LABORATORY EVALUATION OF MICROWAVES FOR CONTROL OF THE WESTERN DRYWOOD TERMITE

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ABSTRACT

Lethal effects of microwaves on the western drywood termite, *Incisitermes minor* (Hagen), were evaluated under laboratory conditions. Douglas-fir 2 by 4 boards were artificially infested with 75 drywood termite workers, 25 in each of three routed-out galleries. The boards containing termites were randomly assigned to microwave ovens rated at 500, 1,000, and 2,000 watts (W). All ovens had the same wavelength frequency: 2.4 GHz. Seventy boards were treated: 25 each for the 500-W oven and the 1,000-W oven, and 20 for the 2,000-W oven. Boards were randomly chosen and oriented within ovens and were treated with one of five treatment times. The treatment times varied with the wattage of oven and ranged from 20 to 150 seconds. Untreated boards (controls) were also prepared to measure nontreatment sources of termite mortality. All boards were split open 1 day after treatment, and counts were made of live and dead termites. Termite mortality exceeded 84 percent for all treated boards irrespective of oven wattage. Higher wattage ovens had higher termite mortality levels. However, the difference was not significant. Variance in mortality for treated boards was considerable. Only for the last three treatment times did means for all treated boards reach 100 percent mortality. The results suggest drywood termites can escape the lethal effects of microwaves. Although the exact mechanism of escape is not known, additional laboratory studies measuring changes in temperature using optically heat sensitive devices and water vials confirmed unequal heat distribution within ovens. Results of this study support the variation in mortality during an earlier field study using commercial microwave devices for controlling drywood termite infestations in structures.

Drywood termites cause significant damage to homes and wood structures nationwide. There are 14 species of drywood termites in the United States, however only 5 species have economic importance: *Cryptotermes brevis* (Walker), *Incisitermes minor* (Hagen), *I. snyderi* (Light), *Kalotermes approximatus* Snyder, and *Marginitermes hubbardi* (Banks) (28). Estimates of the total economic impact from drywood termites and their control costs vary from 5 to 20 percent of the total $1.5 billion to $5 billion spent on wood-destroying insect control each year in the United States (17,26).

Control for drywood termites in California is dominated by localized chemical treatments. As much as 70 percent of all drywood termite treatments are localized treatments with chemicals (16). Fumigation and nonchemical methods account for 20 and 10 percent, respectively. Public opinion polls over the last several decades show increasing concern and caution towards chemicals for pest management (11,22). Interest and use of less toxic and nonchemical pest control methods by homeowners and pest management firms is also increasing (2,17). However, laboratory and field efficacy data are sporadic or lacking for many less toxic and nonchemical methods of drywood termite control.

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Because of the disparity in efficacy information and marketing claims, actions by state attorney generals have resulted in legal actions against some commercial firms (1).

Microwaves were first commercially available for cooking food (27) in the 1960s. However, their uses also include wood drying (21) and management of pests of stored foods (4,5,9,13,15, 18-20,29,30), herbarium materials (13), and fabrics (24). Although microwave technology has been available in California for drywood termite control since at least 1989, only one paper, a study that simulated actual use conditions, has presented results of efficacy (17).

The findings presented in our study constitute the laboratory component of the field study conducted earlier (17). The objective of the study was to determine the relationships among increased oven wattage, exposure time, and drywood termite mortality.

MATERIALS AND METHODS

MICROWAVE OVENS

Three microwave ovens 500-W, 1,000-W, and 2,000-W were used during the study. All ovens had the same wavelength frequency (2.4 GHz), same manufacturer (Amana Company, Amana, Iowa), and were shielded for safety while operating. The three ovens also varied in interior capacity: 29.2 by 28.6 by 20.3 cm, 34.3 by 34.3 by 25.4 cm, and 36.8 by 40.0 by 22.9 cm, respectively.

A 2-mm-diameter hole was drilled into the back of each oven for insertion of heat-monitoring equipment. Recording of temperatures within ovens was conducted using a nonconducting optical device (Luxtron, Santa Clara, Calif.) (**Fig. 1**). The device measured temperature changes on wood surfaces in microwave ovens by sending a pulse of blue-violet light down a silicon tube. The end of the tube had a quartz crystal coated with phosphorus that glows when exposed to blue-violet light. The decay of the phosphor fluorescence with each pulse of blue-violet light varies precisely with temperature. Separate channels on the device allowed for simultaneous temperature reading from four different locations within ovens. Probes could record temperatures from −200°C to 450°C. All data were automatically downloaded to a DOS computer (Evergreen Computers, Richmond, Calif.) and stored in Lotus 123 Version 5.0 software (Lotus Development Corp., Cambridge, Mass.). A Microwave Survey Meter (Holaday Industries, Eden Prairie, Minn.) was also used to ensure leaks did not occur in ovens through drilled holes or doors during tests.

OVEN TEMPERATURE CALIBRATION

Microwave ovens are known to have uneven heating (27). Initial testing consisted of determining if the wattage while running met the manufacturer's specifications and mapping of heat ex-

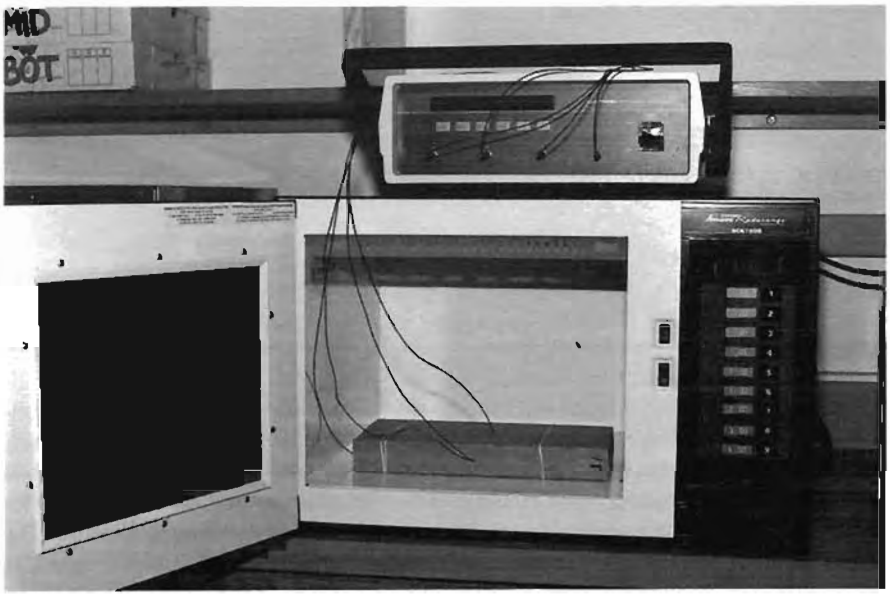

Figure 1. — Optical temperature recording device (Luxtron, Santa Clara, Calif.) and silicon probe positions for an artificially infested board containing 75 drywood termites. Microwave oven (1,000-W Amana, Amana, Iowa) is also seen in picture.

Figure 2. — Two vertically stacked cardboard trays containing 64 25-mL water-filled vials. Ovens producing 500-W, 1,000-W, and 2,000-W were run at full power for 4 minutes, 2 minutes, and 45 seconds, respectively. Initial and final temperature was recorded for each vial to calculate oven wattage.

tremes and distribution within ovens. Oven wattage was determined using the following formula $W = (t_1 - t_2) * 69.8$, where W was watts, t_1 and t_2 (C°) were initial and final temperature after heating 1 L of water at full power for 60 seconds, and 69.8 is the constant used when using Celsius thermometers. Four replicates were conducted for each oven. A digital thermometer was used for all temperature readings in water (Omega, Fisher Scientific, Santa Clara, Calif.).

Heat distribution within ovens was determined measuring temperature differences in water vials. Thirty-two 25-mL vials were arranged in a 4 by 8 grid contained in a cardboard tray (**Fig. 2**). Two trays (64 vials) were vertically stacked and placed in the 500-W oven. Three trays (96 vials) were vertically stacked and placed in the 1,000-W and 2,000-W ovens. The initial temperature for each vial was recorded prior to heating in the oven. Stacks of vials were heated at full power for 4 minutes for the 500-W oven, 2 minutes for the 1,000-W oven, and 45 seconds for the 2,000-W oven. Each tray was then removed from the oven and the temperature for each vial was recorded immediately a second time; 2 to 4 minutes were needed to record temperatures for all vials within ovens. Heating stacked trays of water vials was replicated five times for each oven. The difference in initial and final temperature (Δt) among water vials was calculated and used for statistical analysis.

Insects

Termites placed in artificially infested boards were collected from structural lumber containing *I. minor* acquired from pest control firms and homeowners from northern and southern California. Termites were removed from wood by dissection using hammers and chisels. We selected healthy and uninjured larvae, nymphs, and pseudergates of at least the 4th instar.

Preparation of artificially infested boards

Boards used during the study were similar in design to those in a previous study (17). Kiln-dried, vertical grain, and clear Douglas-fir 2 by 4s (3.5 by 8.0 cm) were cut into 28-cm lengths. Each board consisted of four pieces made from three longitudinal cuts (**Fig. 3**). Three gallery spaces were routed into each board (**Fig. 3**). Seventy-five drywood termites were placed within each board, 25 per gallery. Boards with termites were held together with two rubber bands. Before installation, boards were stored at ambient conditions in the laboratory for 24 hours. With the exception of untreated boards (controls), no individual board was used in more than one treatment or test.

Temperature changes in galleries within wood blocks were also recorded. This was additional calibration work and was conducted in empty galleries not containing termites. Probes were inserted into the centers of gallery, 1, 2, and 3 (**Figs. 1** and **3**). One additional probe was placed on the outside of the block to measure air temperature changes while ovens were operating. Temperature was continuously monitored using the same recording device, computer, and software as mentioned earlier in this paper. Maximum treatment time for galleries within blocks varied with oven wattage. For the 500-W, 1,000-W, and 2,000-W ovens, the maximum treatment times were 90, 60, and 30 seconds, respectively.

Microwave treatment

A three-factor analysis of variance model incorporating oven wattage, treatment time, and board orientation was used in the design of the experiment. Treatment times varied with the wattage of the oven. For the 500-W oven, the five treatment times used were 30, 60, 90, 120, and 150 seconds. Treatment times for the 1,000-W oven were 20, 40, 60, 80, and 100 seconds. The shortest treatment times were for the 2,000-W oven: 10, 20, 30, 40, and 50 seconds. The longest treatment time for each oven was chosen at a temperature that exceeded 100°C but before board ignition. Within the ovens, boards were

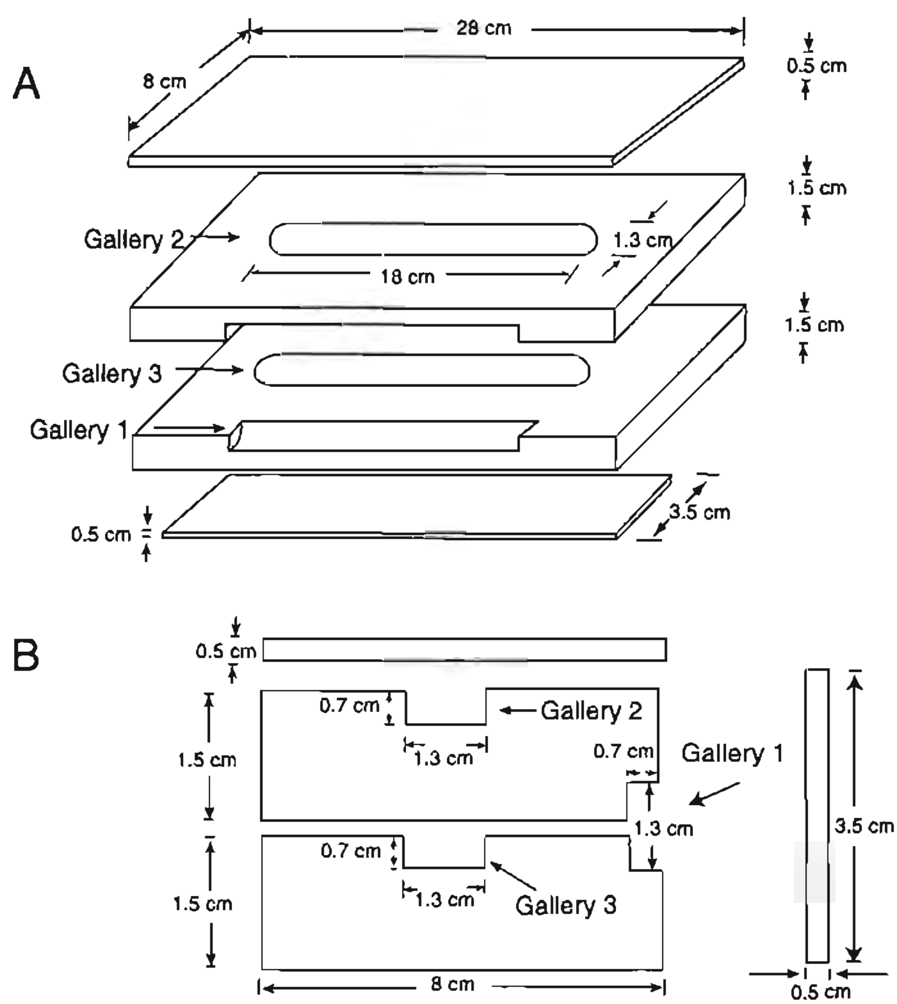

Figure 3. — Disassembled (A) and cross-sectional (B) views of a 2 by 4 Douglas-fir board showing routed gallery locations. Drawings not to scale.

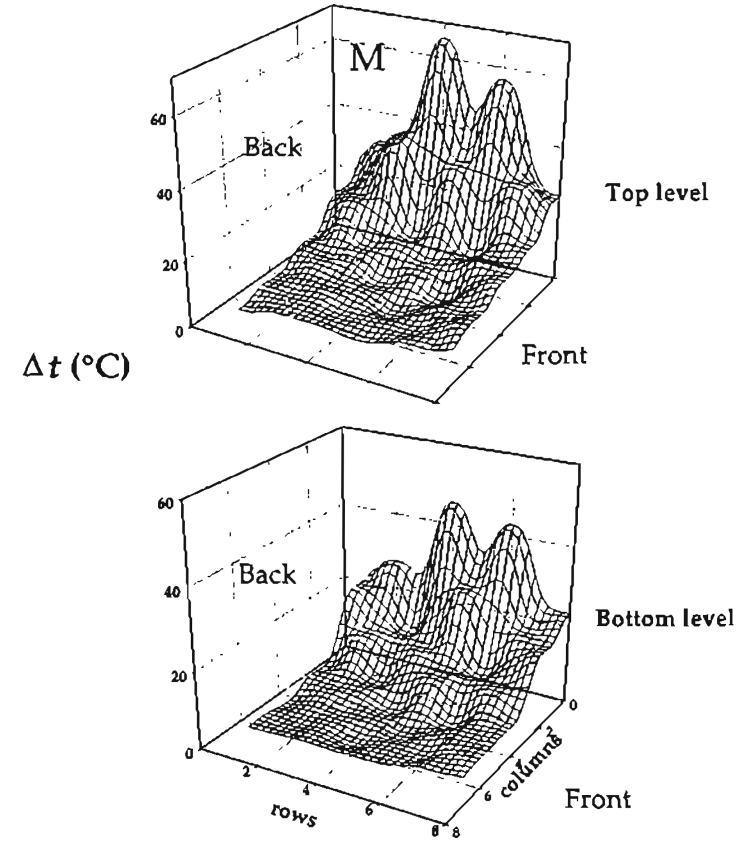

Figure 4. — 3-D plot of change in temperature (Δt) among 64 sampling locations within a 500-W oven. Sampling locations consisted of 25-mL vials filled with water and heated at full power for 4 minutes. *M* denotes the location of the megatron, the source of microwave emissions.

TABLE 1. — Maximum accumulated microwave dosage for 500-W, 1,000-W, and 2,000-W ovens for each of five treatment times.

Oven wattage[a]	Treatment time[b]	Maximum accumulated dosage[c]
	(sec.)	(W• hr./cm^2)
500/550 W	30	0.006
	60	0.012
	90	0.018
	120	0.024
	150	0.030
1,000/920 W	20	0.007
	40	0.013
	60	0.020
	80	0.027
	100	0.034
2,000/2009 W	10	0.007
	20	0.015
	30	0.022
	40	0.029
	50	0.037

[a] First number represents manufacturer's specification. Second number represents mean wattage calculated from 1-liter water calibration tests. Calculated means rounded-off to the nearest watt were used in maximum accumulated dosage determination.
[b] Treatment time in equation adjusted to fraction of hour.
[c] Area of test board: 759.5 cm^2 (Fig. 3).

randomly oriented in one of two positions: gallery 1 in either an upward or downward facing position. Boards were placed inside each oven, centered on the bottom floor, and their long axis parallel to the source of microwave emissions (megatron). From the front of the 500-W and 1,000-W ovens, the megatron was located on the right side. The 2,000-W oven had two megatrons located at the top. Boards were immediately removed from ovens after treatment and left to cool at room ambient conditions. Seventy boards were prepared and treated, 25 each for the 500-W and 1,000-W ovens and 20 for the 2,000-W oven. Fifteen untreated boards (controls) were also prepared to measure nontreatment sources of termite mortality.

STATISTICAL ANALYSIS

Summary statistics for wattage and temperature extremes in ovens were derived with the MEAN procedure (PROC MEAN, SAS Institute (25)). Figures of temperature extremes within ovens and galleries within boards were constructed using Sigmaplot (SPSS Science, Chicago, Ill.). Differences in initial and final temperature (Δt) for rows and columns of water vials vertically and horizontally near or away from the megatron (source of microwave emissions) were analyzed for significant differences using Ryan-Einot-Gabriel-Welsch Q multiple range test (PROC GLM, SAS Institute (25)). Mortality levels for treated and untreated boards were derived with the MEAN procedure (PROC MEAN, SAS Institute (25)). Means for drywood termite mortality levels among oven wattage, exposure time, board orientation, and gallery designation were analyzed for significant differences using the Ryan-Einot-Gabriel-Welsch Q multiple range test (PROC GLM, SAS Institute (25)).

RESULTS AND DISCUSSION

OVEN TEMPERATURE CALCULATIONS.

The manufacturer's wattage specifications were similar to those calculated from water beaker tests. Calculated mean wattage for the 1,000-W and 2,000-W ovens were 919.6 W ± 16.5 (SE) and 2,008.5 W ± 4.4, respectively. For the 500-W oven, the calculated wattage was almost 10 percent higher than the manufacturer's specifications: 549.7 W ± 6.0.

Ovens displayed uneven heating patterns within the interior compartment (**Figs. 4-6**). Temperature differences (Δt) were significantly greatest ($F = 55.32$, df = 2,1279, $p < 0.0001$) in the 500-W oven compared to the other two ovens. The hottest location in the 500-W oven was the upper right-hand side (**Fig. 4**). The temperature difference (Δt) exceeded 60°C and was significant for vertically ($F = 23.71$, df = 1,319, $p < 0.0001$) and horizontally ($F = 304.38$, df = 2,319, $p < 0.0001$) stacked rows and columns of water vials. As expected, there also was a statistically significant interaction ($F = 7.85$, df = 2,319, $p < 0.0005$) for Δt among rows and columns of water vials depending on their proximity to the megatron.

The 1,000-W and 2,000-W ovens had lesser changes in Δt temperatures (**Figs. 5 and 6**). The top level for both ovens exceeded 30°C, less than the 60°C for the top level of the 500-W oven. Similar to the 500-W oven, the 1,000-W and 2,000-W ovens were significantly hottest at the top level ($F = 255.61$, df = 2,479, $p < 0.0001$; $F = 2,029.06$, df = 2,479, $p < 0.0001$). For the 2,000-W oven, there was a significant ($F = 81.62$, df = 2,479, $p < 0.001$) edge effect along the interior sides due to two emitting sources of microwaves.

Since microwaves vibrate dipolar water and protein molecules to cause heat (14), the higher temperatures of water at the top of ovens near the megatron is not surprising. Although comparison of shielded laboratory ovens and unshielded field devices are tenuous, it appears both technologies create hot areas within treated boards. Lewis and Haverty (17) similarly showed a commercial device for treating wood within structures creates hot spots within boards; six boards were scorched during a simulated field test.

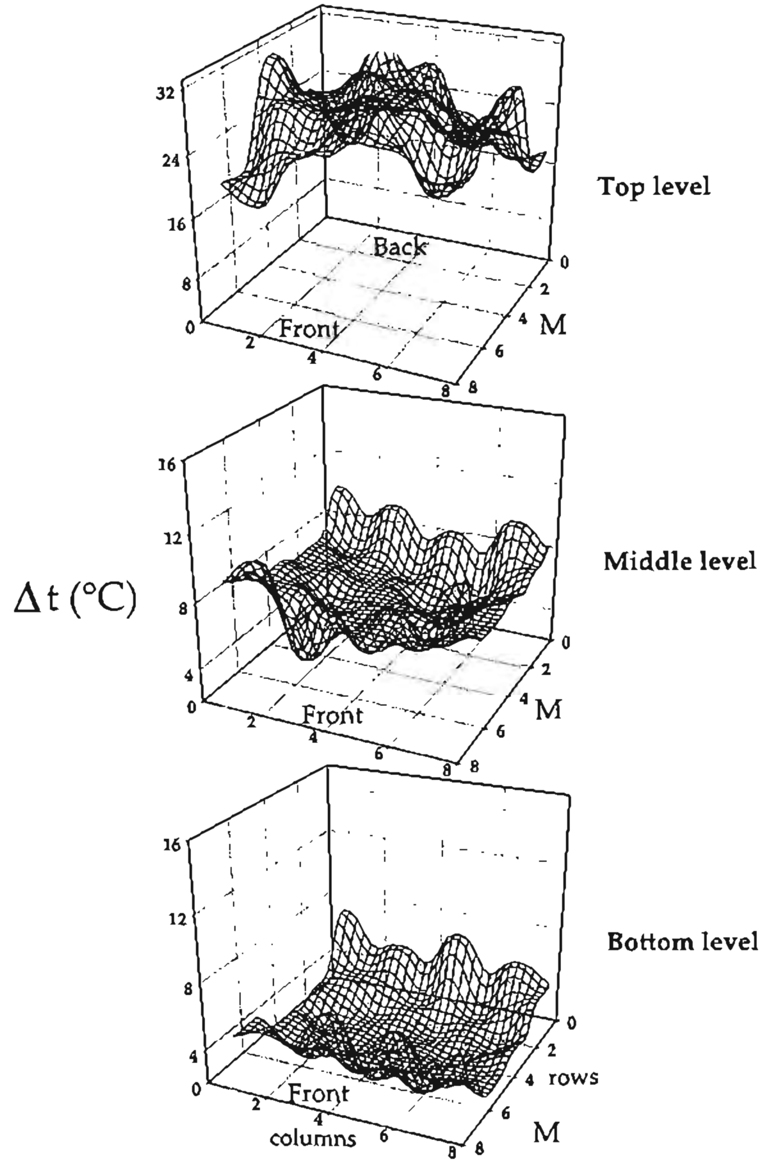

Figure 5. — 3-D plot of change in temperature (Δt) among 96 sampling locations within a 1,000-W oven. Sampling locations consisted of 25-mL vials filled with water and heated at full power for 2 minutes. *M* denotes the location of the megatron, the source of microwave emissions.

MICROWAVE ACCUMULATED DOSAGE

The theoretical accumulated dosage (W• hr./cm^2) for 2 by 4 boards treated by microwaves varied with duration of treatment and was similar within and between ovens (**Table 1**). Depending on the duration of treatment, the accumulated dosage varied from ≈ 0.01 to 0.03 W• hr./cm^2. Accumulated dosage for a 700-W unshielded commercial device used for treating drywood termite infestations within homes in California was reported to be 0.3 W• hr./cm^2 by the vendor conducting the treatments (17). The difference in accumulated dosage between laboratory and field devices is at least an order of magnitude. We cannot explain the discrepancy in accumulated dosage between field and laboratory microwave ovens (e.g., differences in microwave technology or vendor reporting of wattage capability). Comparisons among shielded laboratory ovens and unshielded field devices are difficult since the authors do not know the configuration or shielding used in oven construction. However, it appears that commercial unshielded microwave devices used for pest control deliver greater wattage per unit area of board compared to shielded laboratory ovens. Some unshielded commercial devices are even more powerful and claim their total wattage exceeds 10,000 W (16).

TERMITE MORTALITY

All ovens caused considerable termite mortality within artificially infested boards. Termite mortality 1 day after treatment for the 500-W, 1,000-W, and 2,000-W ovens was 81.1 ± 6.4 percent (SE), 88.1 ± 5.7 percent, and 84.8 ± 7.3 percent, respectively. Mortality at 1 day after treatment in the untreated (con-

TABLE 2. — *Percent mortality (mean ± SE) of drywood termites in artificially infested boards 1 day after treatment at full power in one of three microwave ovens and one of five exposures times.*[a]

Oven wattage	n[c]	Treatment time[b] 1st	2nd	3rd	4th	5th
		(%)				
500 w	25	23.2 ± 9.8 A	82.1 ± 5.7 B	100 B	100 B	100 B
1,000 w	25	40.7 ± 16.1 A	99.7 ± 0.3 B	100 B	100 B	100 B
2,000 W	20	23.9 ± 11.8 A	100 B	100 B	100 B	100 B

[a] Means followed by the same capital letter within the same row are not significantly different (Ryan-Einot-Gabriel-Welsch multiple range test, $p > 0.05$).

[b] Exposure time varied with oven wattage. 500-W (30, 60, 90, 120, 150 sec.), 1,000-W (20, 40, 60, 80, 100 sec.), and 2,000-W (10, 20, 30, 40, 50 sec.).

[c] Number of test boards used, five per exposure time for 500-W and 1,000-W ovens and four per exposure time for 2,000-W oven.

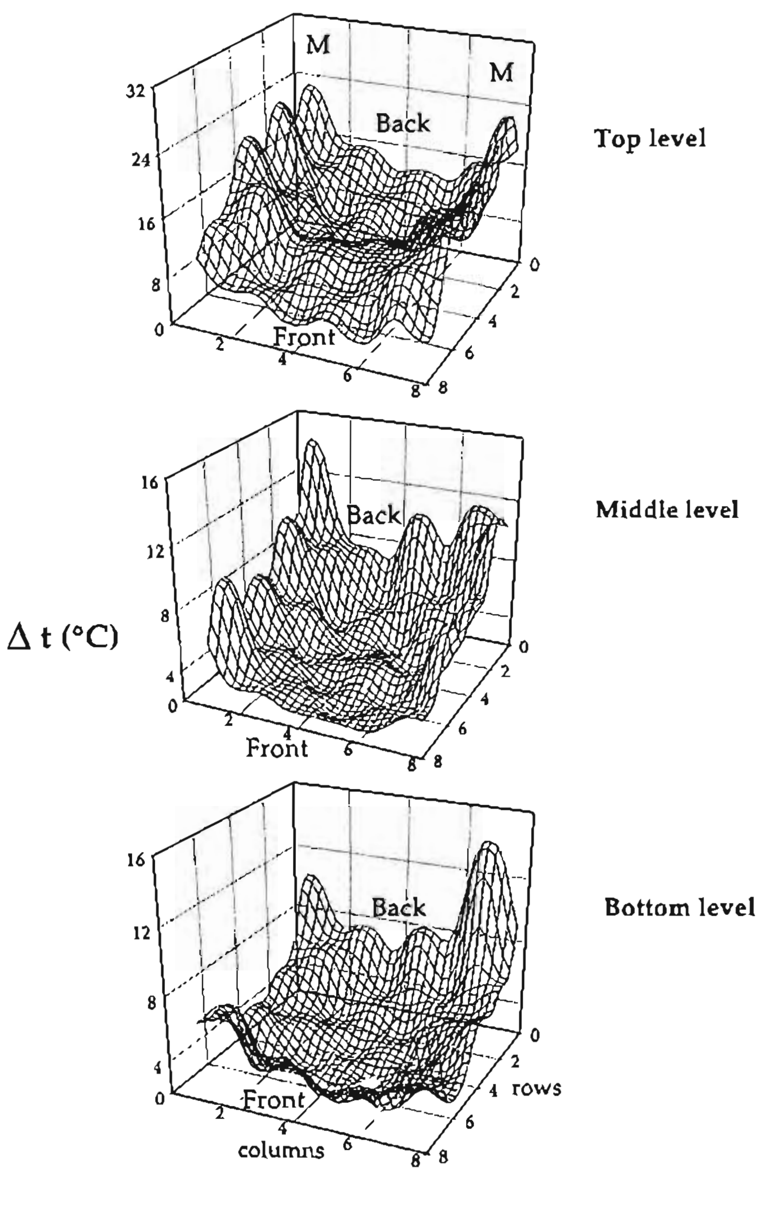

Figure 6. — 3-D plot of change in temperature (Δt) among 96 sampling locations within a 2,000-W oven. Sampling locations consisted of 25-mL vials filled with water and heated at full power for 45 seconds. *M* denotes the location of two megatrons, the sources of microwave emissions.

trols) artificially infested boards was low (< 4%), indicating high survivorship in boards before treatment and a robust test.

The variance in drywood termite mortality among boards treated by microwaves was high. For the 500-W oven, mortality among board replicates varied from 5 to 100 percent. Similarly, the 1,000-W and 2,000-W ovens had considerable variance in mortality, 9 to 100 percent and 8 to 100 percent, respectively. Lewis and Haverty (17) also reported considerable variance among microwave-heated boards from a study that simulated actual use conditions. The overall mean mortality for all ovens ($n = 3$) and all artificially infested boards ($n = 70$) was 84.6 ± 3.7 percent. This value was similar to a previously reported efficacy value (89.6 ± 4.0%) for artificially infested boards treated with microwaves (17).

Termite mortality was greatly influenced by duration of treatment (**Table 2**). Increasing duration of treatment significantly resulted in higher mortality ($F = 78.15$, df = 4,69, $p < 0.0001$). From the results, the lowest treatment duration (30, 20, or 10 sec. depending on the oven wattage) resulted in significantly lower mortality, < 50 percent (**Table 2**). Compared with unshielded field microwave devices, striking differences exist in treatment duration. While the maximum treatment duration for laboratory ovens (500-W) was 2.5 minutes per board (243.6 cm^2), the treatment duration for commercial unshielded field devices was 8 minutes per 311 cm^2 (18). We do not know the specifics on how the unshielded field devices differ from shielded ovens; however, treatment duration varies considerably.

There was little difference in mortality among galleries or gallery orientation 1 day after treatment. Mortality values among galleries ranged from 71.9 to 92.6 percent (**Table 3**). However, these differences were not significant ($F = 1.05$, df = 2, 208, $p > 0.35$). Lewis and Haverty (17) found similar gallery results during their investigations of a 700-W microwave device during their field evaluations of six drywood termite control methods. Board orientation, gallery 1 up or down, also had little impact on increasing mortality levels (**Table 4**). Water vial tests suggest the hottest portion of the oven to be near the top; how-

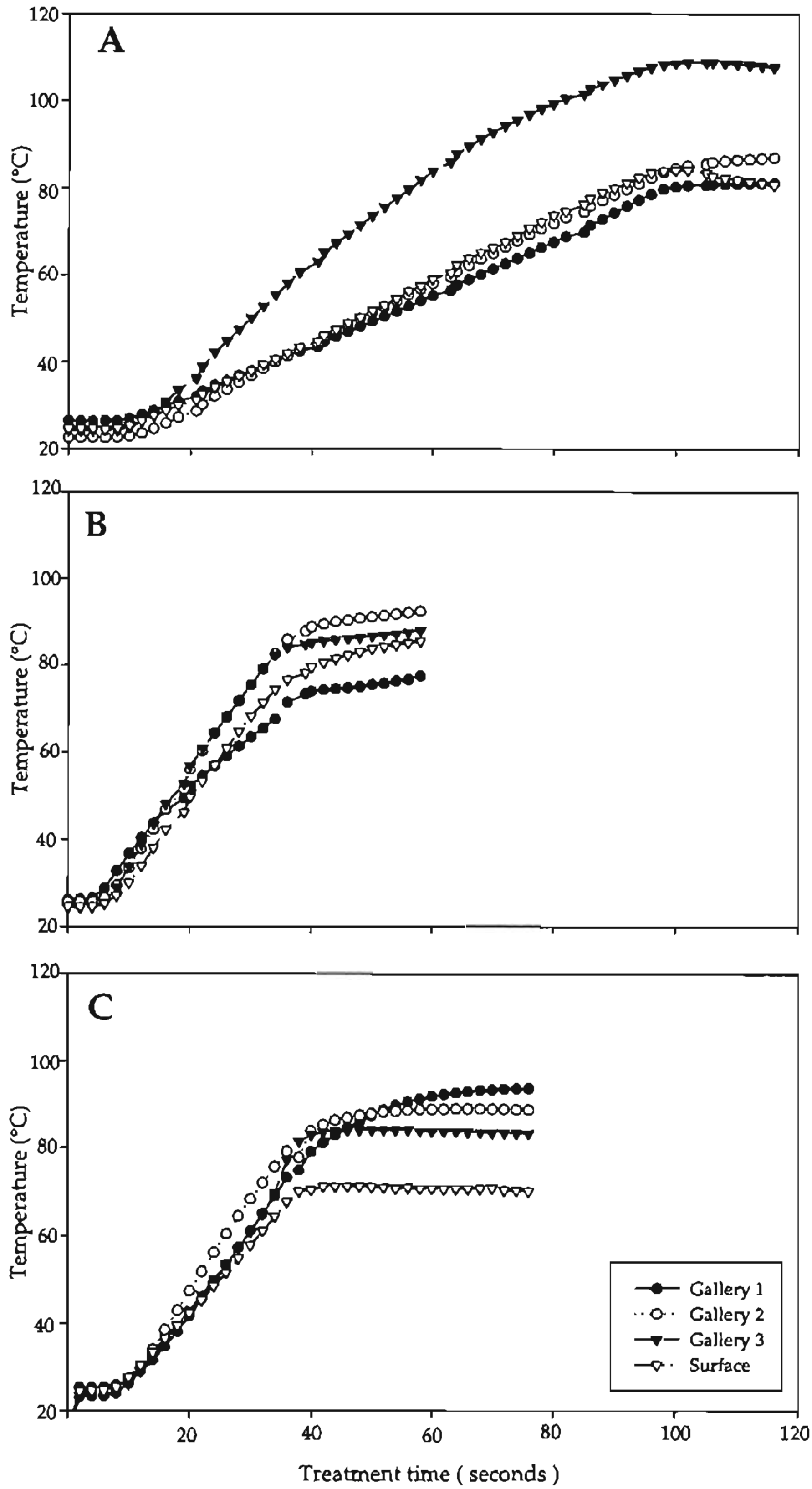

Figure 7. — Temperature changes for three gallery locations within a 2 by 4 Douglas-fir board (Fig. 3). (A) 500-W, (B) 1,000-W, and (C) 2,000-W ovens. Fourth temperature plot for each figure represents temperature on board surface. Exposure times within galleries varied with oven wattage: 1.5 minutes at full power for 500-W oven, 1 minute at full power for 1,000-W oven, and 30 seconds at full power for 2,000-W oven.

ever, gallery mortality results did not confirm these findings. Perhaps future studies can use boards that occupy larger volumes of ovens where temperature extremes are greater.

Temperature within galleries may explain survivorship from treatment. The shortest treatment duration did not achieve lethal temperatures for any of the three ovens (**Fig. 7**). For the drywood termites, temperatures of 51°C or more for > 10 minutes are lethal (6). In this study, it appears survival occurred because galleries did not reach 51°C during the first 30 seconds of treatment (**Fig. 7**). The discrepancy in lethal time of kill between the two studies is that the former involved the use of convection heat. Obviously microwave ovens raise the temperature of termites more quickly than convection heat. Drywood termites also display strong temperature preferences and readily move from areas of high temperature to cooler locations as demonstrated in the laboratory (3) and field (24).

Theoretically, temperature distribution within a microwave field should be homogeneous. In practice, the heat matrix within ovens is uneven due to internal reflection and absorption of energy, both microwave and convection, and by oven contents (18). Convection heating of test boards for the current study continued after removal from ovens (boards were warm to the touch for more than a minute). Lethal effects to drywood termites from convection heating has been previously reported (7,8,10,17,24, 31-33). How boards and termites absorb microwave and convection heat may involve many variables, including proximity to emitting source.

Number of surviving drywood termites generally declined with increasing treatment duration. Microwaves appear to be lethal to drywood termites in both laboratory and field applications. Although the use of microwave ovens for acquiring mortality data appears promising, caution must be taken in comparing the results of shielded and unshielded devices. Additional studies are needed for testing microwaves on termite-infested boards of larger dimension and boards covered with drywall or other wall-covering material. Safety evaluations of unshielded microwave-emitting devices are also needed to determine the effects on humans and wood products.

TABLE 3. — Percent mortality (mean ± SE) of drywood termites in one of three gallery locations within artificially infested boards 1 day after treatment in a microwave oven.[a]

Oven wattage	Gallery[b]		
	1st	2nd	3rd
	(%)		
500 W	71.9 ± 8.5 A	83.5 ± 6.6 A	88.0 ± 5.3 A
1,000 W	85.6 ± 6.8 A	92.6 ± 4.3 A	86.0 ± 6.6 A
2,000 W	82.6 ± 8.0 A	85.0 ± 7.5 A	86.9 ± 6.6 A

[a] Means followed by the same capital letter within a row are not significantly different (Ryan-Einot-Gabriel-Welsch multiple range test, $p > 0.05$).

[b] Three different routed spaces per board (Fig. 3). Twenty-five boards were used to generate each mean for 500-W and 1,000-W ovens; 20 boards were used to generate each mean for the 2,000-W oven.

TABLE 4. — Percent mortality (mean ± SE) of drywood termites in artificially infested boards 1 day after treatment in one of three microwave ovens and one of two gallery orientations.[a]

Oven wattage[b]	n[c]	Gallery 1	
		Up	Down
		(%)	
500 W	38/36	77.0 ± 5.9 A	85.8 ± 5.4 A
1,000 W	33/42	89.4 ± 4.7 A	87.0 ± 4.9 A
2,000 W	21/39	73.8 ± 9.3 A	90.7 ± 3.9 A

[a] Means followed by the same capital letter within a row are not significantly different (Ryan-Einot-Gabriel-Welsch multiple range test, $p > 0.05$).

[b] The 500-W and 1,000-W ovens had a single megatron (source of microwave emissions) on the upper right side. The 2,000-W had two megatrons, left and right side.

[c] Total number of galleries. First number represents the number of replications with gallery 1 in the up position. The second number represents the number of replications with gallery 1 in the down position.

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