Evaluation of Six Techniques for Control of the Western Drywood Termite (Isoptera: Kalotermitidae) in Structures

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ABSTRACT Chemical and nonchemical methods for control of western drywood termites, *Incisitermes minor* (Hagen), were evaluated under conditions that simulated infestations in structures. The efficacy of excessive heat or cold, electrocution, microwaves, and 2 fumigants was evaluated. Termite mortality in artificially infested boards was 100% at 3 d after treatment for both fumigant gases. Heating the whole-structure or spot-applications using microwaves resulted in 96 and 90% mortality, respectively, 3 d after treatment. Mortality levels 4 wk after treatment increased to 98% for heat and 92% for microwaves. Spot-applications of liquid nitrogen at 381.8 kg/m^3 achieved 100% mortality 3 d after treatment. However, for 122.7 and 57.3 kg/m^3, mortality levels 4 wk after treatment were 99 and 87%, respectively. Mortality by spot-applications of electricity was 44% 3 d after treatment in the 1st test. Four weeks after treatment drywood termite mortality increased to 81%. In a 2nd electrocution test, using spot-application techniques infrequently used in structures, mortality levels increased to 93% at 3 d and 99% at 4 wk after treatment. The distribution of termite survivors within the test building and test boards varied for some treatment techniques. For naturally infested boards, both fumigants exceeded 99% mortality. Use of heat and microwaves resulted in 100 and 99% mortality levels, respectively, 4 wk after treatment. Applications of liquid nitrogen resulted in mortality ≥99.8% at 381.8 and 122.7 kg/m^3; however, mortality for 57.3 kg/m^3 was significantly lower (74%). Mortality levels from electrocution were 89 and 95% 4 wk after treatment, respectively, in the 2 tests. Damage to test boards and the test building did occur. Six test boards were scorched during microwave treatment, 80% of test boards were damaged during electrocution, and visible signs of damage to the test building were noted for whole-structure heating. This study provides information for evaluation of the relative efficacy of fumigation and nonchemical alternatives for the control of drywood termite infestations in structures.

KEY WORDS drywood termite, *Incisitermes*, fumigation, nonchemical control, thermal control, electrocution

THE DAMAGE CAUSED by wood-destroying insects has an important economic effect. Nationwide, the cost of control and repair of damage nears $5 billion per year; the outlay in California and Hawaii exceeds $1 billion per year (Brier et al. 1988, Su and Scheffrahn 1990). In California, subterranean and drywood termites are responsible for >95% of all costs resulting from wood-destroying insects (Brier 1987, Rust et al. 1988). Damage by drywood termites is more common in southern California (Wilcox 1979).

For many years, the standard treatment for control of drywood termites has been fumigation with methyl bromide (MB) or sulfuryl fluoride (SF). These fumigants are effective against a variety of termite species in laboratory tests (Bess and Ota 1960, Osbrink et al. 1987, Scheffrahn and Su 1992). The theoretical dosages for MB and SF (3.5 and 3.0 mg/m^3, respectively) are similar (Stewart 1957). Depending on label instructions and conditions, the amount of fumigant used to treat a typical home ranges from ≈5 to 20 kg (Scheffrahn et al. 1995). For CO_2-synergized MB, an additional 106 kg of carbon dioxide (≈10% of the total volume of structure) are also required (Scheffrahn et al. 1995). The use of fumigants is considered a "whole-structure treatment" (the simultaneous treatment of all wooden members and extensive or difficult to access infestations) and should completely eradicate drywood termites within a structure (Scheffrahn and Su 1994). Unfortunately, there is relatively little scientific information on the effectiveness of fumigation from field studies.

The public is showing increased interest in nonchemical insect control in homes (Bennett et al. 1983, Levenson and Frankie 1983). The nonchemical alternatives presently marketed for control of

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drywood termites currently includes excessive heat or cold, electrocution, and microwaves. With the exception of excessive heat, the remaining nonchemical treatments are classified as "local or spot treatment" applications (Scheffrahn and Su 1994). These treatments are often restricted to a single spot within a board or small group of boards.

There is limited published research on any of the alternative control methods presented in this article. Forbes and Ebeling (1987) found that pseudergates of the western drywood termite, *Incisitermes minor* (Hagen), died if exposed to 51°C for >10 min during laboratory studies. When the temperature within wood was maintained at ≥48°C for at least 30 min in field demonstrations, Ebeling (1994) reported 100% mortality for *I. minor* pseudergates. Forbes and Ebeling (1986) reported that *I. minor* individuals died within 5 min at temperatures between −18.5 and −19.4°C. Rust et al. (1995) found that exposure of nymphs and alates in wooden blocks to temperatures below −21.4°C resulted in 100% mortality. Forbes and Ebeling (1986) were the first to demonstrate the spot-application method for killing drywood termites using liquid nitrogen (-180°C) in wall voids. There are no published reports on the efficacy of electrocution under field conditions. Ebeling (1983) reported empirical observations of routine commercial treatments. Mortality from one observed treatment was 74, 81.3, and 96.3% at 0, 26, and 57 d after treatment. Although highly speculative, Ebeling (1983) attributed delayed mortality to the destruction of intestinal protozoans.

Microwaves have been investigated as a means of destroying insects in dried foods, nuts, and stored grain (Watters 1976; Nelson 1977; Reagan et al. 1980; D'Ambrosio et al. 1982; Nelson and Payne 1982; Tilton and Vardell 1982a, b; Del Estal et al. 1986; Rosenberg and Bögl 1987; Locatelli and Traversa 1989) and for preserving textiles and museum specimens (D. Hall 1981, Philbrick 1984, A. Hall 1988). Thus far, there have been no published reports on effects of microwaves on termites.

Nonchemical methods are currently being marketed as replacements for structural fumigation for drywood termite control. Several of these methods are now being applied by pest control companies in several states. Here we report the test results of 2 types of fumigation and 4 methods marketed as alternatives to whole-structure fumigation. We tested each method against 2 levels of efficacy: 90 and 99% at 3 d and 4 wk after treatment.

Materials and Methods

Insects. Artificially infested and naturally infested boards were used. Termites placed in artificially infested boards were collected from wood containing *I. minor*. Termites were removed from wood by placing cut sections in Berlese funnels (Borror et al. 1989) or by dissection of wood. Termites removed by either collection technique were placed into birch, tongue depressor holding chambers (Bess and Ota 1960). Each rearing chamber was provisioned with ≈200 termites from mixed colonies. Rearing chambers were stored in clear plastic boxes and held in an enclosed cabinet in a greenhouse at ambient environmental conditions for several weeks before use. We selected healthy and uninjured pseudergates of at least the 4th instar; nymphs were used occasionally.

Test Building. To simulate field conditions a test building was built specifically for these tests (Fig. 1). The test building is 6.1 by 6.1 m (37.2 m^2; 154 m^3). Walls were built with 3.6 by 14.5-cm studs on 30.5-cm centers. No pressure-treated or otherwise chemically treated wood was used; foundation-grade redwood was used for bottom plates. The test building is symmetrical with doors and windows on all 4 sides (Fig. 1A). This symmetry allowed for testing unbiased by construction or aspect, and it enabled internal replication. The exterior consists of stucco walls and a shingled roof. Wooden panels with a door and 2 windows are detachable and centered on each wall. There are no interior walls, insulation, or fire-blocking. The foundation consists of slab and raised perimeter (Fig. 1A).

Preparation of Artificially Infested Boards. Kiln-dried, vertical grain, and clear Douglas-fir one-by-fours, two-by-fours, and four-by-sixes (cross-sectional dimensions of 1.8 by 8.7, 3.8 by 8.7, and 8.5 by 13.7 cm, respectively) were cut into 61-cm lengths. Each board consisted of 4 pieces made from 3 longitudinal cuts (Fig. 2). Three gallery spaces were routed into each board (Fig. 2). Seventy-five drywood termites were placed within each board, 25 per gallery. Boards with termites were held together with 2 pieces of 2 cm wide masking tape. Before installation, boards were stored at ambient conditions in the laboratory for 24 h. With the exception of untreated boards (controls), no individual board was used in more than 1 treatment or test.

Placement in the Test Building. Two testing options were offered to vendors. Option A consisted of localized treatment within wall voids. Option B, a whole-structure treatment. For option A, 4 one-by-fours, 16 two-by-fours, 4 four-by-sixes were used. Test boards were placed randomly in 1 of the 4 positions: the mid- or lower stud position in either the right or left stud (Fig. 1A). The test boards positioned at lower stud position rested on the sill plate. The orientation of galleries within a wall void was also randomized. Each board was affixed to the studs with two 0.3-cm-diameter drywall screws 5.1 cm long. For option B, the same methods employed in option A were used except an addition, 12 boards were installed in the attic and 12 in the subarea. These boards were also positioned randomly within the test building (Fig. 1). Boards and galleries orientation were randomized before installation. Treatment boards were in-

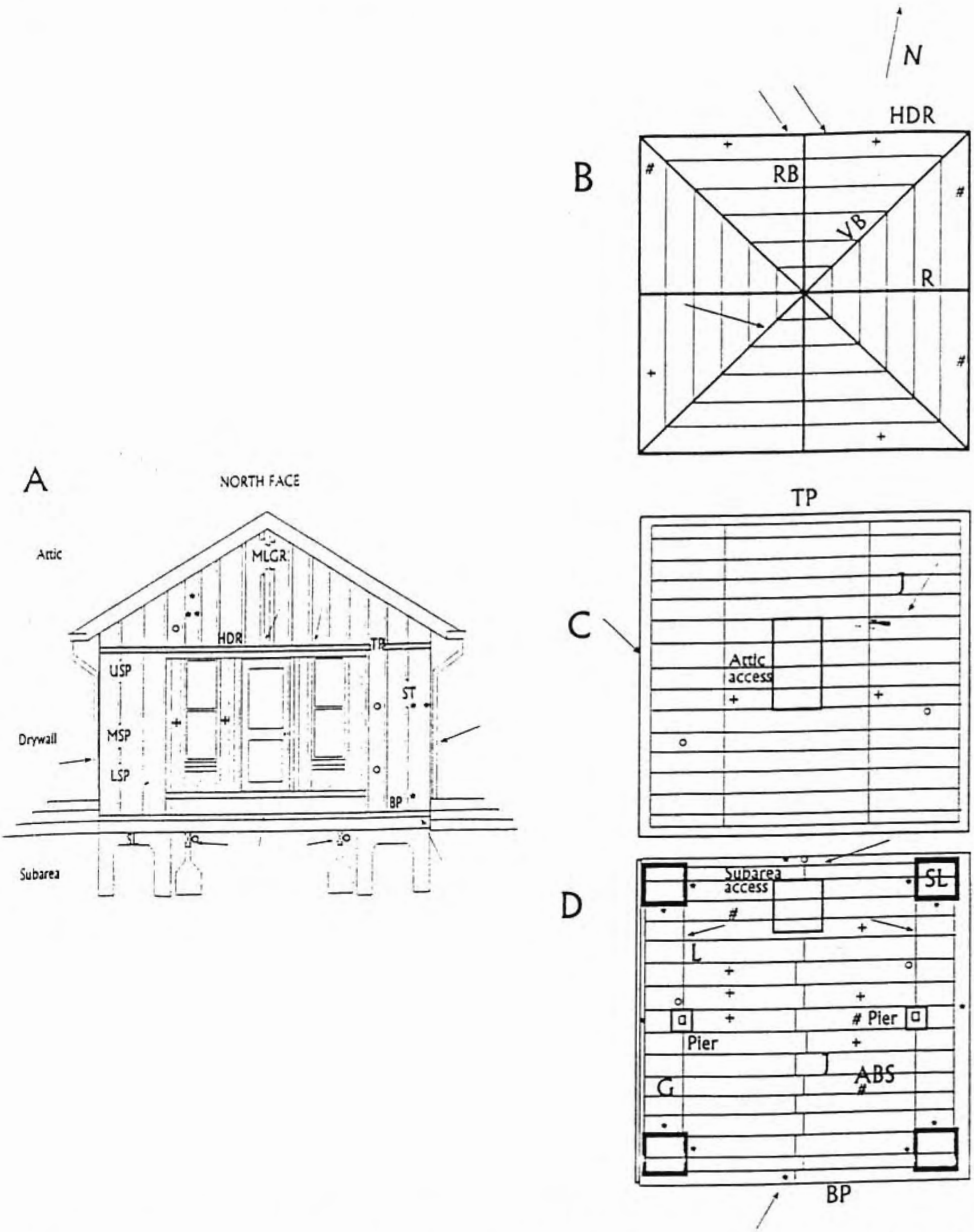

Fig. 1. Sagittal view of entire test building structure (A) and overhead views of attic rafters (B), ceiling joists (C), and subarea joists (D). ABS, plastic waste-water pipe; BP, bottom plate; G, 8.3 by 18.4-cm floor girder; HDR, 14 by 19-cm header; J, 3.7 by 13.5-cm joist; L, fluorescent light; LSP, lower stud position; MLGR, mid line gable roof; MSP, mid stud position; R, 3.7 by 13.5-cm attic rafter; RB, 3.7 by 23.2-cm ridge beam; SL, 1.2 by 1.2-m slab; ST, 3.7 by 13.5-cm stud; TP, top plate; USP, upper stud position; and VB, 8.5 by 23.2-cm valley beam. Artificially infested board locations are indicated by asterisk. Naturally infested board locations indicated by open circle. For the 2nd electrocution test, artificially infested board locations are indicated by + and naturally infested board locations are indicated by #. Thermocouple locations for heat treatments are indicated by arrows.

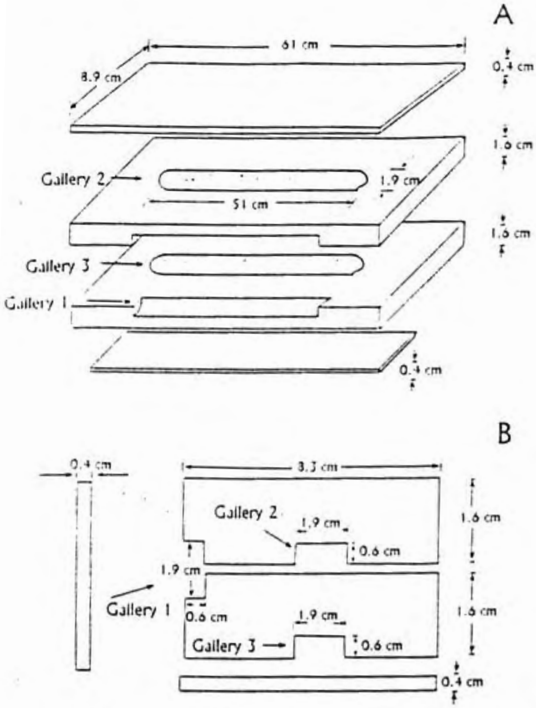

Fig. 2. Disassembled (A) and cross-sectional (B) views of a two-by-four Douglas-fir test board showing routed gallery locations. Drawings not to scale.

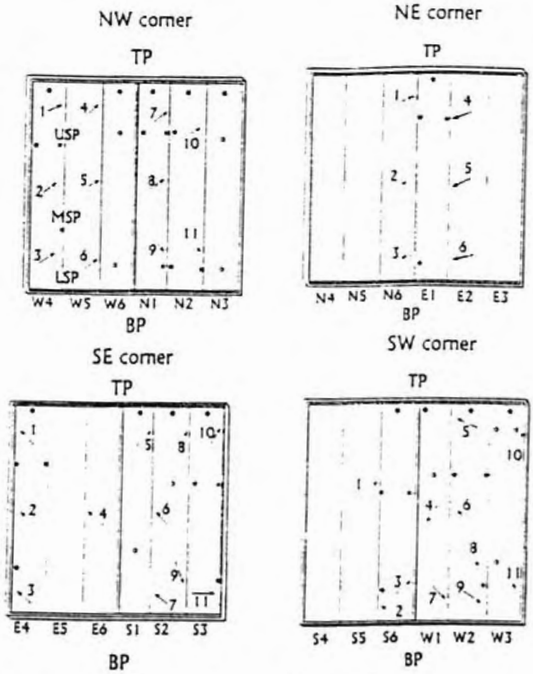

Fig. 3. Schematic drawing of drywall area treated with liquid nitrogen. Within-wall void space designation shown by letter-number combination below each wall. Locations on walls marked BP, bottom plate; LSP, lower stud position; MSP, mid stud position; ST, stud; TP, top plate; and USP, upper stud position. Artificially infested board locations are indicated by asterisk. Naturally infested board locations indicated by open circle. Thermocouple locations indicated by arrowed numbers. Solid circles indicate points of introduction for liquid nitrogen.

stalled in the test building ≈24 h before testing. Untreated boards were left undisturbed in a separate building ≈30 m from the test building.

Placement of Naturally Infested Boards. The criteria used for selecting naturally infested boards for the study were: standard dimensional lumber that fit in wall voids and acoustical emission (AE) readings >10 counts/min in at least 1 monitored position. Scheffrahn et al. (1993) reported AE readings ≥10 counts/min represent ≈20 live termites. We stratified boards into low, medium, and high acoustic activity, with corresponding acoustic emission readings of ≈10, 30, or >40 counts/min using a hand-held Wood-Destroying Insect Detector (DowElanco Indianapolis, IN). When possible, an equal number of boards within each category was installed in the 3 areas of the test building. In total, 9 naturally infested boards were used per test.

For spot application treatments 2 naturally infested boards were installed over doorway headers and 7 in wall voids (Fig. 1A). With liquid nitrogen treatments, all 9 naturally infested boards were installed in wall voids (Fig. 3). For whole-structure treatments, naturally infested boards were positioned throughout the test building (Fig. 1). All naturally infested boards within an AE category and test position were selected randomly.

Vendor Cooperation. Licensed commercial vendors were solicited for all applications in the test building (liquid nitrogen was applied by personnel from the University of California, Berkeley and Riverside campuses). Treatment applications that represented standard procedures in the field were agreed upon by the vendors and authors. Treatment effects, such as temperature or gas concentration, were monitored by the applicators. Electrocution and microwave treatments were not monitored.

Sulfuryl Fluoride. The test building was treated 3 times with SF (Vikane, DowElanco). The total calculated volume treated was estimated to be 198.2 m^3. The initial concentration of SF (Fumiguide, DowElanco) for each fumigation was 37.3, 11.6, and 12.6 g/m^3. All treatments were monitored with a Fumiscope (DowElanco); readings (g/m^3) were taken in the attic, drywall, and subarea. SF exposure time was ≈22 h. Accumulated SF (mg · h/m^3) was calculated for each fumigation (Scheffrahn et al. 1992). Exact placement of test boards was not known to the vendor.

Synergized Methyl Bromide. The test building was treated 3 times with CO_2-synergized MB (MAKR, Integrated Environments, Las Vegas, NV). The number of artificially and naturally infested boards installed was the same as those described above for SF. The total calculated volume treated was estimated to be 177.8 m³. The amount of MB (1.4 kg) and CO_2 (31.3 kg) was the same for each test. Time of exposure was ≈24 h. Initial and final MB and CO_2 gas concentrations were measured by piercing the tarpaulin and taking an internal air sample using a Draeger tube (National Draeger, Pittsburgh, PA). Tube readings 1 h into fumigation for the 1st and 3rd treatments were 1,500 ppm (6 g/m³) MB and 10% CO_2 and 2,000 ppm (8 g/m³) MB and 10% CO_2, respectively. Readings for the 1st and 3rd fumigations were also recorded for MB and CO_2 24 h after fumigation. The 2nd fumigation was not monitored. Accumulated exposure MB (mg · h/m³) was determined according to Scheffrahn et al. (1992). Exact placement of test boards was not known to the vendor.

Excessive Heat. The test building was heat-treated 3 times. The coldest initial temperatures in the test building before heating for each treatment date were 15, 12.2, and 8.9°C. The number and placement of artificially infested boards was the same as described for SF and MB. Exact placement of test boards was not known to the vendor. Thermocouples were used to record temperature changes (Fig. 1). Six thermocouples were used during the 1st test, 10 for the 2nd, and 11 for the 3rd. Four convection heaters (each 400,000 BTUs), powered by propane, were positioned outside and hot air blown inside through flexible ducts. Two 4.3-amp fans were used to improve heat distribution.

Excessive Cold. Three separate dosages were tested. For each test 24 artificially infested and 9 naturally infested boards were used. A 1.3-cm-diameter hole was drilled through the drywall near the top plate of the wall void to be treated (Fig. 3). Liquid nitrogen (Altair Gases & Equipment, Oakland, CA) was then injected from 160-l dewars into the wall cavity through a 1.2-m flexible woven stainless steel hose. The attic and subarea were inaccessible to treatments with this control method.

We calibrated the time it took to deliver a standard dose. Three accumulated dosages (381.8 kg/m³ [30 min at 1.4 kg/min], 122.7 kg/m³ [15 min at 0.9 kg/min], and 57.3 kg/m³ [7 min at 0.9 kg/min]) were tested. Temperature readings were taken with 12 thin-wire thermocouples attached to a scanning thermocouple thermometer (Cole-Parmer model #92800-00) every minute from 11 different locations in studs; one was used to monitor ambient air temperature (Fig. 3). Exact placement of test boards was known to the applicator.

Electrocution. The equipment used is commercially marketed as the Electrogun (Etex, Las Vegas, NV), a device that kills drywood termites by emitting high frequency electricity (100 kHz), high voltage (90,000 V), but low current (≈0.5 amp) (Anonymous 1991). For the 1st test, 48 artificially infested and 9 naturally infested boards were installed.

For exposed two-by-fours and smaller pieces of wood, the probe end of the device was placed against the wood surface. For larger pieces of wood and wood concealed behind drywall, a drill-and-pin method was used. Small holes (1.6 mm diameter) were drilled through the drywall and into the wood, and ≈15.2 cm long straight copper wires were inserted through the holes into the termite galleries. Several consecutive drillings per hole were used to insure that the electrical current was delivered at various depths within the boards. For applications conducted in the test building, knowledge of the exact location of all test boards was known by the vendor.

For the 2nd test, 18 artificially infested boards were installed in locations away from metal or concrete. Six boards each were installed in the attic, wall voids, and subarea (Fig. 1). The vendor was asked to treat the boards as before. Naturally infested boards were similarly installed for this 2nd test. Nine naturally infested boards were installed: 3 each in the attic, wall void, and subarea (Fig. 1).

Microwaves. The attic and drywall locations within the test building were treated twice with microwaves. Treatment procedures included treating infested wood with an unshielded microwave device, reported to be 700 W. This spot application treats a section of wood ≈10.2 by 30.5 cm (311 cm²). Treatment time was ≈8 min per spot. The theoretical accumulated dosage for microwave applications conducted is 0.3 W · h/cm². Thirty-three artificially infested and 9 naturally infested boards were installed. The exact location of test boards was known to the vendor.

Assessment of Treatment Efficacy. The day following treatment, all artificially infested boards were removed from the test building and stored in the laboratory until 3 d after treatment. Live and dead termites were counted. Live termites were placed in tongue depressor holding chambers. Percentage of mortality of these termites was determined at 4 wk after treatment. Termites crushed by handling were excluded for analysis. Untreated boards were assessed in the same manner.

Naturally infested boards were removed from the test building and stored in a greenhouse. At 4 wk after treatment, boards were cut into small lengths (≈10 cm) and carefully dissected. Live and dead termites were counted and sorted by caste.

For each artificially infested board, the percentage of mortality was calculated by combining data for all galleries of a board, i.e., the experimental unit. Separate records were kept for each gallery to account for anomalies in mortality as a function of the placement of a particular gallery within wall voids or near the foundation. An unfortunate complication resulted from the drill-and-pin method for using the Electrogun. Holes were left in the boards, occasionally allowing termites to escape. If the total number of termites remaining in an individual artificially infested board was <48, data for that board were discarded for analysis. Because we had little control over the number of termites in a naturally infested board, we calculated percentage of mortality using all live and dead termites removed from the board.

Statistical Analysis. For each treatment, the weighted mean response ($\overline{\overline{X}}$) and the standard error of the weighted mean ($SE(\overline{\overline{X}})$) for artificially infested and naturally infested boards were determined using the following formulae:

$$\overline{\overline{X}} = \sum_{i=1}^{3} \sum_{j=1}^{3} a_{ij}\overline{X}_{ij}$$

$$SE(\overline{\overline{X}}) = \sqrt{\sum_{i=1}^{3} \sum_{j=1}^{3} [a_{ij}se(\overline{X}_{ij})]^2}$$

where $\overline{X}_{ij}$ = the mean mortality for a board in the ith location in the building and for the jth size board, $se(\overline{X}_{ij})$ = the standard error associated with a particular mortality ($\overline{X}_{ij}$), a_{ij} = the proportion of lumber of dimension j placed in test within location i, i = location in the building: (1) attic, (2) drywall, and (3) subarea, j = dimension of lumber: (1) 1 by 4 or 1 by 8; (2) 2 by 4; and (3) 4 by 4, 4 by 6, 4 by 8, or 4 by 12. The relative proportions of wood (a_{ij}, i = 1, 2, 3, and j = 1, 2, 3) for 1 by 4s, 2 by 4s, and 4 by 6s, for each location within the test building summed to one:

$$\sum_{i=1}^{3} \sum_{j=1}^{3} a_{ij} = 1$$

The efficacy of each treatment was tested against 2 standards. Our null hypothesis was that each treatment is ineffective if the treatment resulted in mortality ≤90% (H_0: $P \leq 0.90$) or ≤99% (H_0: $P \leq 0.99$). At a minimum, to be considered effective, the mortality level for a treatment had to significantly exceed 90%. The equation used to test the significance of each hypothesis is:

$$t = \frac{\overline{\overline{X}} - m}{SE(\overline{\overline{X}})}$$

where m = level of mortality 90 or 99%.

All statistical tests of efficacy were determined by a 1-tailed t-test to determine whether the mean response exceeded the standard level of mortality (Steel and Torrie 1960). Statistical significance was tested at the $\alpha = 0.05$ level with ∞ degrees of freedom. For this study, each board for all treatment methods was considered a replicate.

Summary statistics for mortality levels among test building location, board dimension, and gallery designation were derived with the MEAN procedure (PROC MEAN, SAS Institute 1994). Means for termite mortality levels among test building locations, board dimension, and gallery designation were analyzed for significant differences using the Ryan–Einot–Gabriel–Welsch Q multiple range test (PROC GLM, SAS Institute 1994). Untreated replicates (controls) for each treatment method were pooled and mortality levels analyzed by board dimensional size and gallery designation using Ryan–Einot–Gabriel–Welsch Q multiple range test (PROC GLM, SAS Institute 1994).

All artificially infested boards were visually inspected after treatment for signs of damage according to the categories: drilled holes and burn marks. Differences in treatment time and number of drilled holes between the 2 electrocution tests were analyzed using Wilcoxon rank sum tests (chi-square approximation) (PROC NPAR1WAY, SAS Institute 1994).

Results and Discussion

Sulfuryl Fluoride. Termite mortality for all artificially infested boards in the SF treatments was 100% (Tables 1 and 2). This agrees with previous reports on SF efficacy (Su and Scheffrahn 1986, Thoms and Scheffrahn 1994). The lethal accumulated dosage reported for *I. minor* from laboratory studies is 51 mg · h/m³ (range, 45–66) (Osbrink et al. 1987). For field conditions, the lethal accumulated dosage for SF is higher: ≈160 mg · h/m³ (Stewart 1966). Therefore, even taking into consideration less than optimal treatment conditions (e.g., wind, temperature, tarpaulin conditions) the SF accumulated dosages for the current study appear to have been high (543, 252, and 210 mg · h/m³) and easily resulted in complete mortality.

Mortality at 3 d in the untreated (controls) artificially infested boards was low (<5%), indicating high survivorship in test boards before treatment. However, mortality in the untreated boards after 4 wk increased 5-fold, suggesting the occurrence of nontreatment mortality (i.e., natural and handling). Differences in mortality among board dimensions for untreated boards were not significant (F test, $P > 0.05$) at 3 d or 4 wk after treatment.

Overall mean mortality for naturally infested boards was significantly >99% (Table 3); only 1 soldier survived. Although a single survivor among thousands is insignificant, this finding is scientifically curious. Lethal SF dosages for soldier castes for a number of termite species have been previously reported (Osbrink et al. 1987). However, values for *I. minor* were not included. No visible signs of damage were noted for test boards treated with SF.

CO_2-synergized Methyl Bromide. Termite mortality for all artificially infested boards was 100% (Table 1). Mortality at 3 d in the untreated artificially infested boards was moderate, ranging from 8.0 to 16.2%. Nontreatment mortality for untreated boards increased 2-fold at 4 wk after treatment. The differences in mortality among board dimension for untreated boards for 3 d and 4 wk posttreatment was not significant ($P > 0.05$). The mortality level for naturally infested boards after CO_2-synergized MB fumigation was 99.8% (Table 3). Thirty survivors were found in one 2 by 4 in the subarea. None of these survivors were reproductives, though surviving pseudergates can readily

Table 1. Overall percentage of mortality (mean ± SE) of drywood termites at 3 d after treatment in artificially infested boards treated in situ with 1 of 6 control methods

Treatment	n_1[a]	Mean ± SE	n_2[b]	Location in building[c]			t-statistic[d]	
				Attic	Drywall	Subarea	90%	99%
Sulfuryl fluoride[e]	84	100.0 ± 0	0	100.0	100.0	100.0	∞*	∞*
CO_2-MB[e]	84	100.0 ± 0	0	100.0	100.0	100.0	∞*	∞*
Excessive heat[e]	83	96.1 ± 1.0	10	100.0	100.0	85.8	5.92*	−2.81
Liquid nitrogen[f]								
381.8 kg/m³	23	100.0 ± 0	0	INA	100.0	INA	∞*	∞*
122.7 kg/m³	24	98.2 ± 1.0	3	INA	98.2	INA	8.10*	−0.80
57.3 kg/m³	24	84.3 ± 3.6	18	INA	84.3	INA	−1.59	−4.10
Electrocution[f]								
Test 1	48	43.8 ± 3.0	48	25.9	54.2	40.8	−15.5	−18.5
Test 2	18	93.4 ± 2.5	9	99.8	85.6	95.0	−1.31	−2.15
Microwaves[f]	33	89.6 ± 4.0	9	88.9	89.9	INA	−0.11	−2.35

Values followed by an asterisk are statistically significant at the $\alpha = 0.05$ level. INA, inaccessible to treatment.
[a] Total number of test boards used during treatments.
[b] Number of test boards with live termites 3 d after treatment.
[c] Percentage of mortality for boards placed in the attic, drywall, and subarea.
[d] For artificially infested boards, critical t values must be >1.65 to reject the null hypothesis.
[e] Whole-structure treatments.
[f] Spot- or localized treatments.

differentiate into secondary reproductives and initiate new infestations.

Lethal accumulated dosages for MB (including synergized form) have been reported previously for 2 *Incisitermes* species (Stewart 1957, Bess and Ota 1960, Scheffrahn and Su 1992). From laboratory studies, the lethal accumulated dose for 99% mortality range from 40 to 67 mg · h/m³. Label dosages recommended for field use, accounting for uncontrolled MB losses and sorption, are higher, 256–1,156 mg · h/m³ (Scheffrahn and Su 1992). Lethal accumulated dosages for the current study were more comparable to laboratory findings (118–142 mg · h/m³). Scheffrahn and Su (1992) have reported that label rates for MB in structures were excessive by as much as 4-fold. In a subsequent study, a synergized ratio of ≈2-fold supports claims of high levels of efficacy for reduced MB dosages (Scheffrahn et al. 1995). Results from our study support the published findings. There were no visual signs of damage to test boards from CO_2-synergized MB exposure.

Excessive Heat. Termite mortality in artificially infested boards was 100% except in the subarea (Tables 1 and 2). The overall mean for all artificially infested boards treated was 96.1% at 3 d and 97.5% at 4 wk after treatment. Both aggregate mortality values were significantly above the 90%

Table 2. Overall percentage of mortality (mean ± SE) of drywood termites at 4 wk after treatment in artificially infested boards treated in situ with 1 of 6 control methods

Treatment	n_1[a]	Mean ± SE	n_2[b]	Location in building[c]			t-statistic[d]	
				Attic	Drywall	Subarea	90%	99%
Sulfuryl fluoride[e]	—[f]	—	—	—	—	—	∞*	∞*
CO_2-MB[e]	—	—	—	—	—	—	∞*	∞*
Excessive heat[e]	83	97.5 ± 0.8	10	—	—	91.1	9.00*	−1.80
Liquid nitrogen[g]								
381.8 kg/m³	—	—	—	INA	—	INA	∞*	∞*
122.7 kg/m³	24	99.6 ± 0.8	3	INA	98.2	INA	12.1*	0.75
57.3 kg/m³	24	87.0 ± 3.1	17	INA	84.3	INA	−0.98	−3.93
Electrocution[g]								
Test 1	48	81.2 ± 3.0	40	75.2	85.3	79.2	−4.27	−8.64
Test 2	18	98.5 ± 1.0	3	100.0	95.6	100.0	9.33*	−0.55
Microwaves[g]	33	91.9 ± 3.5	9	90.0	93.0	INA	0.54	−2.02

Values followed by an asterisk are statistically significant at the $\alpha = 0.05$ level. INA, inaccessible to treatment.
[a] Total number of test boards used during treatments.
[b] Number of test boards with live termites 4 weeks after treatment.
[c] Percentage of mortality for boards placed in the attic, drywall, and subarea.
[d] For artificially infested boards, critical t values must be >1.65 to reject the null hypothesis.
[e] Whole-structure treatments.
[f] Treatments had 100% mortality 3 d after treatment.
[g] Spot- or localized treatments.

Table 3. Overall percentage of mortality (mean ± SE) of drywood termites at 4 wk after treatment in naturally infested boards treated in situ with 1 of 6 control methods

Treatment	n_1[a]	Mean ± SE	n_2[b]	Location in building[c]			t-statistic[d]	
				Attic	Drywall	Subarea	90%	99%
Sulfuryl fluoride[e]	15	99.9 ± 0.2	1	100.0	99.8	100.0	123.6*	11.2*
CO_2-MB[e]	17	99.8 ± 0.3	1	100.0	100.0	99.5	57.6*	4.7*
Excessive heat[e]	18	100.0 ± 0	0	100.0	100.0	100.0	∞*	∞*
Liquid nitrogen[f]								
381.8 kg/m³	8	100.0 ± 0	0	INA	100.0	INA	∞*	∞*
122.7 kg/m³	9	99.8 ± 0.1	2	INA	99.8	INA	98.0*	8.0*
57.3 kg/m³	9	74.3 ± 11.7	5	INA	74.3	INA	−1.34	−2.11
Electrocution[f]								
Test 1	9	88.6 ± 4.9	8	92.5	87.9	85.3	−0.29	−2.12
Test 2	8	95.1 ± 1.31	5	98.7	92.4	95.4	3.89*	−2.98
Microwaves[f]	9	98.7 ± 0.8	3	INA	98.7	INA	10.9*	−0.38

Values followed by an asterisk are statistically significant at the $\alpha = 0.05$ level. INA, inaccessible to treatment.
[a] Total number of test boards used during treatments.
[b] Number of test boards with live termites at 4 wk after treatment.
[c] Percentage of mortality for boards placed in the attic, drywall, and subarea.
[d] For artificially infested boards, critical t values must be >1.86 to reject the null hypothesis.
[e] Whole-structure treatments.
[f] Spot- or localized treatments.

level of acceptance (Tables 1 and 2). Mortality in the subarea at 3 d and 4 wk after treatment was 85.8 and 91.1%, respectively. Both values were significantly different from mortality values for the attic and drywall ($F = 17.6$; df = 2, 80; $P < 0.0001$; $F = 11.4$; df = 2, 83; $P < 0.0001$).

There was an uneven distribution of mortality for artificially infested test boards in the subarea. The size of artificially infested boards did not have a significant impact on mortality levels achieved at 3 d or 4 wk after treatment. However, survival occurred only in gallery 2, when positioned against the foundation wall. At 3 d after treatment, mortality in gallery 2 (78.2%) was significantly lower than gallery 1 (94.5%) and gallery 3 (92.2%) ($F = 7.1$; df = 2, 208; $P < 0.0011$). Similarly at 4 wk after treatment, mortality for gallery 2 (80.7%) was significantly lower than gallery 1 (95.3%) and gallery 3 (92.8%) ($F = 6.4$; df = 2, 208; $P < 0.002$). All thermocouples reached the 50°C lethal temperature for at least 1 h. The maximum air temperature recorded in the test building was 87.2°C during the 2nd treatment. However, there were still survivors. We do not know how much more time would have been required to achieve 100% mortality for all test boards in the subarea.

Termite mortality (mean ± SD) in untreated artificially infested boards was initially moderate, 12.7 ± 14.7%. However, at 4 wk, mortality increased to 33.5 ± 16.8%. These results suggest that termites used for the heat trials were less robust than for other methods tested.

In naturally infested boards, mortality was 100% across all test locations in the test building (Table 3). From these results with both artificially and naturally infested boards, we conclude that excessive heat, applied as described, results in mortality that significantly exceeds 90% and may exceed 99%.

These treatments resulted in few visible signs of damage; minor warping of some two-by-four and four-by-six test boards. Other changes noted in the test building included doors sticking (reversible damage), fluorescent lights going-out (reversible damage), and warping of a nonfunctional ABS waste-water pipe (nonreversible damage). Under normal field conditions, however, a low volume of cold running water would be left on to prevent the deformation of plastic pipes. Minor structural damage from heat treatment, as well as pretreatment preparations to minimize damage to household items, have been reported previously (Forbes and Ebeling 1987, Ebeling 1994).

Excessive Cold. Our assessment of the effectiveness of spot-treatments with liquid nitrogen was mixed and highly influenced by dosage and thermocouple placement. At the highest dosage tested, 381.8 kg/m³, both 3-d and 4-wk mortality of drywood termites in artificially infested boards was 100%. The 3-d and 4-wk mortality levels for the 122.7 kg/m³ dosage was also very high and exceeded 90% level of efficacy (Tables 1 and 2). However, for the 57.3 kg/m³ dosage neither 3-d mortality (84.4%) nor 4-wk mortality (87.0%) exceeded the 90% efficacy level (Tables 1 and 2). Rust et al. (1995) reported that the minimum dosage required to achieve 100% control with liquid nitrogen was 202 kg/m³ from tests conducted in an uninsulated wall. Their results agree with ours. Dosage rates below 200 kg/m³ are not likely to achieve the minimal lethal temperature or result in eradication of drywood termites in walls.

Mortality in untreated artificially infested boards 3 d after treatment was <5%, suggesting termites were robust before treatment. Mortality in untreated artificially infested boards at 4 wk increased ≈5-fold, indicating the occurrence of nontreatment mortality. There were no significant differences in mortality among board dimensional sizes or gallery designations for untreated boards ($P > 0.05$).

Lumber dimensions appear to affect termite mortality, at least for the 2 lower dosages of liquid nitrogen tested. At 4 wk after treatment, termite mortality (mean ± SD) for four-by-sixes treated with the 122.7 and 57.3 kg/m^3 dosages was 92.3 ± 9.4% and 77.3 ± 23.8%, respectively. By comparison, mortality for one-by-fours treated with the 122.7 and 57.3 kg/m^3 dosages was 100% and 97.7 ± 3.1%. For two-by-fours treated with the 122.7 and 57.3 kg/m^3 dosages, the corresponding mortality was 99.8 ± 0.7% and 86.7 ± 13.8%. However, these differences in mortality were statistically significant only for four-by-sixes treated with the 122.7 kg/m^3 dosage at 3 d and 4 wk posttreatment ($F = 7.7$; df = 2, 23; $P < 0.003$; $F = 7.5$; df = 2, 23; $P < 0.004$). Wood is a poor thermal conductor. Results from these tests suggest that wood, if relatively sound, may provide termites with insulation and protection from the lethal effects of excessive cold.

Considerable variation in temperature was recorded in wall voids for all liquid nitrogen dosages tested. Of the 26 wall void spaces treated with 122.7 or 57.3 kg/m^3 dosages, 15 (58%) were found to contain test boards with live termites. Minimum lethal temperatures (−28.9°C) were not achieved in 7 of these void spaces.

However, 8 void spaces containing boards with live termites had thermocouples that recorded minimum lethal temperatures. For the 122.7 kg/m^3 dosage, wall voids and minimum temperatures achieved were N3 (−67°C), E1 (−83°C), and W6 (−33°C). At the 57.3 kg/m^3 dosage, the wall void designation and minimum temperatures achieved were E1 (−37°C), S2 (−45°C), S3 (−56°C), W2 (−88°C), and W3 (−35°C) (Fig. 3). These results emphasize that higher dosage rates and thermocouple placement for verification of temperature are critical for achieving high levels of efficacy.

Naturally infested boards revealed a pattern similar to that of artificially infested boards, i.e., decreasing levels of mortality with decreasing dosage rates (Table 3). For the 381.8 kg/m^3 rate, termite mortality was 100%. Similarly, the 122.7 kg/m^3 dosage significantly exceeded 99% mortality (Table 3). The 57.3 kg/m^3 dosage, however, achieved an overall mortality level of only 74.3%, well below the 90% level of efficacy (Table 3). Live alates were found among the survivors for the 122.7 and 57.3 kg/m^3 rates. Similar to the results with artificially infested boards, it was difficult to predict successful treatment from thermocouple readings. For example, survivors were found in a two-by-four treated at the 122.7 kg/m^3 dosage even though lethal minimum temperatures (−37°C and −67°C) were achieved at the top and bottom thermocouples, N3-#10 and N3-#11, respectively (Fig. 3).

Because we could not obtain information on application rates from a vendor who applies liquid nitrogen, we assessed different dosage rates to identify a minimum application rate that was efficacious. The 57.3 kg/m^3 (6.3 kg of liquid nitrogen per wall void) dosage would not be effective for achieving a satisfactory level of mortality. The 122.7 kg/m^3 (13.5 kg of liquid nitrogen per wall void) application rate would be the absolute minimum to achieve a reasonable level of mortality (>95%). Application rates exceeding 200 kg/m^3 (42 kg of liquid nitrogen per wall void) are more likely to guaranty mortality levels in excess of 99%.

There were no visual signs of damage to boards treated with liquid nitrogen. However, frost formation during treatment can be considerable and may cause damage to wall coverings. With this treatment, repair of drilled insertion holes is required.

Electrocution. Efficacy in the 1st test was below the minimum level of acceptance (90%) for artificially infested boards. The overall mortality value for the entire structure was 43.8% at 3 d after treatment. Drywood termite mortality in artificially infested boards was well below 50% in the attic and subarea at 3 d after treatment (Table 1). In the drywall, area mortality reached 50% and was significantly greater than in the attic ($F = 8.0$; df = 2, 47; $P < 0.001$). There were no significant differences in mortality among board dimensional sizes ($P > 0.05$). Differences in mortality (mean ± SD) within boards were considerable; 61.8 ± 30.1% for gallery 1, 26. 8 ± 32.3% for gallery 2, and 46.0 ± 36.7% for gallery 3; were significantly different from one another ($F = 13.9$; df = 2, 142; $P < 0.0001$).

Four weeks after treatment, mortality increased to 81.2%. However, treatment efficacy was still significantly below the 90% minimum (Table 2). There were no significant differences in percentage of mortality among treated areas or boards within the test building ($P > 0.05$). Within test boards, gallery 2 had significantly lower mortality (66.9 ± 29.9%) than galleries 1 (89.9 ± 15.8%) or 3 (82.3 ± 24.9%) ($F = 11.4$; df = 2, 140; $P < 0.0001$). Variable results while using electrocution (mortality ranging from 3 to 100% for artificially infested boards) have been reported previously (Ebeling 1983).

Mortality in the naturally infested boards used in the 1st test showed a pattern of low mortality similar to that observed in the artificially infested boards (Table 3). Eight of 9 boards contained surviving termites, whereas 2 of these 8 boards had several hundred survivors. The overall mortality level, 88.6% at 4 wk after treatment, clearly did not exceed the 90% level of efficacy (Table 3).

There are several possible explanations for the poor performance of electrocution during the 1st test. First, penetration of electrical current into wood is limited. Ebeling (1983) reported that the surface application of electricity is restricted to only 1.3 cm deep into wood. In the current study, the size of boards containing termites was not a factor as there were no significant differences in mortality among board dimensional sizes ($P > 0.05$). The depth of galleries containing termites also appeared to be unrelated to termite mortality because the deepest gallery, gallery 3, had a higher mortality percentage than gallery 2, the shallowest. In fact, the drywall locations, sites where wood was not exposed, had significantly higher levels of mortality in artificially infested boards than the exposed artificially infested boards in the attic (Tables 1 and 2).

A 2nd possible limiting factor for electrocution treatments is delayed mortality (Ebeling 1983). However, the increased mortality observed at 4 wk after treatment, as high as 4-fold (i.e., 22% 3 d after treatment versus 87% 4 wk after treatment in artificially infested one-by-fours in the attic), was probably not caused by the effects of electrocution. Mortality in the untreated artificially infested boards was also high, as high as 60-fold (i.e., 0.5% 3 d after treatment versus 30% 4 wk after treatment in two-by-fours), and suggest that increased mortality seen in boards treated by electrocution at 4 wk after treatment was caused by nontreatment sources, such as handling and missing.

Results for test 2 from boards installed away from metal and concrete were improved. Three-day assessment of artificially infested boards showed increased mortality, but not significantly above the 90% level (Table 1). However, mortality at 4 wk after treatment (98.5%) exceeded the 90% efficacy level (Table 2). In the 2nd test there were no significant differences in percentage of mortality among locations within the test building, board dimensional size, or gallery ($P > 0.05$). Mortality in untreated boards during the 2nd test was low at 3 d and 4 wk: 1.5 and 8.3%, respectively. These data suggest robust termites occupied boards before treatment.

Mortality in naturally infested boards was also higher than in the 1st test (Table 3). Only 5 boards contained survivors, as compared with 8 in the 1st test. However, one board contained >100 survivors. The mortality level in naturally infested boards for the entire structure was 95.1%, significantly exceeding 90%, but not the 99% level of efficacy (Table 3).

The improved performance of electrocution in the 2nd test warrants discussion. Ebeling (1983) claimed that mortality effects of electrocution were heightened when test boards were placed on a metal table. Results of our study suggest an opposite interpretation: metal impedes the effects of electrocution. However, this finding is confounded by 2 factors: significantly more time was spent treating each test board in the 2nd test (27.0 ± 21.7 min, $n = 33$ verses 6.9 ± 5.6 min, $n = 16$; $\chi^2 = 26.2$, df = 1, $P < 0.0001$) and significantly more holes were drilled per board during the 2nd test (13.1 ± 6.8 holes verses 6.5 ± 5.0 holes; $\chi^2 = 15.3$, df = 1, $P < 0.0001$). Range in treatment time for the 1st test varied from 1.5 min (artificially infested one-by-four) to 25 min (artificially infested four-by-six). The range of treatment time during the 2nd test was considerably longer: 10 min (artificially infested one-by-four) to 1.75 h (naturally infested two-by-four). The range in number of drilled holes varied from 4 (artificially infested 2 by 4) to 48 (naturally infested two-by-four). Because most of the test boards were treated with the drill-and-pin technique (59 of 66 for artificially infested boards and 14 of 18 naturally infested boards), statements cannot be made about passing the probe end emitting electricity over boards when treating. Additional research is needed to determine the effects of treatment time and use of metal pins on termite mortality. Without these studies a minimally effective application rate cannot be determined.

We conclude that the efficacy of this treatment appears to be excessively technique driven and displayed poor control for drywood termites. Clearly, electrocution causes mortality in termites. To achieve reasonable levels of mortality the operator should use the drill-and-pin technique and spend as much time as possible treating an infested area. However, it is unclear how often the drill-and-pin method of application is used under field conditions. This control method, more than any of the others evaluated in this study, requires precise information as to the extent and location of the drywood termite infestation. Without accurate delimiting of the infestation, efficacy will likely drop to unacceptable levels.

Damage to test boards using electrocution was considerable. Eighty percent (53 of 66) of artificially infested boards and 78% (14 of 18) of naturally infested boards, showed visual signs of damage. Drill holes from administration of the drill-and-pin technique comprised most of the damage. Twenty-nine test boards also had minor burn marks. Ebeling (1983) reported that because wood is a poor insulator it could be carbonized or destroyed during treatment as current seeks a path to ground. Future studies involving varied time exposures and currents are necessary to more fully understand effects of electrocution on wood strength and appearance, especially for wood in concealed locations.

Microwaves. Considerable variability in mortality was observed in artificially infested boards treated with microwaves. Mortality at 3 d and 4 wk after treatment did not significantly exceed the 90% efficacy level (Tables 1 and 2). At 3 d or 4 wk after treatment there were no significant differences in termite mortality between the attic and drywall, among board sizes, or gallery locations within boards ($P > 0.05$). However, there was considerable variation in mortality, especially among one-by-fours in the attic and wall voids and two-by-fours in wall voids. This high variance among treated boards resulted in the acceptance of the null hypothesis (i.e., the treatment did not exceed the minimum criteria of 90% mortality) even though the individual means were ≥90%. In wall voids, one-by-four test boards had lower mortality than two-by-fours and four-by-sixes, but this difference was not significant ($P > 0.05$). Mortality in untreated artificially infested boards was low (<5% at 3 d after treatment), but increased 5-fold at 4 wk after treatment. Mortality was not significantly different in untreated boards of various size dimensions ($P > 0.05$).

The mean mortality (mean ± SD) for naturally infested boards was 98.7 ± 2.4% and significantly exceeded the 90% efficacy level (Table 3). Forty-five survivors were found among 3 boards.

The results of the microwave tests were mixed. Without a doubt, sufficient microwave energy applied to infested wood would kill termites. Termite mortality in artificially infested boards approached 90% but did not exceed 90% with statistical certainty. Mortality of termites in naturally infested boards exceeded the 90% efficacy level. Because microwaves applications were not monitored, comparisons of theoretical ($W \cdot h/cm^2$) and actual dosage can not be determined. As with electrocution, definition of the extent of an infestation, location of the infested wood, and access to the infested wood are critical to achievement of the desired level of mortality with microwave treatments.

Visible signs of damage were noted for some artificially infested boards. Minor warping of test boards was noted and 6 boards were burned, 2 severely. In shielded microwave ovens, internal oven reflection and nonuniform absorption of energy prevent uniform heating of materials in the microwave field (Locatelli and Traversa 1989). Unshielded microwave devices may also produce nonuniform heating of boards during treatment for termites.

The microwave method of drywood termite control appears to have promise as an effective spot-treatment technique. However, we feel more information is needed to determine the correct exposure time to achieve the desired level of control. Studies are needed on penetration of microwave energy into wood for varying wattage levels. Monitoring temperature changes in building materials during treatment could improve efficacy.

Sources of Nontreatment Mortality. Less than 3% of all termites in treated artificially infested boards died because of nontreatment mortality. The largest source of handling mortality (1.9%) was the accidental crushing of individuals between veneer sections of test boards. Nontreatment mortality of termites in untreated artificially infested boards (controls) was slightly higher at 7%. For untreated boards, the greatest source of nontreatment mortality (5.7%) was missing individuals. Because only 2 artificially infested boards (total 493) were excluded from analysis for insufficient numbers of termites, we conclude that our methods employed minimized nontreatment mortality and experimental error.

General Discussion. Three of the 6 methods tested (both fumigants and whole-structural heat) for control of drywood termite infestations achieved or exceeded the 90% efficacy level for both artificially and naturally infested boards for all dosages tested. This study was a test of treatment efficacy under best case conditions. Under normal field conditions, treatments may not always be done so carefully and with such advance knowledge regarding the location and intensity of infestation. Before testing, all vendors made claims of high or total elimination of drywood termite infestations within homes. Test results from whole-structure treatments for artificially and naturally infested boards reveal that only the fumigant gases demonstrated near 100% elimination. Whole-structure treatment with heat was very similar.

For localized treatments, 381.8 and 122.7 kg/m^3 dosages of liquid nitrogen and long application times using drill-and-pin techniques with electrocution were efficacious at the 90% level. Microwave treatments (700 W) were deemed efficacious at the 90% level, but only when treating naturally infested boards. Not efficacious, even at the 90% level, were electrocution without drill-and-pin technique and 57.3 kg/m^3 treatments of liquid nitrogen.

In general, treatments that used monitoring instruments fared better than nonmonitored treatments. Although damage may occur from fumigation, heat, or microwaves, it is a certainty for liquid nitrogen (repairs to drilled holes in wall voids) and electrocution (drill-and-pin applications). The development of improved devices to monitor termite populations termite in situ could improve the performance of all spot-treatment techniques. Field efficacy rates for all available drywood termite control methods, mode of action of these techniques, safety to technicians, and potential damage to structures are important areas for future research.

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