invasive pests in heavy timbers of solid wood packaging material (SWPM) used to ship steel or heavy consignments. Large-size timbers (20- to 30-cm-thick) are common and used in heavy-duty skids and crates. These large timbers present a greater risk because the fumigation and heat treatment currently applied to SWPM are not effective or practical on such sizes of wood material.

It is likely that the current Asian long-horned beetle infestation in Bethel, Ohio was introduced through heavy skids used to ship tractor parts that were shipped to a local business in the core area (Haack 2006). Certain dunnage, because of its irregular and large shapes, also remains a suspected carrier of invasive pests.

Research has shown that pallets with wood parts of smaller dimensions can be heat-treated to ISPM 15 (IPPC 2013) requirements of 56/30 with steam and vacuum, in less than half the time, and using 30% less energy than conventional hot air oven systems (Chen *et al.* 2012). Additionally, research has also shown that this process may be very effective for heat-treating wood commodities with larger cross-sections, such as hardwood firewood and hardwood veneer logs (Chen *et al.* 2017). This process, which incorporates the latent heat of water phase transition, the exothermic reaction of condensation, and a vacuum to distribute the heat, may effectively treat large timber SWPM in skids and crates without adversely affecting the material quality and skid's structural integrity.

This study aims to determine the effectiveness of steam and vacuum for phytosanitary heat-treating large cross-section timbers (20.32 cm × 20.32 cm × 182.9 cm) in wood skids and crates, according to the heat-treating requirements of ISPM 15 (IPPC 2013).

EXPERIMENTAL

Materials

Large timber

Three wood species groups were tested to represent a range of wood densities and species currently used in skids. They are mixed oak (*Quercus spp.*), yellow-poplar (*Liriodendron tulipifera*), and southern yellow pine (*Pinus spp.*). Timbers were acquired from the Blue Ridge Timberwrights in Virginia. These timbers were partially air-dried as is typical of large timbers used in heavy skids. The moisture contents are 39.1% for poplar, 38.3% for pine, and 60.6% for mixed oak. Figure 1 is a photograph of the 20.32 cm × 20.32 cm × 182.9 cm (8 in × 8 in × 6 ft) long timbers used in tested wood skids. The 10.16 cm × 10.16 cm × 121.9 cm (4 in × 4 in × 4 ft) long deck timbers of the same wood species are shown in Fig. 1.

Large skids

Skids were manufactured according to the base design in ASTM D6039 (2011) for type V, style B crates. Figure 2 shows this basic design with the dimensions and test skids made ready for treatment. The parts were connected with lag screws in accordance with ASTM D6039 (2011).



Fig. 1. The 20.32 cm × 20.32 cm large timbers (A) and the 10.16 cm × 10.16 cm deck timbers (B) of southern pine, yellow-poplar, and oak spp.

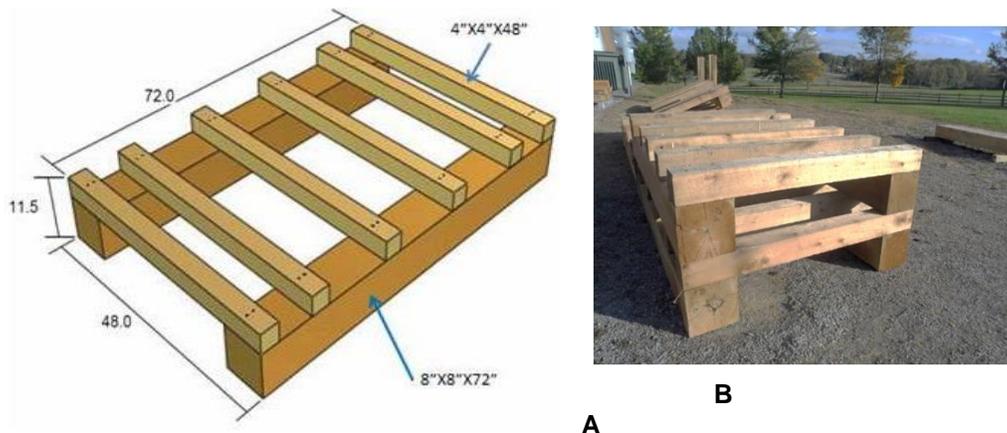


Fig. 2. Schematic diagram of the skids dimension (A) and skids (B) used in the test

Pine sawyer beetles

Pine sawyer beetles growing in the eastern United States were inoculated into the large wood at the locations shown in Fig. 3. The sawyer beetles (*Monochamus spp.*) were selected because these long horned beetles of family Cerambycidae inhabit living trees and have life cycles similar to the Asian long horned beetle. The larvae of the last stage (Fig. 6) weighed between 500 mg to 1.2 g.

Test equipment

Figure 4 shows the 1.52 × 1.52 × 2.44 m³ long vacuum steam chamber manufactured by Vacutherm INC, Vermont. The chamber is equipped with a 5.22 KW vacuum pump with a 1.39 m³/min (56 CFM) exhaust capacity and a 100 KW electric steam boiler. The conditions in the chamber were controlled semi-automatically with temperature

controlled by regulating the steam injection. The system also included a data acquisition system for the real time recording of temperatures from eight separate sensors.

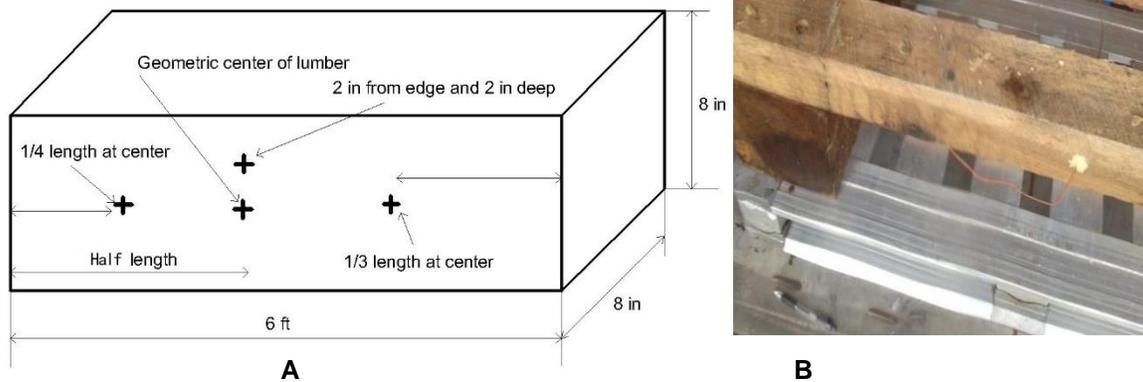


Fig. 3. The locations in the large timber of larvae (A) and temperature probes (B)



Fig. 4. Vacuum steam chamber used in the tests

Experimental design

Three skids were treated at a time to simulate the commercial treatment of such structures. Each wood species skid was replicated three times. Therefore, nine skids of each species were treated. Additionally, there was one control of large timbers for each species that was not treated.

Methods

Test conditions and test procedures

Eight larvae were placed in two large timbers and one in a deck board in each skid. Four larvae were placed in the large control timber and one in the small timber. Three skids were loaded into the chamber. Door was closed and vacuum pump was turned on to draw the air.

The initial vacuum pressure was 100 mm Hg and the test chamber temperature was set to 90 °C. The treatment cycle continued until the core temperature of the largest timber reached the required 56 °C for 30 min. Then, the vacuum was relieved and door was open. The skids were unloaded. Larvae were retrieved, and the mortality of larvae was checked. Skids were inspected and disassembled. The moisture sections were cut from the timbers, and MCs were measured.

Measuring temperatures

Thermocouples (K-type, Omega Engineering, INC, Connecticut) were placed in the large timbers as shown in Fig. 3. One, randomly selected 4 in × 4 in (10.1 cm × 10.2 cm) piece of the skid was probed at the geometric center to monitor the core temperatures. This was done to determine the extent of the treatment to smaller wood pieces and whether this would degrade these pieces.

The holes with a diameter of 0.48 cm (3/16 inches) were plugged with plumber putty and sealed after thermocouples were placed at the locations shown (Fig. 3). Real time temperature profiles were recorded, and cycle times were determined.

Inoculation with live pests

The larvae of the pinewood sawyer beetles (*Monochamus* spp.) were used as simulants of the invasive long-horned beetle (Cerambycidae). The larvae were collected from the infested pine trees (Fig. 5). After they were removed from the trees, the larvae were placed on an artificial agar diet prior to their use to keep them healthy (Fig. 5). The larvae were transported in plastic containers to Blacksburg, Virginia. During the tests, the larvae were placed at the same locations as the temperature probes shown in Fig. 3. There were three large timbers during each test. One was used for measuring temperature and two for placing the larvae. It was assured that the temperature to which the larvae were exposed was the same as the temperature measured at the corresponding location in a different skid.



Fig. 5. Pine sawyer beetles used as simulant in the tests (A) and were raised on a diet (B)



Fig. 6. The 0.48 cm (3/8 inches) hole was drilled (A) and tightly plugged with the dowels (B) after the larva was inserted

The larvae were also placed in a control, non-treated timber, such that the mortality could be compared and the efficacy of the treatment verified. The holes in which the larvae were placed were plugged with wood dowels (Fig. 6).

Inspection of skids and dunnage parts

To monitor any effect of the treatment on the quality of the timbers and the structural integrity of the skid structures, all parts and connections were inspected before and after treatments. Any observed degradation of the parts or connections was noted. The ends of the large timber in each skid were photographed before and after treatment to determine any change in end splits.

Moisture content (MC) measurement

Large timbers were weighed before and after treatment. After the treatment, 2.54 cm (one-inch) moisture sections were cut at least one foot from each end of the timber. The moisture sections were oven-dried to calculate the MCs of the timber. From these MCs and the weight change of the timber, the change in the MC can be determined using formula: $MC = (\text{initial weight} - \text{oven dry weight}) / \text{oven dry weight} \times 100 (\%)$.

Larvae were weighed

The larvae were also weighed before and after treatment using a scale to determine if desiccation occurred during treatment.

Mortality of larvae was determined

The larvae were kept at 20°C and 60% relative humidity and observed for two days. If no movement was evident, the larvae were assumed dead.

Densities of large timber

Wood density was measured using the water displacement method. Oven-dried wood samples were pressed below the water surface in a beaker on a top loading balance. The volume of the wood was read accurately on the balance as the mass of the displaced water.

RESULTS AND DISCUSSION

Temperature Profiles

Figures 7 through 9 show the typical temperature profiles for each wood species. The temperature profiles for all tests are in the appendix. The chamber and surface temperatures increased rapidly as soon as steam entered the chamber. Next, the temperature next to the surface slowly rose. The temperature at the center of the timber initially remained unchanged for a certain time and linearly increased later to the final set point of 56 °C. This profile was similar to those recorded when treating large diameter logs (Chen *et al.* 2012). The center of the 10.16 cm × 10.16 cm deck timber reached 56 °C within 60 to 90 min and remained at 85 °C for approximately 4 h for many tests. The concern was the potential for degradation of small timber in an attempt to treat the large timber to 56/30. There is very little temperature gradient along the length. The rate of heating was similar at 1/4, 1/3, and 1/2 of the timber length. When wood cross-sections are uniform along the

length, probing the geometric center is recommended, but depending on the ease of the thermocouple placement, it is not necessary.

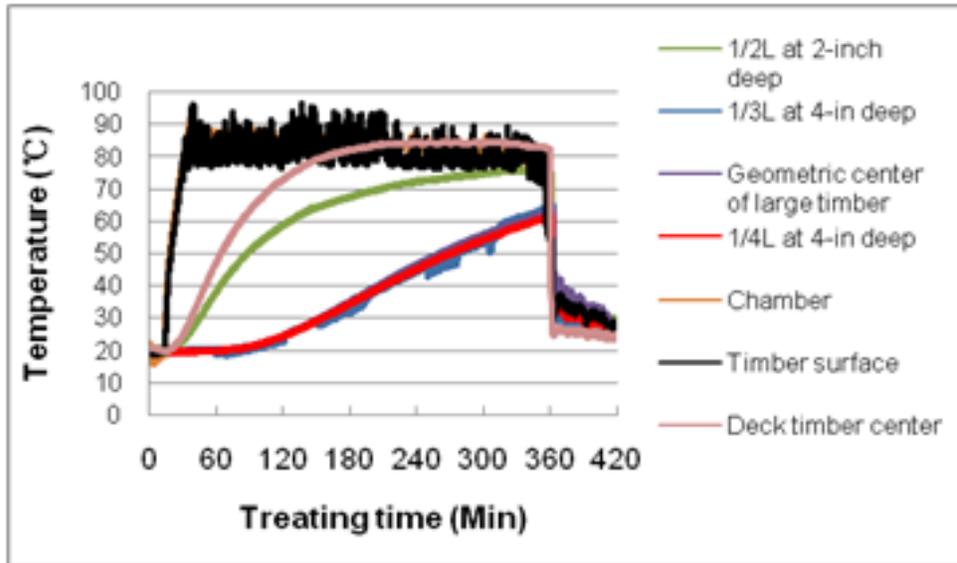


Fig. 7. Typical temperature profile of the 20.32 cm × 20.32 cm timber in the yellow-poplar skid at the initial vacuum pressure of 100 mm Hg

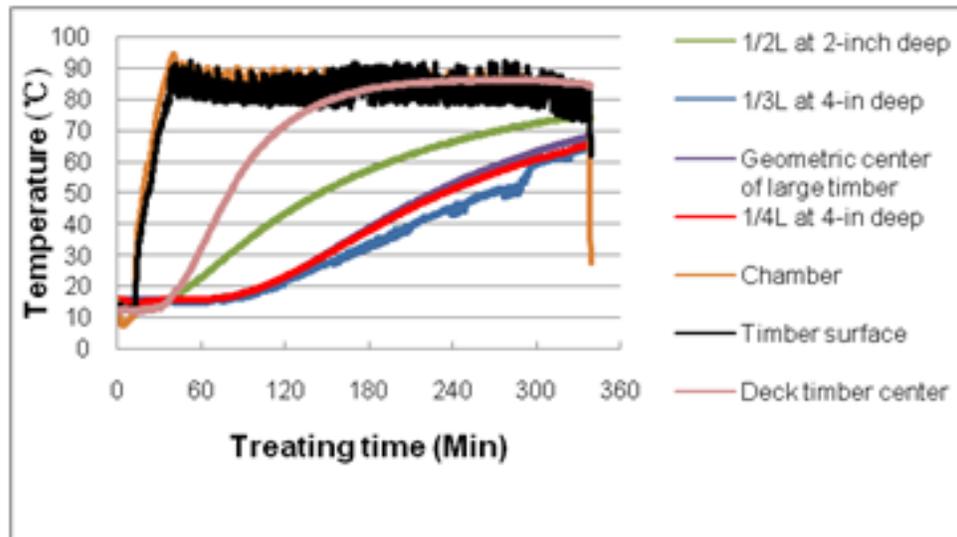


Fig. 8. Typical temperature profile of the 20.32 cm × 20.32 cm timber in the pine skid at the initial vacuum pressure of 100 mm Hg

Treating Time

The total treating times (including vacuum time and 30 min holding time) for the tests are presented in Table 1.

From Table 1, the treating time for 20.32 cm × 20.32 cm varied from 311 min (5.2 h) to 409 min (6.8 h), depending on the wood species. Methyl bromide log fumigation schedules require at least 24 h. The results indicated that the large 20.32 cm × 20.32 cm timbers could be heat-treated with vacuum steam technology to 56 °C for 30 min, faster than fumigating.

In a vacuum steam treatment, several variables affect the time required to heat wood to a given temperature. Heating time is influenced by wood density, wood MC, initial wood temperature, and the geometry of the wood.

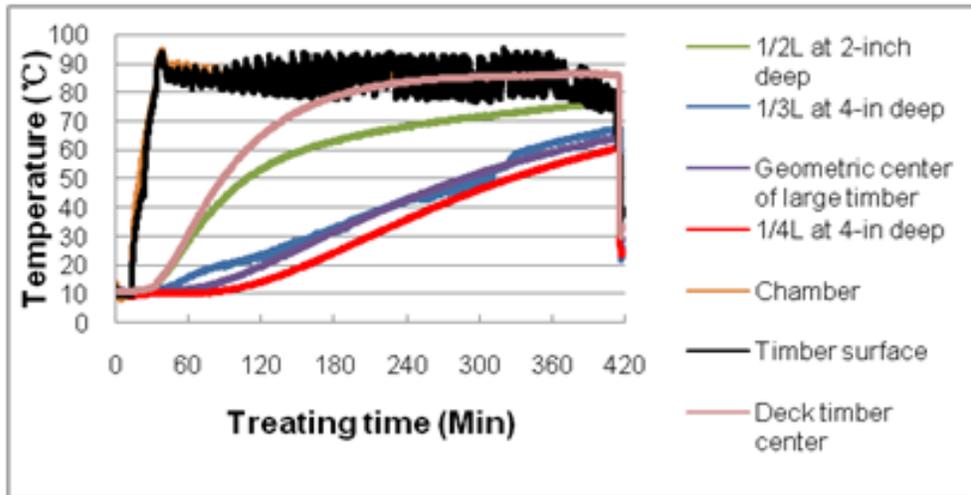


Fig. 9. Typical temperature profile of the 20.32 cm x 20.32 cm timber in the oak skid at the initial vacuum pressure of 100 mmHg

Table 1. Treating Time at the Initial Vacuum of 100 mm Hg for 20.32 cm x 20.32 cm Timbers and Measured Densities

Test	Red Oak			Southern Pine			Yellow-poplar		
Density	0.71 (g/cm ³)			0.48 (g/cm ³)			0.52 (g/cm ³)		
	Initial Wood Temp.	Vacuum Time	Total Time	Initial Wood Temp.	Vacuum Time	Total Time	Initial Wood Temp.	Vacuum Time	Total Time
	(°C)	(min)	(min)	(°C)	(min)	(min)	(°C)	(min)	(min)
1st	20	13	409	16	13	326	12	14	345
2nd	14	14	407	11	12	318	15	13	311
3rd	13	12	403	8	13	320	7	12	384
Avg.	16	13	406	12	13	321	11	13	347

The Effect of Species on the Treatment Time

From Table 1, it was clear that it took the least amount of time to treat southern pine. The hardwood of the less dense wood, yellow poplar, was heated up faster than the heavier wood, oak spp. The softwood, such as pine, has a straight, linear tracheid, which transported steam faster. The hardwood has more types of cells and its cells have irregular shape and arrangement

Effect of Size on the Treating Time

A larger timber size resulted in a longer treatment duration. This is shown in the temperature profile (Figs. 7 through 9). The average time it took for 10.16 cm x 10.16 cm oak deck timber to reach 56°/30 min was approximately 100 min compared to the 311 to

409 min required to heat-treat the 20.32 cm × 20.32 cm (8 in × 8 in) cross-section. Larger cross-sections required more time and energy to heat treat.

The vacuum steam process was ideally suited for treating wood structures with different size timber. The process does not degrade smaller timber that will heat more rapidly and remain at a higher temperature than the larger timber. A hot air system would likely degrade the small timbers in the skid.

Effect of Wood Density and Initial MC on the Treating Time

In general, it took longer to treat the oak than the yellow-poplar or the southern pine. The southern pine required the shortest duration. The southern pine had the lowest density and oak had the greatest. However, at the time of treatment, the oak timber contained approximately 57% more water. For this reason, it was not possible to separate the effects of wood MC and oven-density. There was a linear relationship between the gross density (effect of both the oven-dry density and the MC) and the treating time with $R^2 = 0.85$ and $p\text{-value} = 0.0004$ for the slope using simple linear regression. A higher value for gross density resulted in a longer time to treat the timber. The oak with high MC had a higher gross density than the oak containing less water. It took longer to treat high MC oak timber even though it had the same oven-dry density as the oak timber containing less water.

Moisture Gained During Treatment

Based on the MCs from the moisture sections measured in the oven-dry method, the MC content before and after treatment for the large timber was calculated. The moisture gained during the treatment was also calculated. The average MC increase from the large timber was approximately 4.1%. The average MC of hardwood timber increased 2.8% and southern pine timber increased 6.8%.

Larva Weight Change During the Treatment

The statistical analysis (T-test) indicated that there was no significant difference in larvae weight before and after treatment with sample size of 79. Therefore, desiccation was not a mechanism of mortality, as previously shown by Chen *et al.* (2008) where only vacuum was used for treatment.

Larva Mortality

After each treatment, the larvae were recovered from the treated and control large timbers and they were checked for mortality. They were then placed on the new diet and observed for two days. After the larvae were retrieved from the testing samples, they were soft and pale; apparently, they were dead. If they remained immobile after two days they were assumed dead. Additionally, 100% mortality was observed for those larvae in the treated timbers. All larvae that were retrieved from the control samples were alive. They burrowed into the food and remained active.

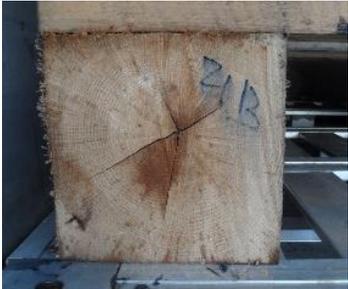
Quality Evaluation, Checking, and Color Change of Large Timbers

The timber quality of both the control and treated timbers was carefully monitored and compared before and after treatment. The primary measure of the timber quality was any change in the size and number of end splits. Photo images of the ends of the treated timbers were taken before and after treatment. Photos from the three timbers of each species are in Table 2. There were no obvious checks occurring after treatment or any

measurable increase of the existing checks. The color of the timbers did not change during the treatment.

The structural integrity of the skid structures was not affected. All connections were inspected, and no difference was observed before and after treatment.

Table 2. Typical End Grain Images of Large Timbers Before and After Treatment

Sample	Image Before Treatment	Image After Treatment
Yellow-poplar		
Pine		
Oak		

CONCLUSIONS

1. Total treating time to achieve 56 °C for 30 min at the timber core was less than 7 h for all three wood species tested (100 mm Hg and 90 °C steam). The treating cycle was less than that of methyl bromide fumigation 5.
2. With treatment, there was complete mortality (100%) of the larval surrogates.

3. The quality of the 20.32 cm × 20.32 cm timbers, 10.16 cm × 10.16 cm timbers, and skids was not affected by the treatment.
4. During treatment, the average timber MC increased 4.1%.

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