Simulated Field Evaluation of Six Techniques for Controlling the Drywood Termite *Incisitermes minor* (Isoptera: Kalotermitidae) in Residences

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ABSTRACT Nonchemical and chemical methods for control of drywood termites were evaluated under simulated field conditions. Specifically, we assessed the efficacy of four methods currently marketed as alternatives to whole-structure fumigation for control of drywood termites: excessive heat, excessive cold, electrocution, and microwaves. In addition, we evaluated a reduced dosage of methyl bromide synergized with carbon dioxide, as well as a standard fumigation treatment with sulfuryl fluoride.

Tests were conducted using *Incisitermes minor* (Hagen) in artificially infested or naturally infested boards of various dimensions used in construction. Infested boards were placed into the attic, drywalls, or subarea of the *Villa Termiti*, a symmetrical building constructed specifically for these tests. Commercial pest control operators performed 5 of the 6 control methods; liquid nitrogen was applied by University of California personnel. For artificially infested boards, mortality was measured 3-d and 4-wk post-treatment. For naturally infested boards, mortality was evaluated only 4-wk post-treatment. Efficacy performance of all treatments was compared to 90, 95, and 99 percent levels of mortality.

Termite mortality in artificial boards was 100 percent at 3-d and 4-wk post-treatment for both fumigant gases. Heating the whole-structure or spot-applications using microwaves resulted in 96 and 90 percent mortality, respectively, 3-d post-treatment. Mortality levels 4-wk post-treatment increased to 98 percent for heating and 92 percent for microwaves. Spot-applications of liquid nitrogen at the 30-min@1.4 kg/min dose (highest dose tested) achieved 100 percent mortality 3-d post-treatment. However, for the 15-min@ 0.9 kg/min and 7-min@ 0.9 kg/min dosages, 4-wk post-treatment mortality levels were 99 percent and 87 percent, respectively. Mortality by electrocution of termites in artificially infested boards was 44 percent 3-d post-treatment in the first test. Four-weeks post-treatment drywood termite mortality increased to 82 percent. In a second electrocution test, using spot-application techniques infrequently used in structures, mortality levels increased to 93 percent 3-d and 98 percent 4-wk post-treatment.

For naturally infested boards, both fumigants exceeded the 99 percent level of mortality. Nonchemical applications of heat for whole-structure and spot-applications with microwaves resulted in 100 percent and 99 percent mortality levels for naturally infested boards. Chemical applications of liquid nitrogen were at or near 100 percent for naturally infested boards tested at the 30-min@1.4 kg/min and 15-min@0.9 kg/min dosages. However, mortality was significantly lower (74 percent) for the 7-min@0.9 kg/min dose. Mortality levels from electrocution were 89 percent and 95 percent 4-wk post-treatment, respectively, in the two tests.

The distribution of termite survivors varied for some techniques by : 1) location within the test structure and 2) galleries within test boards. Visual signs of damage to test boards, drywall, and the *Villa Termiti* were noted for some treatment techniques. This study provides information for evaluation of the relative efficacy of nonchemical alternatives and fumigation technology for the eradication/elimination of drywood termite infestations in structures.

THE DAMAGE CAUSED by wood-destroying insects results in a significant economic impact on many structures throughout the United States. Nationwide, the cost for wood-destroying insect control and repairs of damage approaches $5 billion per year; the outlay in California and Hawaii alone probably exceeds $1 billion per year (Su & Scheffrahn 1990, Brier et al. 1988). In California, a breakdown of these expenditures by insect species reveals that subterranean termites, primarily *Reticulitermes* species, and drywood termites, specifically the western drywood termite, *Incisitermes minor* (Hagen), are responsible for over 95 percent of all costs due to wood-destroying insects (Rust et al. 1988, Brier 1987). Damage attributed to wood-boring beetles and carpenter ants amounts to about 3 percent of the total cost (Rust et al. 1988, Brier 1987). Subterranean termites cause problems throughout California; however, damage by drywood termites is more common in the southern portion of the state (Wilcox 1979). According to Wilcox (1979), over 70 percent of all inspection reports from Los Angeles and San Diego Counties submitted to the California Structural Pest Control Board from 1976 to 1977 indicate the presence of damage by drywood termites. Infestations in northern California, including the San Francisco Bay Area, the Sacramento and San Joaquin Valleys, appear to be increasing (Lewis & Haverty, unpublished observations). Kofoid (1934) stated that *I. minor* exhibited a preference to infest rafters, roof sheathing and southern exposures of dwellings in the northern part of its range. In southern or desert areas, infestations are more likely to be found lower in the structure.

For many years, the standard treatment for elimination of drywood termite infestations was fumigation with either methyl bromide or sulfuryl fluoride. The use of fumigants is considered a "whole-structure treatment" (for treating simultaneously all wooden members and extensive or difficult to access infestations in structures) (Scheffrahn & Su 1994). When properly applied, these toxic gases are effective in eliminating infestations of drywood termites throughout the treated structure. Both gases are highly toxic biocides that kill termites and other organisms by disruption of biochemical pathways. Specifically, these fumigants cause cessation of lipid catabolism and glycolysis (Meikle et al. 1963, Su & Scheffrahn 1986). For methyl bromide, symptomology includes the darkening of unpigmented appendages (Scheffrahn & Su 1992).

Several studies have demonstrated the effectiveness of chemical fumigants against a variety of termite species (Bess & Ota 1960, Osbrink et al. 1987); however, relatively little information has been presented on the effectiveness of fumigation on an operational basis. Ebeling and Wagner (1964) found that 26 to 37 percent of structures in Los Angeles that had been fumigated with methyl bromide showed evidence of active drywood termite infestations within 3 to 5 years. In the same study, they found comparable rates of "re-infestation" for drill-and-pin applications, ranging from 63 to 79 percent. We suggest, however, that the "re-infestation" rate of this insecticidal spot-treatment includes a significant proportion of termite infestations that were never eliminated.

The public is showing increased interest in nonchemical or "least toxic" approaches to insect control. In a survey in Indiana, 87 percent of the respondents claimed to have attempted a nonchemical method for control of household insect pests (Bennett et al. 1983). In a similar survey, 72 percent of the respondents in Berkeley, California, said that they had personally used nonchemical control techniques in their homes (Levenson & Frankie 1983). A more telling statistic from this study is that 67 percent of respondents, representing three different geographic locations of the United States (Berkeley, California; Dallas, Texas; and New Brunswick, New Jersey), said they were increasingly cautious about the use of pesticides. Closely paralleling the public's interest in "Urban Environmentalism" in California is the development and commercialization of nonchemical alternatives directed against wood-destroying insects. The list of these control techniques presently marketed in California for control of drywood termites is growing and currently includes excessive heat, excessive cold, electrocution, and microwaves (also based on temperature elevation). Excessive cold, electrocution, and microwaves are "spot or localized" treatment methods (treatment often restricted to a single spot within a board or small group of boards). Whole-structure heating of homes comes closest to conventional fumigation.

A reason for interest in the effectiveness of alternatives to fumigation is that ownership of homes change, on average, every three years in California (Ebeling & Forbes 1988). A usual requirement of home sales is a guarantee that the home is free of infestations and infections of wood-destroying organisms. Assurance of pest-free homes, without the use or overuse of chemical pesticides, is becoming more important in closing real estate transactions.

There has been limited published research, either in the laboratory or in the field, on any of the alternative control methods examined in our study. Forbes and Ebeling (1987) found that nymphs of *I. minor* died if exposed to 51° C for more than 10 min. Those results form the basis for recommendations for heat fumigation of structures. Death from exposure to excessive heat no doubt has a complex mechanism. Hyperthermia affects insects at the cellular level, disrupting the function of cell membranes and stability of enzymes (Bowler 1981, Ebeling 1994).

The effects of low temperatures on termites have scarcely been investigated. Lund (1962) determined that workers of the eastern subterranean termite, *Reticulitermes flavipes* (Kollar), succumbed after less than 5 min exposure at -9.5° C (14.9° F) to -13.0° C (8.6° F). Temperate species such as the drywood termite *Kalotermes flavicollis* (F.), the Pacific dampwood termite, *Zootermopsis angusticollis* (Hagen), and a European subterranean termite, *Reticulitermes lucifugus* (Rossi) were able to survive for long periods of time when held below 18° C (64° F) (Becker 1967). Feeding was minimal when the Formosan subterranean, *Coptotermes formosanus* Shiraki, and *R. flavipes* were maintained at 5° C (41° F) and 10° C (50° F) (Smythe & Williams 1972). At 5° C all termites of both species died within 8 wk. All *C. formosanus* died when maintained at 10° C, whereas *R. flavipes* survived (Smythe & Williams 1972).

In initial experiments with *I. minor*, Forbes and Ebeling (1986) reported that individuals died within 5 min at temperatures between -18.5 to -19.4° C (-1.3 to 2.9° F). Rust et al. (1995) corroborated the experiments of Forbes and Ebeling (1986) and found that exposure of workers (sic) and alates in wooden blocks to temperatures below -21.4° C resulted in 100 percent mortality. This temperature is apparently below that which causes the formation of ice crystals in the hemolymph resulting in disruption of cell membranes and eventual death of the insect (Heinrich 1981). Both studies surmised that chilling wood below that minimum lethal temperature will result in the elimination of all *I. minor* present in timbers.

To date, there has been only one published study evaluating efficacy of electrocution for control of drywood termites in wood. Ebeling (1983) used the Electrogun® to treat blocks of wood artificially infested with nymphs of *I. minor*. When the probe of this device was placed into a hole near the gallery in wood containing nymphs and short bursts of electricity were applied, sparks were seen jumping from termite to termite. The mode of action for mortality in termites is not known. Even after exposure to the electric shock, not all termites were killed immediately. However, within 5 days of treatment, all termites in each "test" were dead. Ebeling (1983) attributed delayed mortality to the destruction of intestinal protozoans.

Similarly, when nymphs within galleries were treated by passing the Electrogun® over the surface of the wood for one minute many termites survived initially, although efficacy in these tests was equivocal (Ebeling 1983). As with the technique of drilling and inserting the Electrogun® probe into the gallery, there was delayed mortality as a result of passing the probe over the surface of the wood. After 5 days, all termites in treated blocks were dead.

Direct treatment of termites in natural gallery systems for one minute caused 10 percent mortality (Ebeling 1983). By placing the probe of the Electrogun® in a "kick-out" hole, direct observation of sparking and termite mortality demonstrated the fact that galleries in that piece of wood were interconnected, and the device was effective in killing *I. minor* nymphs.

Microwaves have been investigated as a means of destroying insects in nuts and stored grain (Locatelli & Traversa 1989, D'Ambrosio et al. 1982, Tilton & Vardell 1982a&b, Nelson & Payne 1982, Nelson 1977, Watters 1976, Rosenberg & Bögl 1987) and for preserving textiles and museum specimens (Hall 1981, 1988, and Philbrick 1984, Regan et al. 1980). Direct application of microwaves to insects does not affect various life stages of insects equally (Del Estal et al. 1986).

Microwaves can be used to heat the substrate and then subsequently kill the infesting insects by extreme temperature (Locatelli & Traversa 1989). Microwaves can also act directly on insects within relatively dry substrates by agitating water and/or fat molecules. Friction caused by this agitation creates heat which likely causes death by protein denaturation and membrane disruption (Hall 1981). Most investigators measure the effect of the time of exposure on insects and/or substrate, keeping the power and wavelength constant (Crocker et al. 1987). Thus far, there have been no published reports on effects of microwaves on termites either in the laboratory or under field conditions.

Field tests of these alternative control methods are scant. Forbes & Ebeling (1987) reported on a demonstration of heating a mock-up house above a critical temperature. Air from an electronically-driven blower was passed through a gas-fired heater and delivered into the interior of this "house." This treatment eventually raised the internal temperature of wood in the crawl space, attic, and wall voids. Their objective was to determine a relationship between a given room temperature and the time required to reach lethal temperatures within structural timbers with various cross-sectional dimensions (3.8 X 8.6, 8.9 X 28.6, or 13.9 X 28.6 cm (2 X 4, 4 X 12, or 6 X 12 inches, respectively)). For nymphs of *I. minor*, 100 percent mortality was achieved when the temperature within wood was maintained at >48° C for at least 30 min.

Forbes and Ebeling (1986) documented a method for chilling infested structural members below the survival threshold temperature for drywood termites. They reported that wall voids do not have to be chilled below -80° C (-112° F) in order to reach temperatures within wooden structural members that are lethal to drywood termites. To speed the process, however, liquid nitrogen was used to produce temperatures as low as -180° C (-292° F) in wall voids. These spaces remained at temperatures lethal to termites for more than 2 hours. These authors suggested that the use of strategically placed insulated mats decreased the amount of liquid nitrogen required to chill the area and prevented frost formation on the walls.

There have been no published reports on the efficacy of the Electrogun® under actual or simulated field conditions. Ebeling (1983) reported empirical observations on the efficacy of this device after routine commercial treatments. Softwood boards in a pile in a shed were treated by a pest control operator who spent about 5 min treating a 3.8 X 13.9 cm (2 X 6 inches) by approximately 1 m long timber. Mortality from this treatment was 74 percent immediately after treatment, 81.3 percent after 26 days, and 96.3 percent after 57 days. It is important to emphasize that this particular piece of wood was not treated *in situ*, rather it "...was placed on a concrete slab and was treated with Electrogun®, paying special attention to 'thin areas' and 'kick-out' holes."

Ebeling (1983) also examined 35 termite colonies 1-4 mo after treatment with the Electrogun® by pest control operators. His measure of efficacy was the appearance of new fecal pellets. Three of the 35 colonies needed retreatment. In a survey of pest control operators who used the Electrogun®, nearly all reported fewer call-backs than with previously employed drill-and-treat localized chemical treatment methods (Ebeling 1983). However, Mampe (1990), citing Ebeling (1983), considered the use of the Electrogun® to be similar to localized chemical treatments. He described the use of the Electrogun® as follows: "the operator moves the gun along wood members, creating an arc of high-voltage which penetrates the wood." He does not mention penetrating the wood or galleries with the probe of the Electrogun®. Mampe (1990) claimed that this technique "...has met with only limited success, but may be useful for isolated infestations."

Nonchemical methods have been proposed as replacements for structural fumigation for drywood termite control. Several of these methods are now being applied operationally by pest control companies in California, Florida, and Hawaii.

The economic impact of wood-destroying insects in our structures will likely continue to increase significantly into the next century, as will the demand for protection of wood-in-service. The reasons for this increase are many including: 1) increased urbanization and population growth, 2) additional environmental constraints on timber cutting and an increase in the value of wood in North America, 3) the apparent reduced efficacy of currently registered soil termiticides, and 4) a growing concern of the public over the use of toxic chemicals in and around households. Justification for development of nonchemical control technology for drywood termites is obvious. However, the public must be assured that alternatives to fumigation offered to them are efficacious when properly applied.

Here we report the efficacy test results of two types of fumigation and four methods currently marketed as alternatives to whole-structure fumigation. We tested each method against three levels of efficacy: 90, 95, and 99 percent, after 3-d and 4-wk post-treatment. Our purpose in this research was solely to evaluate the efficacy of each treatment, not to make direct comparisons among treatments.

Materials and Methods

Insects. In this study, two types of infested material were used: artificially infested and naturally infested boards. Termites placed in artificially infested boards were extracted from naturally infested wood (lumber, firewood, and grape prunings) containing *I. minor*. Infested wood was collected from 12 cities in California: Concord, Fremont, Fresno, Los Angeles, Novato, Oakland, Riverside, Sacramento, San Jose, San Luis Obispo, San Rafael, and Ventura. Termites were removed from wood using Berlese funnels or direct extraction. For the Berlese technique, cut sections of wood were placed into the 0.5-m diameter anterior ends of funnels and covered with friction-fitting lids containing a 100-watt light bulb. Wood sections were left in the Berlese funnels overnight; termites fleeing from the heat were collected at the bottom of funnels in 0.9 l glass Mason® jars containing a damp paper towel. The method of direct extraction consisted of using hammers and wood chisels to tap termites out of naturally infested wood.

Termites removed by either collection technique were put into hollowed-out birch tongue depressor rearing chambers 1.9 X 15.9 cm long.(Bess & Ota 1960); the hollowed-out space was 1.2 X 5.0 cm long (Fig. 1). Seven of these tongue depressors were stacked onto each other and held together with masking tape. The top and bottom of the chamber was sealed with intact depressors; the entire unit was held together at both ends with 2-cm wide masking tape and a rubber band.

Each tongue depressor's chamber contained approximately 200 termites. Termite groups were from mixed colonies. It has been shown that drywood termites can be mixed together with minimal mortality (Atkinson, 1994). All rearing chambers were stored in 14.3 X 10.4 X 3.4 cm (length, width, height; lwh) clear plastic boxes with friction-fitting lids. Plastic boxes containing the rearing chambers were held in an incubator in a glass greenhouse for several weeks before use. Environmental conditions, which ranged from 18 to 37 ^{o}C with relative humidities of 40 to 80 percent, were monitored with a hygrothermograph maintained inside the incubator.

For all treatments, only healthy termites were used. Primarily, we selected pseudergates of at least the fourth instar; however, some younger nymphs were occasionally used. Alates and soldiers were not used in the study.

Villa Termiti. To simulate field conditions, a mock-structure we call the *Villa Termiti*, was built specifically for these tests of drywood termite control methods. The *Villa Termiti* is a 6.1 X 6.1 m (37.2 m^2; 20 by 20 ft or 400 ft^2) building constructed of construction-grade Pacific Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*). Walls were built with 3.6 X 14.5 cm (2 X 6 in) studs on 30.5 cm (12 in) centers. These studs allowed for easy installation of test boards of varying sizes. Other dimensional sizes of wood used in construction were 2.0 X 11.6, 3.7 X 8.6, 3.8 X 23.5, 9 X 9, and 8.7 X 23.5 cm (approximately 1 X 5, 2 X 4, 2 X 10, 4 X 4, and 4 X 10 in). No pressure-treated or otherwise chemically-treated wood was used in this building. Foundation-grade redwood (*Sequoia sempervirens* (D. Don) Endl.) mudsill plates were used in lieu of pressure-treated wood.

The *Villa Termiti* was designed to be symmetrical with doors and windows on all four sides (Fig. 2). This symmetry of design allowed for testing unbiased by construction or aspect, and it enabled internal replication using an entire wall of wall voids. To better reflect the different building styles used in northern versus southern California (wooden exteriors on raised foundations versus stucco exteriors on slabs), combination exterior walls and foundation were included in the *Villa Termiti* design. The *Villa Termiti* contains an attic, “living space,” and a subarea (Figs. 3 & 4). The exterior of the *Villa Termiti* consists of stucco walls and a shingled roof. Wooden panels with a door and two windows are detachable and centered on each of the four walls. There are no interior walls, insulation, or fire-blocking. However, the building does have electrical wiring and a nonfunctional waste-water plastic (ABS) pipe. The foundation consists of slab and a raised perimeter wall (Fig. 4C).

The*Villa Termiti* was designed and constructed by licensed contractors approved by the Operations Center, Richmond Field Station (RFS), University of California, Berkeley. Design, construction, building materials, and safety permits for the *Villa Termiti* complied with

University of California and Contra Costa County building codes and were approved by RFS and the Fire Marshall's office, University of California, Berkeley.

Preparation of Artificially Infested Boards. Kiln-dried, vertical grain, and clear Douglas fir "'1 X 4s," "2 X 4s," and "4 X 6s" (1.8 X 8.7, 3.8 X 8.7, and 8.5 X 13.7 cm cross-sectional dimensions, respectively) were cut into 61 cm lengths. On each board, 3 longitudinal cuts were made. The first cut was a 0.6-cm thick veneer piece cut along the 3.8-cm and 8.5-cm edge for the 2 X 4s and 4 X 6s, respectively. For 1 X 4s, a 0.3-cm thick longitudinal cut was made along the 1.8-cm edge. The second cut was also a 0.6-cm thick veneer piece along the 8.7-cm and 13.7-cm edge for the 2 X 4s and 4 X 6s, respectively. The 1 X 4s had a slightly thinner (0.3 cm) cut on the 8.7-cm edges. The third longitudinal cut divided the non-veneer 8.7-cm and 13.7-cm side of each board in half (Fig. 5).

Three gallery spaces were routed into each board. The dimensions of each routed space was 50.8 X 1.9 X 0.6 cm (lwh) for 2 X 4s and 4 X 6s. Due to the smaller size of the 1 X 4s, the routed spaces were slightly smaller: 50.8 X 1.6 X 0.9 cm on the 1.8-cm side and 50.8 X 1.9 X 0.3 cm on the 8.7-cm side. Each gallery had a unique designation (Fig. 5). Gallery 1 was a centrally-routed space just under the veneer piece on the 1.8-, 3.8- or 8.5-cm side of the 1 X 4s, 2 X 4s, 4 X 6s, respectively. Gallery 2 was also a centrally-routed space just under the veneer piece on the 8.7- or 13.7-cm sides of the boards. Gallery 3 was the routed space centrally located in the half of the board that did not contain Gallery 2 (Fig. 5).

Since individual treatments may have varying penetration within wood, the exposure of individual galleries to treatment could be important. The random and asymmetrical positioning of galleries within boards allowed us to determine how gallery orientation and wood thickness affected treatment performance. Prior to installation, boards were held together with two rubber bands and stored at ambient environmental conditions in the laboratory away from excessive light. With the exception of boards used in the untreated group, no individual board was exposed to more than one treatment or used in more than one test.

Insertion of Insects into Boards. Seventy-five drywood termites were placed within each board, 25 into each of the three routed galleries. Once the termites were in place, boards were held together with a 2.5-cm wide masking tape and individually labeled with a unique identification number and treatment type.

Placement in the *Villa Termiti*. Since all treatment methods varied in application and mode of action, two testing options, A and B, were offered to vendors participating in this study. Option A consisted of localized treatment of test boards only behind drywall in the *Villa Termiti* wall voids. Option B consisted of a whole-structure treatment, with test (or infested) boards positioned in the attic, the wall voids of the "living space" and the subarea.

For Option A, 24 test boards were installed in the *Villa Termiti*. The dimensional sizes of boards used were: four 1 X 4s, sixteen 2 X 4s and four 4 X 6s. Excluding the detachable segments (the four side panels each with one door and two windows), 24 wall voids (six in each wall) in the drywall area of the *Villa Termiti* could be used (Fig. 3). The experimental design required the use of two wall voids from each of the four sides of the building (8 wall void spaces total). These 8 wall voids were randomly selected from the available 24 voids, excluding the 6 wall voids which contained electrical wiring. Three test boards were placed into each of the randomly selected wall voids: two 2 X 4s and either one 1 X 4 or one 4 X 6. All test boards were also randomly selected.

Within each void space, there were four possible positions for board placement, the upper and lower locations for both the right and left studs (Fig. 3). The upper locations were positioned mid-stud and lower locations rested on the sill plate. Three of these positions were randomly chosen for installation of three test boards.

The orientation of galleries in the test boards within a wall void was also randomized for each board. When viewed straight on, Gallery 1 had two possible positions: facing the back wall of the void space or rotated 180 degrees and facing the installer. Gallery 2 also had two possible positions, affixed to the stud or rotated 180 degrees directed away from the stud. Because

Gallery 3 was centrally located within boards, its orientation was not greatly affected by rotation. 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. Twenty-four boards were installed in wall voids behind the drywall in the "living area." In addition, 12 boards were installed in the attic and the subarea. Thus, a total of 48 boards were installed within the entire structure. Treatment locations of test boards in the attic were exposed void spaces located near the mid-line of the gable roof (Fig 3.). Two possible sampling locations, the right or left void space, were used in each of the four exterior walls of the attic. After randomly selecting a void space, three test boards were installed: two 2 X 4s and either one 1 X 4 or one 4 X 6. There were three possible board locations within the void space: the right or left stud, or against the void's exterior wall. Individual boards were randomly assigned to a location. Two drywall screws, described in Option A, were used to affix boards to test locations.

In the subarea, test board installation consisted of affixing boards to the mudsill; overhanging them onto the concrete foundation or affixing them along the mudsill plate (Fig. 3). There were three test locations per side of the building: right and left locations on the concrete wall and the middle of the mudsill plate.

As mentioned above, boards were randomly selected and galleries randomly oriented prior to installation. For boards overhanging the concrete, Gallery 1 had two possible orientations, up or rotated down 180 degrees in a vertical plane. Gallery 2, when viewed straight on, either faced towards or was rotated 180 degrees away from the concrete wall. The orientation of Gallery 3 remained unchanged through rotation. Boards installed centrally on the mudsill plate were affixed midway in a horizontal plane. The orientation for Gallery 1 when viewed straight on, either faced the installer or was rotated 180 degrees towards the outside wall. Gallery 2 also had two possible orientations, down towards the mudsill or rotated 180 degrees facing upwards in a vertical plane. The orientation of Gallery 3 remained unchanged through rotation. Two drywall screws, aforementioned, were used to affix boards in place.

Treatment boards were installed in the *Villa Termiti* approximately 24 h before testing. Untreated boards were left undisturbed in a separate building approximately 30 m from the *Villa Termiti*.

Placement of Naturally Infested Boards. The criteria used for selecting naturally infested boards for the study were: 1) standard dimensional lumber, 2) 1.8 X 18.4 cm, but not more than 8.5 X 13.7 cm in cross-section, and 3) acoustical emission readings greater than 10 counts per min in at least one monitored position within the board (Scheffrahn et al. 1993). Boards were further stratified into low, medium, and high acoustic activity. Corresponding acoustic emission readings for stratified levels were approximately 10, 30, and >40 counts/min as registered by a hand-held acoustic emission detector (Wood-destroying Insect Detector®, DowElanco Indianapolis, IN). When possible, an equal number of boards within each stratum were installed in the three areas of the *Villa Termiti*. An additional consideration in the placement of boards was its ability to fit within selected test positions in the *Villa Termiti*.

The actual test positions within the *Villa Termiti* varied between whole-structure and localized treatment methods. For whole-structure treatments, boards were installed in the attic, “living space,” and subarea. Three boards were placed in the attic, two in spaces between the ceiling joists (one on the east side of the building and one on the west side) and one in an exposed north-facing wall space (Fig. 3). In the “living space”, three boards were installed: one on the east and west header beneath the drywall and one in a wall void (Fig. 3). For the subarea, three boards were installed, one on each east and west 4 X 8 (8.3 X 18.4 cm) subfloor support joists and one laid on top of the north-facing mudsill (Fig. 3).

All test boards were randomly selected and test positions randomly assigned among boards. Localized treatments, for the most part, used the same test positions (for exceptions, see Vendor Cooperation section). In total, nine naturally infested boards with measurable termite activity (>10 acoustical counts/min) were used for each test.

Vendor Cooperation. The authors did not conduct any of the applications. Licensed commercial vendors were solicited for all applications in the *Villa Termiti*. All control methods tested are services offered by firms licensed by the Structural Pest Control Board of the State of California. Letters soliciting cooperation were written to the vendors providing the six methods undergoing tests. Cooperation was voluntary.

We felt treatments should represent standard procedures in the field as outlined by usage levels and vendor training manuals. Before treatments, we requested detailed information on procedures to be used by vendors. We also requested that all vendors use procedures that minimize test board and structural damage. Photographs and video-recording, if allowed by vendors, were also used to document exact procedures. All vendor treatments were conducted separately when vendor schedules and availability of termites allowed. Treatment effects such as temperature and gas composition were monitored by the vendor. For a complete review of operating procedures, safety and limitations, individual vendors should be contacted for complete training and operating manuals. The following are the names and normal operating procedures for firms that agreed to participate in this efficacy study.

Fumigant gases. Sulfuryl fluoride, Vikane® fumigant gas (a licensed product of DowElanco), was one of the two fumigants used during the study. This fumigant is colorless, odorless and extremely harmful or fatal to humans; therefore, it must be handled with extreme caution by trained and certified personnel. This technique is a whole-structure treatment. Two firms conducted the work during the testing period: Knight Fumigation and Ultratech Division, both from San Jose, California. In addition, the Senior Industry Specialist of DowElanco for northern California also participated.

Normal fumigation procedure for the treatment of homes involves sealing the house with vinyl-coated nylon tarpaulins, fans (5 amps) for circulation of the fumigant, gas dosage calculation, infusion of the warning agent chloropicrin, and aeration and clearing for occupant re-entry. Dosage rate (g/m^3) is dependent upon many factors: condition of tarps, soil type, soil and air temperature, and wind conditions. Monitoring gas concentrations is optional.

Many studies have been conducted which describe, in detail, pre- and post-treatment preparations (Thoms & Scheffrahn 1994). For safety, all pets, plants, and occupants must be removed from the premises during treatment. Normal treatment time is approximately 22 h. After treatment, the structure is aerated and cleared for re-entry according to mandated regulatory and industry standards (Anonymous 1993). Since the entire structure was treated, knowledge of the exact location of boards in the *Villa Termiti* was not known to the vendor.

The *Villa Termiti* was treated three times with sulfuryl fluoride (November 19, 1993, April 11, 1994, and September 29, 1994). In the first fumigation 48 artificially infested boards were placed in the structure. For the second treatment, only naturally infested boards (9 total) were placed. For the last fumigation, both artificially and naturally infested boards were included: 36 artificially and 9 naturally infested. All treatment days were clear and sunny. The temperature, soil readings from the subarea, was 10, 15.5, and 18.9º C, respectively. Wind speed was less than 1.4 km/hr, except for the November 1993 treatment, when the wind was recorded at 3.6 km/hr. The tarp conditions were good or excellent. Soil type was clay and the seal condition was good. The total calculated volume treated was 198 m^3 (the actual volume of the *Villa Termiti* is 154 m^3). The extra treated volume included the additional tarp space for eave overhangs and porches. The amount of sulfuryl fluoride used for each fumigation was 7.4, 2.3, and 2.5 kg. Differences in the amounts of the fumigant used reflected the varying temperature and wind conditions for each day. A Fumiguide® was used to calculate exact dosages required for successful treatment. All treatments were monitored with a fumiscope; readings (ppm) were taken in the attic, drywall, and subarea. Sulfuryl fluoride gas levels were monitored at approximately 1 h and 22 h (just prior to tarp removal) after gas insertion. First hour fumiscope readings for all three treatments, 39.1 g/m^3, 14.4 g/m^3 and 13.5 g/m^3, were at or above recommended rates. Twenty-two hour post-fumigation fumiscope readings for the three treatments was 14.0 g/m^3, 8.9 g/m^3 and 5.9 g/m^3, respectively.

The second fumigant used during the study was CO_2-synergized methyl bromide, employing the MAKR® Fumigation Process. This fumigant is also colorless, odorless, and extremely harmful or fatal to humans and must be handled with extreme caution by trained and certified personnel. Participating vendors included A-1 Fumigation and Farmer Pest Control (Bellflower, California), Cal Ag (Woodland, California), and Discount Fumigation (San Jose).

The active ingredient of this gas is methyl bromide. To enhance the effects of the active ingredient and to minimize aeration time and toxic gas release into the atmosphere, carbon dioxide is added as a synergist. This synergized mixture allows a two-thirds reduction of the normal application rate: 7.3 g/m^3 reduced to 2.4 g/m^3 (24 oz per 1,000 ft^3 reduced to 8 oz per 1,000 ft^3). The amount of carbon dioxide used is approximately 10% of the total cubic volume of structure treated.

The *Villa Termiti* was fumigated three times with CO-synergized methyl bromide (September 24, 1993, January 20, 1994, and October 13, 1994). The treatment pattern involving separate dates for treating artificially and naturally infested boards plus one treatment combing both types of test boards. The number of treated boards was similar to those described above for sulfuryl fluoride. The climatic conditions for all treatment days were sunny and clear with air temperatures of 26.7, 15.6, and 20.0^o C, respectively. Wind speed for all treatments was less than 2.4 km/hr. Trap and seal conditions were excellent for all treatments. The total calculated volume treated was 178 m^3. As with the other fumigant, vinyl-coated nylon tarpaulins were used to enclose the entire structure. The amount of methyl bromide used was the same for each treatment (1.4 kg) because this fumigant has only one dosage rate irrespective of climatic conditions. The amount of CO_2 used was 31.3 kg (approximately 53.7 g/m^3). The time of exposure for all treatments was 22 h. The mixture of methyl bromide and carbon dioxide was heated to a minimum of 70^o C and then introduced into the structure in less than 1-min through a hose. The gases were dispersed by two 5-amp fans. A warning agent, chloropicrin, was also added. The presence of methyl bromide and CO_2 gases was documented by piercing the tarps and taking an internal air sample using a Draeger® tube. Tube readings for all treatments exceeded 1,500 ppm MB and 10% for CO_2 (both values are according to labeled rates). Since the entire structure was being treated, knowledge of the exact location of boards was not known to the vendor.

Heat. The *Villa Termiti* was treated with heat three times. All test days (October 29, 1993, January 17, 1994, and December 1, 1994) were sunny and clear. The coldest initial temperatures in the *Villa Termiti* prior to heating for each treatment date were 15°, 12.2°, and 8.9° C: all were found in the same attic beam. J. H. Steffenson Termite Control (Campbell, California) in conjunction with Isothermics/Thermal Pest Eradication® (TPE) (Orange, California) applied the heat treatments. Two vinyl-coated nylon tarpaulins were needed to enclose the structure prior to treatment. The tarpaulins had several tears to allow air movement through the structure (hot air was continuously circulated through the *Villa Termiti*). Thermocouples were placed throughout the structure to record temperature changes (Fig. 6). The number of thermocouples used varied with each test: 6 thermocouples were used during the first test, 10 for the second, and 11 for the third. Four convection heaters (each 400,000 BTUs), powered by propane, were positioned outside and hot air blown inside through flexible Mylar® ducts.

The objective of heat treatment is to have the temperature of the coolest thermocouple, normally in a large wooden member or mudsill in the subarea, reach at least 48.9° C and remains at that temperature for 30 min. Total treatment time is typically about 6 h for a two-bedroom home (Ebeling 1994). Two 4.3-amp fans were positioned in the structure (subarea and drywall areas) to insure uniform heat distribution. During normal operations, air temperatures within living spaces are not to exceed 65.6° C to minimize any damage to the treated structure or its contents. The *Villa Termiti* was vacated during treatment; however, entry into the building was possible, though uncomfortable, even at these elevated temperatures. Since it as a whole-structure treatment, knowledge of the exact location of test boards was not known to the vendor.

Liquid Nitrogen. There was no vendor cooperation for this treatment method. All liquid nitrogen treatments in the *Villa Termiti* were conducted by research personnel from the University of California, Berkeley and Riverside. Since this is a spot-treatment technique, knowledge of the location of test boards in the *Villa Termiti* was made known to personnel conducting the treatments. Optimal performance of liquid nitrogen requires an enclosed void space for containment of the liquid and vapor. A 1.3-cm diameter hole was drilled through the drywall near the top plate of the void space being treated. Liquid nitrogen (Altair Gases & Equipment, Inc., Oakland, California) was then injected from 160 l dewars into the wall cavity through a 1.2-m flexible woven stainless steel hose. The temperature inside the dewar may be lower than -195.8^{o} C.

In our tests we attempted to have a constant amount of liquid nitrogen delivered to each wall void. We calibrated the time it took to deliver a standard dose. In the first test, we delivered liquid nitrogen at approximately 30 min @ 1.4 kg/min into each 14.5 X 30.5 X 244 cm wall void (n = 13 separate wall voids). In the second test, we delivered slightly less than one-half and the third test one-fourth the rate applied during the first test (0.9 kg/min for either 15 min or 7 min). A digital scale (Pennsylvania 66000, 1.2 m^2 platform, 2,268 kg capacity) was used during the first test to determine pre- and post-application weights of liquid nitrogen. A full-capacity beam scale (Howe Richardson Mechano-Weigh 54 XL) was used to record changes in liquid nitrogen weights for the two additional tests.

Twelve thin-wire thermocouples were used to monitor temperature changes within studs and test boards in wall voids of the *Villa Termiti*. The ends of the wires were inserted into a scanning thermocouple thermometer (Cole-Parmer model #92800-00) that was connected to a serial printer via an RS-232 output. Temperature readings were taken every minute from 12 different locations in "2 X 6-in" (3.6 X 14.5 cm) studs and test boards for each corner of the building (6 possible void spaces per corner) (Fig. 7). Control should be reached when the temperature falls below -28.9^{o} C for at least 5 min (Tallon 1992); the temperature inside the dewar may be less than -184.4^{o} C.. Insulation blankets were used to help maintain the frigid temperatures for the last two tests. For safety, the oxygen content of the living space was monitored, protective clothing was worn, and the “buddy system” was used.

Electrocution. Etex, Ltd., Las Vegas, Nevada, manufacturer and distributor of the Electrogun®, supplied all equipment and personnel for the treatment. The equipment used is commercially marketed as the Electrogun®, a device that kills drywood termites by emitting high frequency electricity (100 kHz), high voltage (90,000), but low current (<1 amp). Whole-house and spot-treatment options are offered by vendors. For exposed 2 X 4s 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.

For the "drill-and-pin" method, small (1.6 mm diameter) holes were drilled through the drywall and into the wood. Approximately 15.2-cm long straight copper wires were inserted into the holes and 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 tests in the *Villa Termiti*, knowledge of the location of test boards behind drywall was revealed to the vendor.

For optimal performance, thorough coverage of infested wood is crucial. This method may also be used with other treatments such as chemical liquids or dusts that can be applied into galleries or onto the surface of infested timbers. The training information and equipment manual do not recommend using this method in close proximity to metals, concrete, excessive moisture, laminated finishes or electronic items. Use in inaccessible areas is also not recommended (nor is it practical). This treatment method is available only to licensed professional operators who lease the equipment and undergo an extensive mandatory training program. When properly used, this device is reportedly safe for operator and building occupants; no potentially harmful radiation is emitted.

An additional and different test in the *Villa Termiti* was requested by the Etex Corporation because they felt the conditions of the first test produced results biased against the Electrogun®. They were concerned about proximity of test boards to metal (wire-mesh in stucco and metal support bars in detachable walls) and to concrete in the foundation of the subarea. They felt the performance of the Electrogun® would be improved if tested against infested boards in locations without interfering metal or concrete.

For the second electrocution test, 18 artificially infested boards were installed in locations away from sources of metal and concrete. Six boards each were installed in the attic, "living space," and subarea. In the attic, boards were randomly placed on one of two 2.7-m long rafters adjacent to the vertical wall for each side of the building; thus, there was a total of 8 possible sampling locations (Fig. 3). In the "living space", each board was installed in a wall void (2.0 X 0.2 X 0.1 m) in the detachable walls only. There were 16 total wall voids possible for selection; four for each side of the building (Fig. 3). Except for the metal window frames and nails, the detachable walls do not contain significant amounts of metal. For the subarea, floor joists were used for board installation; no boards were placed on or near the sill plates or foundation. Six joists were randomly chosen from a possible total of 46. The preparation, fastening, randomization, and orientation of test boards were similar to the earlier test. The vendor was asked to treat the boards as before. Fifteen controls, or untreated boards, were kept in the same nearby building (see above).

Naturally infested boards were similarly installed. In total, nine naturally infested boards were installed in the *Villa Termiti* for this second test: three boards each in the attic, living space, and subarea. In the attic, two ceiling bays and one rafter were used. In the living space, three void spaces in the detachable walls (different from those containing artificial boards) were used. In the subarea, three floor joists (different from those containing artificial boards) were used. The preparation, fastening, randomization, and orientation of boards were also similar to the earlier test.

Microwaves. The Termite Inspector (Mission Hills, California) supplied the equipment and personnel to conduct all tests in the *Villa Termiti*. Treatment procedures included treating infested wood with a 700-watt (more powerful devices are available from other vendors). The 2.4 GHz frequency oscillation causes vibration of water molecules within termites, which produces lethal temperatures above 48.9º C. This spot-application method treats a section of wood approximately 10.2 X 30.5 cm when operating. For safety, the device is operated remotely, and all persons are kept a minimum of 9.1 m from the apparatus while it is operating. Protective blankets are used, if necessary, for added safety. Under field conditions, the vendor uses visual, acoustical, or fiber optical devices to locate infestations. For tests in the *Villa*

Termiti, the location of test boards was disclosed to the vendor. Once boards were identified for treatment, the microwave instrument was positioned over the treatment spot, technicians left the room, and the device was operated by remote. Treatment time was approximately 8 min per spot (10.2 X 30.5 cm; 311 cm^2). A hand-held microwave detection device (Model HI-1801, Holaday Industries, Inc.) was used to selectively monitor emissions from the opposite side of the wall during treatment.

Assessment of Treatment Efficacy. The day following treatment, all artificially infested boards (24 to 48 total) were removed from the *Villa Termiti* and stored in the laboratory until they were opened for 3-d post-treatment assessment of mortality. Live and dead termites were counted and removed from each gallery in every board. Live termites from each gallery were placed in a separate tongue depressor holding chamber (Fig. 1). each individual holding chamber was stored in a clear, 15.5-cm diameter plastic container with a lid and placed in an incubator stored in a glass greenhouse. The percent mortality of these termites was determined at 4-wk post-treatment. Percent mortality was defined to include both carcasses and those missing. Since termites are cannibalistic and eat their dead and injured, we used this measure of mortality. Termites smashed by handling and recording miscounts (gained numbers of termites) were excluded from the analysis. Dead insects were stored in clear 23 X 23 X 20 mm plastic boxes with lids for future verification. Untreated boards (“controls”) containing 25 termites in each of three galleries were assessed in the same manner as treated boards.

After each test, the nine naturally infested boards were removed from the *Villa Termiti* and stored in the same glass greenhouse as the artificial boards. Boards were acoustically monitored at 1-, 2-, and 4-wk post-treatment (these data will be reported separately). At 4-wk post-treatment, the boards were cut into small lengths (approximately 10-cm) and carefully dissected. The sections of board were split with a hammer and wood chisel until it was clear there were no more termites in every gallery and chamber in the board. Live and dead termites were counted and sorted by caste (alate, soldier, and nymph/pseudergate) and percent mortality was calculated based on these data for each board. All insects, dead and alive, were stored in labeled, clear 23 X 23 X 20 mm plastic boxes with lids for future verification.

For each artificially infested board, the percent mortality was calculated by combining the counts of live and dead termites for all three galleries. Thus, the experimental unit for this portion of the test was the board. In addition, separate records were kept for each gallery so that we could explain anomalies in mortality as a function of the unique placement of a particular gallery within the wall voids or near the foundation. Occasionally the termites burrowed through the sawed portion of the board and moved from one gallery to another. An additional complication was that as a result of the "drill-and-pin" method of applying the Electrogun®, holes were left in the boards, allowing termites to escape. If the total number of termites remaining in an individual artificially infested board was less than 48, the data for that particular board was discarded for analysis. Galleries not containing any termites were also discarded from further analysis. Since we had little control over the number of termites in a naturally infested board, we calculated percent mortality using all of the live and dead termites removed from the board.

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:

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

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

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) living area, and (3) subarea.

j = dimension of lumber: (1) 1 X 4 or 1 X 8; (2) 2 X 4; and (3) 4 X 4, 4 X 6, 4 X 8, or 4 X 12.

The relative proportion of wood, 1 X 4s, 2 X 4s, and 4 X 6s, for each location within the *Villa Termiti* was calculated using the following formula and was equal to one.

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

In calculating a weighted percent mortality for a building, we assumed equal rates of infestation for all three areas of a home. For a given locality this may not be true. For example in Riverside and Palm Springs, California, or Phoenix, Arizona, infestations of drywood termites would likely be restricted to the subarea or window and door frames. Infestations are not common in the attic area in these desert locations. In contrast, drywood termite infestations in coastal California are common in the attic, walls, and even in the subarea.

We assumed no density dependence in efficacy of any of the treatments. For the artificially infested boards, this is not a problem since we kept density constant. For the naturally infested boards we were not able to regulate density of drywood termite populations. We did estimate relative densities of the populations in each board before each test using acoustic emission counts (Lewis et al. 1991). We then stratified the boards used for a particular test into low, medium, and high populations. We positioned these boards, stratified on the basis of apparent termite density, throughout the *Villa Termiti* by placing an equal number of each category in each location/level.

Treatments were not statistically compared to one another. The efficacy of each treatment was tested against a set of standards. Our null hypothesis was that each treatment is ineffective, i.e. the treatment resulted in mortality less than or equal to 90 percent (H_o: $p \leq 0.90$). The alternative hypothesis was that each treatment resulted in a mortality greater than 90, 95 or 99 percent (H_a: $p > 0.90$). The equation used to test the significance of the hypothesis is:

$$t = \frac{\overline{\overline{X}}_{ij} - m}{SE\left(\overline{\overline{X}}\right)}$$

where

m = level of mortality desired or required.

All statistical tests of efficacy were determined by a one-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 equal to the number of boards minus 1. The number of boards, or replicates, varied among treatment methods. For spot-treatments, a replicate was an individual board. For whole-structure treatments, one application of the method to the entire structure would ideally be considered a replicate. However, for this study, each board for all treatment methods was considered a replicate.

Summary statistics for mortality levels among location, board dimension, and gallery designation were derived with the MEAN procedure (PROC MEAN, SAS Institute 1994). Means for termite mortality levels among *Villa Termiti* 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 board replicates 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: drilled holes and burn marks. Differences in the number of damaged boards among treatment methods were analyzed using the Ryan-Einot-Gabriel-Welsch Q multiple range test (PROC GLM, SAS Institute 1994). Differences in treatment time and number of drilled holes between the two electrocution tests were analyzed using paired *t*-tests (PROC TTEST, SAS Institute 1994).

Results and Discussion

Fumigant Gases

Sulfuryl fluoride. Termite mortality for all treated artificially infested boards was 100% (Table 1). The overall mean mortality value for the entire structure was significantly greater than the 90, 95, and 99% levels of acceptance (Table 2). Therefore, the efficacy of this treatment significantly exceeds the 99% mortality level. These data agree with previously reported laboratory studies in sulfuryl fluoride efficacy (Su & Scheffrahn 1986, Osbrink et al. 1987, Thoms & Scheffrahn 1994). Control mortality at 3-d was low (< 5%), suggesting high survivorship in test boards prior to treatment. However, mortality after 4-wk increased more than 5-fold, suggesting increased natural and handling mortality post-treatment. Differences in mortality among board dimensions for controls were nonsignificant (F test, $P > 0.05$) at 3-d and 4-wk post-treatment.

The overall mean mortality value for naturally infested boards was also significantly greater than the 99% (Tables 2 & 3). Only a solitary soldier survived. Although a single survivor among thousands is insignificant, this finding is scientifically curious. Lethal sulfuryl fluoride 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. Perhaps future studies may include the determination of the lethal dose for the soldier caste for *I. minor*.

Except for warping, no visual signs of damage were noted for test boards treated with sulfuryl fluoride (Table 4). However, all test boards experienced some signs of wood distortion, especially the thin veneer pieces. Desorption and residual studies for sulfuryl fluoride report its safety for many household commodities if properly used and aerated after treatment (Kenaga 1957, Osbrink et al. 1988, Scheffrahn et al. 1987, 1989a, 1989b).

CO_2-synergized methyl bromide. Termite mortality for all artificially infested boards was 100% (Table 5). The overall mean mortality value was significantly greater than the 99% level of efficacy (Table 2). Control board mortality at 3-d was moderate and ranged from 8.0 to

16.2% (Table 5). Natural and handling mortalities for controls increased at least 2-fold 4-wk post-treatment. The differences in mortality among board dimension for control boards for 3-d and 4-wk post-treatment was nonsignificant ($P > 0.05$). The mortality level for naturally infested boards was also significantly above the 99% level (Tables 2 & 6). However, 30 survivors were found in one 2 by 4 in the subarea. None of the survivors were reproductives. Therefore, we conclude that this synergized, reduced application rate of methyl bromide significantly exceeds the 99% mortality level.

Dose mortality curves for drywood termites (*I. synderi*) using CO_2-synergized methyl bromide have been reported (Scheffrahn et al. 1995). Scheffrahn & Su (1992) have also reported that label rates for methyl bromide were excessive by as much as 4-fold. Both papers support claims of high levels of efficacy for reduced methyl bromide dosages. Results from this study support these earlier findings and suggest that care must be taken in calculating dosage, as well as placement and number of fans when using reduced methyl bromide methods, especially in subareas.

Visual signs of damage to test boards was minimal for this treatment and restricted to warping of some 2 by 4 and 4 by 6 test boards (Table 4). However, other studies have shown that some household foods, if not enclosed in protective nylon bags, can serve as sorptive matrices for this fumigant (Scheffrahn et al. 1990, 1992). **(Rudi, can your "Indoor airborne residues of methyl bromide and sulfuryl fluoride following aeration of fumigated houses" paper be cited?)**. Methyl bromide has also been reported to be an ozone depletor (Cicerone 1987). Registration of methyl bromide is scheduled for phase-out by the U. S. Environmental Protection Agency (EPA) by the end of the decade (Kramer 1992).

Nonchemical Methods

Excessive heat. Termite mortality in artificially infested boards was 100 percent except in the subarea (Table 7). Mortality levels were significantly greater than the 90 percent efficacy levels after 3-d and significantly greater than the 90 and 95 percent levels after 4-wk (Table 2). The subarea was the only location that mortality levels did not reach 100 percent. Mortality values for the subarea at 3-d and 4-wk post-treatment was 85.8 and 91.1 percent. Both values were significantly different from mortality values for the attic and "living space" (F = 17.6; df = 2, 80; P < 0.0001; F = 11.4; df = 2, 83; P < 0.0001). It was initially thought that the early removal of test boards during the first test, immediately after treatment to protect termites from predation by Argentine ants, *Linepithema humile* (formerly *Iridomyremex humilus*), may have interfered with test results. However, results from the second test, when boards were not removed early, revealed a similar pattern of survivorship in the subarea.

Analysis of data for the subarea revealed an uneven distribution of mortality for artificially infested test boards. The size of the artificially infested boards did not have a significant impact on mortality levels achieved at 3-d or 4-wk post-treatment (P > 0.05)(Table 7). However, the data for individual galleries within boards revealed that survivorship only occurred in Gallery 2; locations affixed against the foundation wall (Fig. 4). At 3-d post-treatment the mortality value for Gallery 2 (78.2 percent) was significantly lower than Gallery 1 (94.5 percent) and Gallery 3 (92.2 percent)(F = 7.1; df = 2, 208; P < 0.0011). Similarly at 4-wk post-treatment the mortality value for Gallery 2 (80.7 percent) was significantly lower than Gallery 1 (95.3 percent) and Gallery 3 (92.8 percent) (F = 6.4; df = 2, 208; P < 0.002). Data from thermocouples revealed that all probes reached the 50º C lethal temperature for at least 1 h (Table 8); however there were still survivors. It is not known how much more additional time would have been required to achieve 100 percent mortality for test boards in the subarea. Perhaps future studies can focus more on thermocouple position and number in subareas and sill plates on slabs.

Termite mortality for controls was initially high for 1 by 4s (Table 7). Four-week control mortality values among boards, albeit were large and ranged from 24.2 percent in 2 by 4s to 43.5 in 1 by 4s, were not significant (P > 0.05). These results, probably due to overheating of some boards while in transit to the laboratory from the *Villa Termiti*, suggest termite robustness was less for the heat treatment than for other methods tested.

Mortality results for naturally infested boards was 100 percent for all test locations in the *Villa Termiti* (Table 9). Mean mortality was statistically significant at the 90, 95, and 99 percent levels of efficacy (Table 2). From the results with artificially infested and naturally infested boards we conclude that excessive heat, applied as described, results in a mortality level that significantly exceeds 95 percent and perhaps as high as 99 percent.

There were a few visual signs of damage, minor warping for some 2 by 4 and 4 by 6 test boards (Table 4). Other changes noted in the *Villa Termiti* included sticking of doors (reversible), fluorescent lights going-out (reversible) and warping of a non-functional ABS plastic waste-water pipe (non-reversible). However, under normal field conditions, a low volume of cold running water is left on to prevent the warping of plastic pipes. Minor structural damage from heat treatment, as well as pre-treatment preparations to minimize damage to household items, have been previously reported (Forbes & 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, 30 min @1.2 kg/min, both 3-d and 4-wk mortality of drywood termites in artificially infested boards was 100 percent (Table 10). At this dosage, mortality was significant for all efficacy levels tested (Table 2). Similarly, the 3-d and 4-wk mortality levels for the 15-min @ 0.9 kg/min dosage was statistically significant at the 90 and 95 percent efficacy levels (Tables 2 and 10). However, for the lowest dosage of 7-min @ 0.9 kg/min, the 3-d mortality value, 84.4 percent, was much less efficacious (Table 10); this value was not statistically different at the 90 percent level (Table 2). The 4-wk mortality value, 87 percent, although slightly higher, was still not statistically significant at the 90 percent level of efficacy (Tables 2 and 10). Control mortality levels at 3-d post-treatment were less than 5 percent, suggesting termites were robust prior to treatments. However, 4-wk mortality increased approximately 5-fold for controls indicating considerable natural and handling mortality. There were no significant difference in mortality levels among board dimensional size or gallery designation for control boards ($P > 0.05$). Rust et al. (1995) contain data tables that report the minimum dosage rate required to achieve 100 percent control with liquid nitrogen was at least 21 min @0.9 kg/min in an uninsulated 2.4 by 2.0 m (8-ft by 6.6-ft) artificial wall used in their tests. Their results are clearly in agreement with those reported in Table 10. Lower dosage rates and application times are not likely to achieve the minimal lethal temperature.

Lumber dimensions appear to affect termite mortality, at least for the two lower dosages of liquid nitrogen tested. The 4 by 6 boards suffered less mortality than the other board dimensional sizes when treated with the 15-min and 7-min @ 0.9 kg/min dosages (Table 10). The termites in the 1 by 4 boards always experienced the greatest level of mortality in these two lower dosages. However these differences were not statistically significant ($P > 0.05$). Wood is a poor thermal conductor (Forest Products Laboratory 1987). Results from the current suggest that wood, if relatively sound, may provide termites with insulation and protection from the lethal effects of excessive cold.

Considerable variance in temperature was recorded in wall voids for all liquid nitrogen dosages tested (Tables 11, 12, and 13). Treated boards containing live termites for the 15-min and 7-min @ 0.9 kg/min dosage rates appeared to be associated with thermocouples failing to achieve lethal temperatures (Tables 12 and 13). However, for the 7-min @ 0.9 kg/min dose, three artificially infested boards (two 2 by 4s and one 4 by 6) contained termite survivors. These boards were located in treated wall voids containing thermocouples that reported minimum lethal temperatures (S3 and W2, Table 13). These results suggest that higher dosage rates and thermocouple placement are critical for achieving high levels of efficacy.

Naturally infested boards revealed a similar pattern to that of artificial boards; decreasing levels of mortality with decreasing dosage rates (Table 14). For the 30-min @1.4 kg/min rate, termite mortality was 100 percent. The overall mean mortality value was significantly greater than 90, 95 and 99 percent (Table 2). Similarly, at the 15-min @ 0.9 kg/min dosage, mortality was significantly greater than all efficacy levels tested (Table 2). However, the 7-min @ 0.9 kg/min dosage rate achieved an overall mortality level of 74.3 percent (Table 14). This mortality rate was not significantly greater than the 90 percent level of efficacy (Table 2) and live alates were found among the survivors for the 15-min and 7-min @ 0.9 kg/min rates. Similar to the results with artificially infested boards, the existence of termite survivors was associated with failure of achieving minimum lethal temperatures. Three termite survivors were found in a naturally infested 2 by 4 at the 15-min @ 0.9 kg/min dose rate albeit lethal minimum temperatures were achieved for top and bottom positioned thermocouples (N3, Table 12).

Because we were not able to obtain information on application rates from a vendor who applies liquid nitrogen, we had to assess different dosage rates to determine a minimum application rate that was efficacious. The wall voids in the *Villa Termiti* are approximately 14 by 28 by 224 cm with an internal volume of 87,808 cm^2 (87.8 l). Clearly, the 7-min @ 0.9 kg/min (63 kg of liquid nitrogen) dosage is not an effective treatment for any reasonable level of mortality that would be desired. We feel that the 15-min @ 0.9 kg/min (13.5 kg of liquid nitrogen) application rate is the absolute minimum to achieve a reasonable level of mortality (> 95 percent). This application rate places liquid nitrogen into the wall void at a concentration of 154 g of liquid nitrogen/liter. Application rates exceeding this level are more likely to provide mortality levels in excess of 99 percent.

Visual damage to boards from liquid nitrogen treatments was minimal (Table 4). Frost formation during treatment can be considerable and may cause damage to some wall coverings. However, the possibility exists for microscopic wood damage that may result in structural failure during stress (e.g., earthquakes). Future studies are needed to explore microscopic damage and the possible loss of wood strength for varying dosage levels of liquid nitrogen. With this treatment, repair of drilled insertion holes is required.

Electrocution. Efficacy of electrocution treatments from the first test were below the minimum level of acceptance for artificially infested boards. Drywood termite mortality levels at 3-d post-treatment in artificially infested boards were well below 50 percent in the attic and subarea (Table 15). Only in the drywall area did mortality levels reach 50 percent or higher. The overall mortality value for the entire structure was 43.8 percent 3-d post-treatment (Table 2). Four weeks post-treatment, mortality levels increased to 81.2 percent. However, this efficacy value was still significantly below the minimum 90 percent level of acceptance (Table 2). For treated locations within the *Villa Termiti*, the attic, drywall, and subarea locations had mortality values of 25.5, 54.2, and 46.3 respectively. At 3-d post-treatment, mortality values for the drywall and subarea locations were significantly greater than the attic ($F = 9.6$; df = 2, 142; $P < 0.0001$). The were no significant difference in mortality values among board dimensional sizes ($P > 0.05$). However, gallery differences in percent mortality within boards were considerable; 61.8 percent for gallery 1, 26. 8 percent for gallery 2, and 46.0 percent for gallery 3. All gallery mortality levels were significantly different from each other ($F = 13.9$; df = 2 142; $P < 0.0001$). Similarly, 4-wk post-treatment, mortality values among treated areas within the *Villa Termiti* and gallery locations within boards were still significantly different ($F = 31.3$; df = 3, 187; $P < 0.0001$; $F = 13.6$; df = 2, 187; $P < 0.0001$). Variable results while using electrocution ranging from 3 - 100 percent mortality for boards artificially infested with drywood termites have previously been reported (Ebeling 1983). Mortality results for naturally infested boards in the first test resulted in a similar pattern to artificially infested boards of low mortality (Table 16); 8 of 9 boards contained termite survivors while 2 of these 8 boards had several hundred survivors. The overall mortality level, 88.6 percent at 4-wk post-treatment, did not significantly exceed the 90 percent level of efficacy (Table 2).

There are several reasons that may explain the poor performance of electrocution during the first test. First, penetration of electric current into wood is limited. Ebeling (1983) reported that the surface application of electricity is restricted to only 1.3 cm deep into wood. However, for the current study, the size of boards containing termites was not a factor; 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 since the deepest gallery, Gallery 3, had a higher mortality percentage than Gallery 2, the shallowest. In fact, the drywall locations, sites on non-exposed wood had significantly higher levels of mortality than the exposed test boards in the attic (3-d and 4-wk results, Table 15).

A second possible limiting factor for electrocution treatments is delayed mortality (Ebeling 1983). However, the increased mortality observed at 4-wk post-treatment, as high as 4-fold, was probably not due to the effects of electrocution. Levels of mortality in the controls were also higher, as high as 60-fold, and suggest that increased mortality seen in boards treated by electrocution at 4-wk post-treatment was due to natural mortality and handling (Table 15).

The results from the first test of both artificially and naturally infested boards were challenged by the vendor conducting the electrocution techniques as being bias against the electrocution techniques because standard operating procedures were not strictly adhered to. The reasons given for this poor performance (the presence of test boards next to stucco walls, wire supports in stucco, and concrete in the subarea) suggest that electric current was drawn away from the treated areas and thus away from the targeted termites. A second test, smaller in scope and with test boards positioned in more favorable, “wooden” locations was conducted to remedy these concerns.

The results from a second test of electrocution of boards in locations away from metal and concrete were much improved. Three-day assessment of artificially infested boards resulted in mortality levels that were not significantly above the 90 percent level (Tables 2, 16). Mortality levels at 4-wk post-treatment (98.5 percent) significantly exceeded the 90 and 95 percent levels of efficacy (Table 2).

Mortality of naturally infested boards was also higher than in the first test (Table 16). Only 5 boards contained survivors, as compared to 8 in the first test. However, one board contained over 100 survivors. The mortality level in naturally infested boards for the entire structure was 95.1 percent and significantly exceeded only the 90 percent level of efficacy (Table 2).

The improved performance of electrocution in the second test requires some discussion. Ebeling (1983) claimed the mortality effects of electrocution are heightened when test boards were placed on a metal table. The results of the current 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 test boards in the second test as opposed to the first (7.5 min vs. 20.0 min, t = 5.9; df = 1, 38; $p < 0.0001$) and significantly more holes were drilled per board during the second test (6.5 versus 12.0, t = 3.3; df = 1, 61; $p < 0.0015$). Range in treatment time for each board varied from 5 min to 1.75 h. Since 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. Future studies are needed to determine the effects of treatment exposure time and insertion of metal pins upon termite mortality.

We conclude that the efficacy of this treatment appears to be technique-driven. Clearly, electrocution causes mortality in termites. However, 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. This control method, more than any of the other tests 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 surely drop to unacceptable levels.

Damage to test boards using electrocution was considerable (Table 4). Eighty percent (53 of 66) of artificially infested boards and seventy-eight percent (14 of 18) of naturally infested boards, revealed visual signs of damage. Most signs of damage were drill holes from administration of the drill-and-pin technique. However, 29 boards revealed minor burn marks within test boards. Ebeling (1983) reported wood is a poor insulator and could be carbonized or destroyed as a current seeks a path to ground during treatment. Future studies including varying time exposures and currents are necessary to more fully understand the 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 by microwaves. Mortality at 3-d and 4-wk post-treatment did not significantly exceed the 90 percent level of efficacy (Tables 2 and 18). There were no significant differences in termite mortality between the attic and “living space” at 3-d or 4-wk post-treatment ($P > 0.05$). However there was considerable variance (SD) in mortality especially among 1 by 4s in the attic and “living space” and 2 by 4s in the “living space.” 1 by 4 test boards in the “living space” had lower mortality values than 2 by 4s and 4 by 6s but this difference was not significant ($P > 0.05$). Control mortality values were low (< 5 percent at 3-d post-treatment) and suggest high survivorship in test boards prior to treatment. However, a 5-fold increase 4-wk post-treatment suggest elevated mortality due to handling and natural causes (Table 18). Mortality values among control boards of various size dimensions were not significant ($P > 0.05$).

The overall mortality value for naturally infested boards was 97.4 percent (Table 19). This mortality value significantly exceeded the 90 and 95 percent levels of efficacy. Forty-five survivors were found among three boards containing live termites, none of which were alates.

The results of this study were mixed. Without a doubt, microwave energy applied to infested wood will kill termites. Mortality of termites in artificially infested boards approached 90 percent but did not exceed 90 percent with statistical certainty. Mortality of termites in naturally infested boards was good, statistically exceeding the 95 percent level of control. As with electrocution, definition of the extent of an infestation, location of the infested wood, and access to the infested wood are all critical to achievement of the desired level of mortality with microwave treatments.

Visual signs of damage were noted for some artificial boards (Table 4). Minor warping of test boards was noted and 6 boards were burned, 2 severely (Table 4). For shielded ovens, there is no uniform heating of materials in the microwave field due to internal oven reflection and non-uniform absorption of energy (Locatelli & Traversa 1989). From the current study, it appears that unshielded microwave devices also may produce non-uniform heating of boards during treatment for termites. Monitored microwave emissions were not detectable at the 9.1 m required safe operating distance and were less than 6 mw/cm^2 within 0.3 m of a treated wall.

This is the first published report on the efficacy and safety of microwaves for the control of drywood termites. This method of nonchemical control appears to have promise as an effective spot-treatment technique. However, more information is needed to determine the correct time necessary to achieve the desired level of control and wood penetration of microwave energy for varying levels of wattage output. Monitoring of temperature changes in building materials during treatment could improve efficacy and promoted increased safety.

Handling and Controls. During the course of investigation, over 86,000 termites were handled. *I. minor*, like most termites, are fragile and excessive handling can result in mortality (**REFERENCE**?). Sources of handling mortality include smashed individuals and miscounts (Table 20).

Less than 3 percent of all handled insects for treated artificially infested boards resulted in non-treatment mortality. The greatest source of handling mortality was from the smashing of individuals between the veneer sections of boards. Boards placed in the subarea had significantly more smashed individuals than the attic and drywall areas (**F = test**?). Dragging boards in the subarea prior to installation was probably responsible for the increased levels of smashed individuals as compared to control boards. More secure closing of test boards might/could have reduced this source of handling mortality.

Control boards were placed into the *Villa Termiti*, but removed before treatment -- check hard copy. Handling mortality of control boards was also low; less than 7 percent. For control boards, the greatest source of handling error was missing individuals; these individuals could be the result of miscounts or cannibalism. For this current study, missing individuals were more likely to have resulted from cannibalism because “gained individual” counts, another form of miscounts, were very low for both treated and control boards. Since handling mortality was minimal, we conclude that any post-treatment mortality observed was primarily due to natural or delayed treatment effects, not experimental error.

For naturally infested boards, the accuracy of the detection equipment used (Wood-Destroying Insect Detector®) was also investigated. Over 94 percent (102/108) of treated, naturally infested boards contained termites when dissected. Boards determined to contain active termite infestations by acoustic emissions and used as controls did, in fact, contain termites 100 percent of the time upon dissection (Table 21). False positives occurred 17 percent of the time (3/18) (Table 21). Three of these false positives were boards that contained 1, 2, or

18 live individuals. Our work substantiates earlier claims on the potential use of the Wood-Destroying Insect Detector® by identifying pieces of structural lumber as actively infested by *I. minor* (Scheffrahn et al. 1993). However, the authors reported a poor relationship between acoustical counts and termite population density for detection experiments conducted with *I. synderi* (Scheffrahn et al. 1993). From observations of the 140 naturally infested boards included in this report, a significant correlation ($r^2 > 0.5$) between detection level and termite number was found (Lewis & Haverty, unpublished data). More technologically advanced acoustic emission devices may be developed which could improve the predictability of termite population density in naturally infested wood.

Conclusions

Over 90 percent of all test insects for both artificially and naturally infested boards were killed during treatment. This high mortality level attests to the fact that all techniques “work” to some degree. Prior to testing in the *Villa Termiti*, all vendors claimed high or total elimination of drywood termite infestations within homes. Test results from whole-structure treatments for artificially and naturally infested boards reveal that at the very highest standard of efficacy, 99 percent, only the fumigant gases demonstrated near 100 percent elimination. Whole-structure treatment with heat was, however, very similar in efficacy level to the fumigant gases. Perhaps improved application techniques or the addition of synergists could elevate heat to higher levels of efficacy.

For localized treatments, 30-min @ 1.4 kg/min and 15-min @ 0.9 kg/min dosages of liquid nitrogen and long application times using drill-and-pin techniques with electrocution were significantly efficacious at the 95 percent level. Microwave treatments (750 W) were deemed efficacious at the 95 percent level, but only when treating naturally infested boards. Not efficacious, even at the 90 percent level, were electrocution without drill-and-pin techniques and 8-min @ 0.9 kg/min treatments of liquid nitrogen.

In general, monitored treatments fared better than non-monitored 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 termite monitoring devices *in situ* could also improve the performance of all spot-treatment techniques. Field efficacy rates for all available drywood termite control methods, including drill-and-treat with chemicals, mode-of action, and damage to structures especially at the micro-level are potential and important areas for future research. In addition, standardization of acceptance levels of efficacy and damage to structures and stricter oversight for advertising claims will be needed.

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Figure Captions

Figure 1. Tongue depressor holding chambers used for maintaining groups of *Incisitermes minor* prior to testing or after testing to measure 4-wk mortality.

Figure 2. *Villa Termiti* used to test fumigation techniques and nonchemical alternatives to fumigation for control of drywood termites. The *Villa Termiti* is symmetrical with all four sides structurally identical.

Figure 3. Sagittal view of *Villa Termiti* showing test board placement locations for attic, drywall, and subarea.

Figure 4. Sagittal view of foundation showing test board placement locations for tests on or near the sill plate.

Figure 5. Douglas-fir "2 by 4" cut so that artificial infestations of 25 *I. minor* pseudergates and nymphs could be placed in each of three galleries.

Figure 6. Thermocouple placement for attic, drywall, and subarea treated by excessive heat.

Figure 7. Schematic drawing of drywall area in *Villa Termiti*. Shaded circles indicate points of introduction for liquid nitrogen. Location of thermocouples are indicted by arrows.