Parameters for scale-up of lethal microwave treatment to eradicate cerambycid larvae infesting solid wood packing materials

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Abstract

The use of microwave irradiation to eradicate insects infesting wood used to manufacture packing materials such as pallets and crates was evaluated. The focus of this preliminary study was to determine which microwave parameters, including chamber-volume to sample-volume ratios, variations of power and time, and energy density (total microwave power/wood volume), affect the lethal microwave dose required for laboratory-size samples of red pine infested with cerambycid larvae. Energy density was an acceptable parameter to predict lethal 2.45 GHz microwave doses when wood moisture content was held constant. Studies designed to verify these results using commercial-size loads are in progress.

The introduction and spread of invasive non-native species of exotic insect pests is a major threat to the health and biological diversity of rural and urban areas. Invasive exotic insects from infested solid wood packing materials used in international shipping, for example, are threatening both urban and forested areas in the United States and Europe (APHIS 1998, Nowak et al. 2001, Krehan 2002). Microwave irradiation of wood used to make pallets and crates has been proposed as a treatment for eradicating wood-boring insects (FAO 2002).

Microwave treatment of laboratory-size samples of wood proved lethal to larvae of the Asian long-horned beetle, *Anoplophora glabripennis* (Motsch.) (Coleoptera: Cerambycidae) (Fleming et al. 2003). Microwave irradiation is also effective for eradicating termites and beetle larvae in wood (Burdette et al. 1975, Jiang et al. 1991, Andreuccetti et al. 1994, Lewis et al. 2000). Practical application of this technology to commercial-size loads of wood, however, has yet to be realized.

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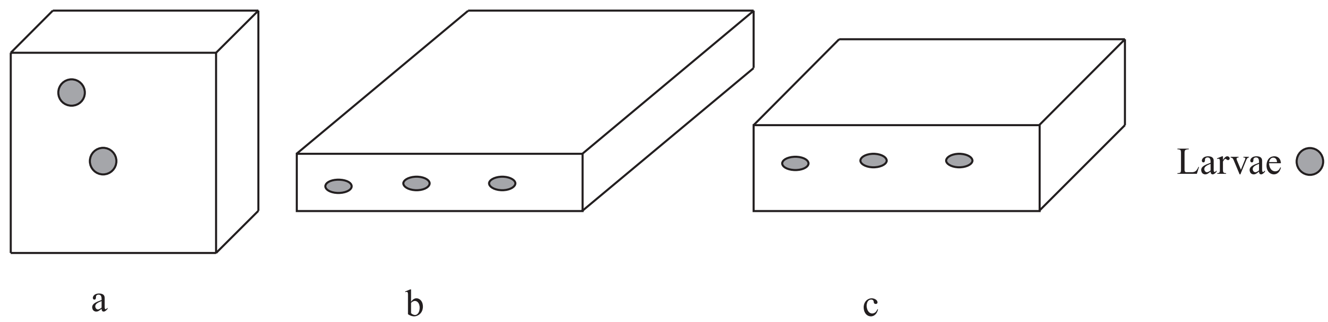

Figure 1. — Larval hole configurations for wood samples used in the cottonwood borer beetle microwave experiments: a) 4- by 4- by 4-inch blocks; b) 1- by 6.5- by 9.8-inch blocks; and c) 2- by 6- by 5.3-inch blocks. All holes approximately 2 inches deep.

To facilitate scale-up and regulatory approval, a variety of parameters for the development of microwave treatment schedules for solid wood packing materials need to be evaluated. Wood moisture content (MC), for example, is one parameter that must be considered in the development of microwave treatment schedules (Fleming et al. 2003). Wood with higher MC requires more irradiation than wood with lower MC to ensure 100 percent larval mortality. Water molecules translate microwave energy into frictional heat energy as their dipoles rotate in the microwave field. Increased water content of wood may dissipate the available microwave energy before it reaches larvae inside the wood, effectively shielding them. Lethal microwave exposure is likely reached when either the temperature in the region surrounding the larva is too high to sustain life or the microwave energy interacts with larval body fluids, and internal lethal temperatures are achieved.

Other factors that might affect lethal microwave doses, such as the size of the microwave chamber (holding sample volume and dimensions constant), the input microwave power and treatment time (holding total energy and wood dimensions constant), and the wood volume (holding energy density constant), were investigated in this study. For these trials, we used laboratory-size samples of red pine (*Pinus resinosa* Ait.) with the cottonwood borer (CWB), *Plectrodera scalator* (Fabricius) (Coleoptera: Cerambycidae) as our test insect.

Materials and methods

Two 2.45-GHz microwave systems were used in this study: a kitchen microwave (Sears Kenmore Model #565.69401890) with chamber dimensions of 10.25 by 14 by 16 inches and a commercial power, 6-kW microwave generator connected by a waveguide to a 2- by 2- by 1.5-foot chamber (Cober Electronics, S-band, 284). A Holladay Industry detection meter (Model #HI1501: 0.1 to 100 mW/cm^2 at 2450 MHz) was used to test for microwave leaks in both systems. The samples of wood were placed on a 1-inch-thick plastic box on the stationary turntable inside the chamber to center the samples within the microwave chamber.

Laboratory-reared CWB larvae were maintained on a modified meridic diet at room temperature until needed (Fleming et al. 2004). The majority of the larvae weighed between 1.0 and 1.5 g and reached body lengths of 1.0 to 1.5 inches. Two or three CWB larvae were inserted in each wood sample, and after microwave treatment, they were removed to determine their status (living or dead) as described in Fleming et al. (2003). In brief, emaciated body structure, changes in body color or opacity, and lack of movement after prodding were used to indicate larval death; larvae were observed for 12 to 24 hours after treatment for signs of recovery.

Red pine (*P. resinosa*) trees were felled and processed into lumber sections as described in Fleming et al. (2003). American Society for Testing and Materials (ASTM) Standard procedure, ASTM D 2395, was followed to determine wood MC (ASTM 1996) using ovendried weight of the samples. A conventional warming oven (Fisher Isotemp Model #2550, 116V, 9A) at 100°C was used to completely dry the wood sample after microwave treatment. Holes drilled in the red pine samples were of sufficient diameter and depth for insertion of the CWB larvae and to simulate a cerambycid gallery (approximately 2 in. deep and 3/8 in. diameter). The entrance holes were subsequently secured with wood plugs. Time between inserting CWB larvae in the hole and the irradiation treatment was less than 3 hours.

Chamber-volume to sample-volume comparison

Depending upon the material, the chamber-volume to sample-volume ratio may be important when scaling up to commercial-size wood loads (Yannone 2000). For all experiments, the wood volume was kept constant at 64 in.^{3} Three different surface areas were chosen: 96 in.2 (4 by 4 by 4 in.), 108 in.^{2} (2 by 6 by 5.3 in.), and 160 in.^{2} (1 by 6.5 by 9.8 in.). MC of the wood samples used in this study ranged from 33 to 132 percent. Two larvae were placed in each 4- by 4- by 4-inch block as shown in **Figure 1a**. Three larvae were placed in each of the other blocks (**Figs. 1b** and **1c**). Microwave energy of 1000 W was applied for 3 minutes (1000 W × 3 min. × 60 sec. = 180,000 J) using the Kenmore system. Similar experiments in the 6-kW chamber were then conducted to determine if the chamber-volume to sample-volume ratio affected the results.

Input power and time variance

These trials were designed to investigate whether total power per wood volume (energy density) influences efficacy of microwave treatment regardless

Table 1. — Mortality of larvae as a function of wood sample surface area after exposure to 180,000 J of 2.45-GHz microwave energy in a multi-mode microwave oven.[a]

Red pine exposure treatment 1000 W for 3 min. (180,000 J) Kenmore microwave	Volume	Surface area	MC range	No. of test trials	No. of larvae/ no. of dead larvae
	($in.^3$)	($in.^2$)	(%)		
4 by 4 by 4 in.	64	96	33	1	2/2
			39 to 41	2	6/6
			46 to 56	3	6/6
1 by 6.5 by 9.8 in.	64	160	67 to 81	4	12/12
			99 to 111	2	2/1
2 by 6 by 5.3 in.	64	108	45 to 61	4	12/12
			131 to 132	2	4/3

[a]Energy in Joules equals microwave wattage (W) multiplied by the exposure time in seconds.

Table 2. — Mortality of larvae as a function of wood sample surface area after exposure to 180,000 J of 2.45-GHz microwave energy in an industrial 6-kW multi-mode microwave chamber.[a]

Red pine exposure treatment 1000 W for 3 min. (180,000 J) Cober 6-kW microwave	Volume	Surface area	MC range	No. of test trials	No. of larvae/ No. of dead larvae
	($in.^3$)	($in.^2$)	(%)		
4- by 4- by 4-in.	64	96	40 to 44	6	6/6
			49 to 63	9	14/14
1- by 6.5- by 9.8-in.	64	160	46 to 83	3	9/9
			85 to 106	4	12/10
2- by 6- by 5.3-in.	64	108	46 to 79	6	18/18

[a]Energy in Joules equals microwave wattage (W) multiplied by the exposure time in seconds.

of variation in input power and/or time of exposure. The overall power (3,000 W) and sample volume (64 $in.^3$) were held constant. The input power was increased from 1000 W to 1500 W to 3000 W with a corresponding decrease in processing time of 3, 2, and 1 minute, respectively. Surface area was also varied, while target wood MC was approximately 60 percent. The wood dimensions chosen were 4 by 4 by 4 inches (96 $in.^2$), 2 by 6 by 5.3 inches (108 $in.^2$), and 1 by 6.5 by 9.8 inches (160 $in.^2$) in order to closely replicate wood sections common to manufactured pallets. Wood section configurations with the drilled-hole locations are as shown in **Figure 1**.

Energy density

Energy density was calculated by dividing the total microwave input power (J) by the volume of the wood sample ($in.^3$). If energy density that is lethal to cerambycid larvae in a smaller wood volume is also lethal to larvae in a larger wood volume of the same MC, then volume/energy density can be used in microwave treatment schedules. The energy density that was shown to be lethal to cerambycids in the experiments using the 4-inch cubes of wood described previously was 2,812 J/$in.^3$ [(1000 W × 3 min. × 60 sec.)/64 $in.^3$]. We used the same energy density to calculate the number of minutes of irradiation required for the 6-inch red pine cubes, a 216 $in.^3$ volume [(2,812 J/$in.^3$ × 216 $in.^3$)/(1000 W × 60 sec.) = 10 min.)]. Each 6-inch cube was then treated at 1000 W of 2.45-GHz input power for 10 minutes in the 6-kW microwave unit. The section configurations of wood for this trial are also shown in **Figure 1**.

Wood MC lost during the microwave process

Three different species were used for these experiments: loblolly pine (*Populus tremuloides* Michx.) (n = 22), eastern white pine (*Pinus strobes* L.) (n = 42), and aspen (*Pinus taeda* L.) (n = 23). A representative number of samples for each species were dried completely and an average ovendry weight was used to calculate the MC for all of the samples within a species. The weight of the wood sample (4-in. cube) was measured before and after the microwave treatment (5 min. @ 1,100 W) was applied. MC before and after the treatment was calculated (as described previously) and the difference between the two values was defined as the MC lost during the microwave process. In a similar manner, MC loss was calculated for red pine samples (4-in. cube) irradiated with 180,000 J of 2.45-GHz microwave energy under three different treatment schedules: 1,000 W for 3 minutes (n = 12), 1,500 W for 2 minutes (n = 5), and 3,000 W for 1 minute (n = 4).

Results

Chamber-volume to sample-volume comparison

The target MC range was between 39 and 83 percent. Within this MC range, 100 percent larval mortality was attained after 3 minutes of 1000-W irradiation, regardless of the chamber size or

Table 3. — Mortality of larvae as a function of wood sample surface area after exposure to 180,000 J of 2.45-GHz microwave energy (1500 W for 2 min.) in an industrial 6-kW multi-mode microwave chamber.[a]

Red pine exposure treatment 1500 W for 2 min. (180,000 J) Cober 6-kW microwave	Volume	Surface area	MC range	No. of test trials	No. of larvae/ no. of dead larvae
	(in.^{3})	(in.^{2})	(%)		
4- by 4- by 4-in.	64	96	60 to 76	5	10/10
2- by 6- by 5.3-in.	64	108	53 to 67	4	12/12

[a]Energy in Joules equals microwave wattage (W) multiplied by the exposure time in seconds.

Table 4. — Mortality of larvae as a function of wood sample surface area after exposure to 180,000 J of 2.45-GHz microwave energy (3000 W for 1 min.) in an industrial 6-kW multi-mode microwave chamber.[a]

Red pine exposure treatment 3000 W for 1 min. (180,000 J) Cober 6-kW microwave	Volume	Surface area	MC range	No. of test trials	No. of larvae/ no. of dead larvae
	(in.^{3})	(in.^{2})	(%)		
4- by 4- by 4- in.	64	6	45 to 78	5	10/10
2- by 6- by 5.3-in.	64	108	59 to 81	4	12/12

[a]Energy in Joules equals microwave wattage (W) multiplied by the exposure time in seconds.

Table 5. — Mortality of larvae after exposure of 6-inch wood cubes to 607,500 J (2,812.5 J/in^3) of 2.45-GHz microwave energy (1000 W for 10 min.) in a 6-kW multi-mode microwave chamber.

Red pine exposure treatment 1000 W for 10 min. (607,500 J) Cober 6-kW microwave	Volume	Surface area	MC range	No. of test trials	No. of larvae/ no. of dead larvae
	(in.^{3})	(in.^{2})	(%)		
6- by 6- by 6-in.	216	216	61 to 78	7	14/14
			93 to 96	2	4/1

[a]Energy in Joules equals microwave wattage (W) multiplied by the exposure time in seconds.

surface area (**Tables 1** and **2**). As expected from our previous findings, this irradiation level was not sufficient for the 1-inch-thick samples of higher MCs (> 85%) in either treatment chamber. These results indicate that samples exposed in the larger chamber volume (Cober system) had no effect on mortality.

Input power and time variance

When the energy, MC, and sample volume were held constant as the power was increased and the time decreased, 100 percent mortality of larvae was still observed at 1,000 W, 1,500 W and 3,000 W (**Tables 2**, **3**, and **4**).

Energy density

In 6-inch cubes of wood with MCs between 61 and 78 percent subjected to 2,812.5 J/in.^{3} of 2.45-GHz radiation, 100 percent mortality was observed (**Table 5**). This compares favorably to the results using 4-inch cubes (100% mortality for MCs less than 79%). When MC exceeded 92 percent, one larva out of the four survived in the microwave-treated 6-inch cube.

MC lost during the microwave process

The average MC lost during the 5-minute microwave treatment at 1,100 W (330,000 J) was 26 ± 1.4 percent (standard error of the mean), 16 ± 0.8 percent, and 18 ± 0.4 percent for eastern white pine (initial MC between 59% and 153%), loblolly pine (initial MC between 66% and 91%), and aspen (initial MC between 49% and 91%), respectively. Under these treatment conditions, the MC lost by eastern white pine varied the most with a standard error of the mean of 1.4 percent. There was a significant difference in MC lost among the three wood species (ANOVA: F = 19.1; df = 2, 84; p < 0.0001). Eastern white pine lost significantly more MC than the other two wood species (p < 0.0001, PLSD), but MC loss in loblolly and aspen was not statistically different (p = 0.3264, PLSD). Linear regression analysis showed that MC of wood samples before microwave exposure was not predictive of the MC loss in eastern white pine or aspen, but was predictive for loblolly pine (for eastern white pine: F = 0.13; df = 1, 40; p = 0.7176; for aspen, F = 0.39; df = 1, 21; p = 0.5366; and for loblolly pine, F = 6.63; df = 1, 20; p = 0.0181). However, when the data for all tree species were combined, MC loss during treatment could be predicted from MC before microwave treatment and tree species (for multiple regression, F = 9.19; df = 3, 83; p < 0.0001; Equation: mc loss = 213 − 0.46 (wood species) + 1.6 (MC before microwave) − 1.55 (MC before microwave)^2; r^2_{adj} = 0.22).

When 180,000 J of 2.45-GHz microwave energy (1000 W for 3 min., 1500 W for 2 min., or 3000 W for 1 min.) was applied to red pine with initial MCs between 33 and 122 percent, the mean MC lost during the treatment was 11 ± 0.9

percent. Time of microwave exposure did not predict moisture loss for these experiments (linear regression: $F = 3.23$; df = 1,18; $p = 0.0889$). Also, energy input did not predict loss, although it was nearly significant (for linear regression, $F = 3.77$; df = 1, 18; $p = 0.0681$; $r^2 = 0.17$). Including wood MC before treatment in the analysis did not improve the predictive value of these variables. Consequently, one cannot assume that the same moisture loss will occur with the same energy input. However, the data set may be too small for statistical differences to be detected; these preliminary results should be evaluated in larger trials.

Conclusions

From these preliminary results, energy density was found to be predictive of mortality of cerambycid larvae infesting wood samples exposed to 2.45-GHz microwave doses when wood MC was held constant. In addition, power and time can be varied as long as the critical lethal energy density is applied to the wood. The chamber-volume to sample-volume ratio did not affect mortality for these microwave systems and wood dimensions. Wood species can affect the MC loss during treatment. Two variables, wood species and pre-treatment MC, accounted for 22 percent of the predicted moisture loss.

These laboratory experiments provide sufficient justification to begin industrial scale-up of microwave energy as a tool to sterilize wood packing materials infested with insects. We propose that the energy-to-volume ratio for wood with MCs between 30 and 78 percent be designated as 2,812 J/in.^{3} From previous studies (Fleming et al. 2002), 5 minutes of 1100 W irradiation was lethal to cerambycid larvae in 4-inch cubes with MCs lower than 137 percent [(1100 W × 5 min. × 60 sec)/64 in.^{3} = 5,156 J/in.^{3}]. Thus, we propose an energy-to-volume ratio of 5,156 J/in.^{3} for wood with MCs between 78 and 137 percent. Using these values, lethal microwave doses can be calculated for various volumes and MCs of commercial lumber. Additional experiments in industrial microwave ovens with commercial-size loads are planned by this research group to verify the efficacy of these energy-to-volume ratios.

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