Simulation of Remedial Borate Treatments Intended to Reduce Attack on Douglas-Fir Lumber by the Formosan Subterranean Termite (Isoptera: Rhinotermitidae)

J. KENNETH GRACE AND ROBIN T. YAMAMOTO

Department of Entomology, University of Hawaii at Manoa, 3050 Maile Way, Honolulu, HI 96822–2271

J. Econ. Entomol. 87(6): 1547–1554 (1994)

ABSTRACT Formosan subterranean termites, *Coptotermes formosanus* Shiraki, cost residents of Hawaii over U.S. $100 million each year. The aggressiveness of this termite, the unique climate and soil conditions in Hawaii, and the use of Douglas-fir wood, which resists impregnation with chemical preservatives, make the adoption of termite-control methods developed in other regions problematic. Both laboratory and field experiments were designed to simulate spray applications of disodium octaborate tetrahydrate for preventive and remedial termite control. For laboratory assays, sodium borate solutions in water (10%) or in ethylene glycol and water (23.5%) were applied to one face of Douglas-fir heartwood lumber and allowed to diffuse for 1 or 10 wk. Test blocks were cut from the front (treated face) and rear (untreated face) of each board and assayed for boron content and penetration and for susceptibility to attack by *C. formosanus*. Termites died rapidly upon contacting the board face treated with sodium borate in ethylene glycol. After a 10-wk diffusion period, mass losses from termites feeding on boards treated with this solution were significantly less (7–9%) than on those treated with aqueous borate solutions (34–35%) or with solvent controls (37%). However, borate diffusion below the wood surface was <3 mm after 10 wk with all treatments. When Douglas-fir boxes treated either with two or four applications of sodium borate in water or with two applications of sodium borate in ethylene glycol solution were exposed to a field colony of 1.3 million termites for 10 wk, severe damage from termite feeding occurred in all treatments (30–54% mass losses), and there were no significant differences among treated boxes and untreated controls. Although multiple applications of sodium borate solutions are of value in protecting the treated wood surface from insect penetration and also provide some protection from decay fungus growth, such surface applications do not diffuse readily into Douglas-fir heartwood nor wick down termite galleries in the wood rapidly enough to protect the interior of Douglas-fir lumber from termite feeding.

KEY WORDS *Coptotermes formosanus*, wood preservative, disodium octaborate tetrahydrate

DISODIUM OCTABORATE TETRAHYDRATE is an effective termiticide (Grace & Abdallay 1990, Grace et al. 1990, Williams et al. 1990, Grace 1991, Jones 1991, Su & Scheffrahn 1991a). Structural lumber can be protected from severe attack by the Formosan subterranean termite, *Coptotermes formosanus* Shiraki, by either diffusion or pressure impregnation (Morrell & Lebow 1991) with borate solutions to attain concentrations in the wood of at least 1% boric acid equivalents by weight (Grace et al. 1992, Grace & Yamamoto 1994).

The ability of borates to diffuse with moisture into lumber has led to a great deal of interest in applying borate solutions as remedial treatments to protect wood in service (Dickinson 1990, Puettmann & Williams 1992). In the United States, disodium octaborate tetrahydrate is available to contractors and structural pest control operators either as a soluble powder that is dissolved in water and applied to wood as a 10% solution (TIM-BOR, U.S. Borax, Valencia, CA) or as a concentrated liquid formulation of 40.6% disodium octaborate tetrahydrate, 11.9% polyethylene glycol, and 47.5% monoethylene glycol (BORA-CARE, Nisus, Knoxville, TN) that is diluted 1:1 by volume in water and applied as a 23.5% sodium borate solution.

Douglas-fir (*Pseudotsuga menziezii* [Mirbel] Franco) is the principal construction lumber used in Hawaii (Wilcox 1984) and western North America (Harlow et al. 1979) and is both very susceptible to Formosan subterranean termite attack and resistant to preservative penetration. Within the past 2 yr, the use of lumber pressure-impregnated with disodium octaborate tetrahydrate in building construction and remedial treatments of wood in service with borate solutions have increased in popularity in Hawaii. Although the manufacturers do not recommend surface applications of borate solutions to lumber as a primary means of controlling existing termite infestation, such spray applications have been promoted in industry trade journals and in presentations to trade groups as having great value in preventing termite attack and helping to control existing infestations. Great emphasis generally is placed on the diffusible nature of sodium borate and its subsequent ability to penetrate deeply beneath the wood surface. In the face of such encouragement and in the absence of reliable data generated under conditions comparable with field situations, some members of the pest control industry have been quick to adopt borate spray treatments of above-ground wood as replacements, not supplements, for at least part of their current soil treatment protocols to control subterranean termite infestations (J.K.G., personal observation; R. E. Gold, Texas A&M University, College Station, TX, personal communication).

In an earlier laboratory study (Grace & Yamamoto 1992), we found that Formosan subterranean termites were unable to penetrate the surface of western hemlock (*Tsuga heterophylla* [Rafinesque]Sargent) blocks dipped in a 23.5% solution of disodium octaborate tetrahydrate in ethylene glycol and water. Termites exposed to these blocks in laboratory assays died rapidly, leading us to speculate that the high concentration of sodium borate in poly- and monoethylene glycols on the surface of the treated wood was ingested during both attempted feeding and grooming behavior after contact with that surface. Su & Scheffrahn (1991b) also observed high termite mortality and avoidance of feeding on the wood surface when *C. formosanus* and *Reticulitermes flavipes* (Kollar) were exposed to *Pinus* spp. blocks sprayed on all surfaces (except the end grain) to the point of runoff with a solution of sodium borate in ethylene glycol.

The study reported here was designed as a quantitative examination of the value in Formosan subterranean termite control of the following two types of remedial spray applications commonly performed with sodium borate solutions: (1) application to the surface of uninfested structural lumber to provide protection from subsequent termite attack and (2) application to the surface of structural lumber infested by termites to control, or help to control, existing infestation. Our study was also a comparative evaluation of the two formulations available to the pest control industry in North America and Hawaii.

To determine the value of borate surface applications in protecting Douglas-fir from termite attack, we chose to simulate a worst-case, but common, situation in which a pest-control operator might spray borate solution on a Douglas-fir board 38 mm (nominal 2-inch) thick with only one face exposed for treatment, such as a header or rim joist in substructure building framing. Sodium borate in water or in ethylene glycol solutions was applied to the surface of dry Douglas-fir heartwood boards in accordance with the TIM-BOR and BORA-CARE label recommendations. To simulate further field conditions in Hawaii and the uncontrollable factors with which pest-control operators must contend, we purchased clear lumber (smooth faced and free of defects) locally and sprayed and held the boards under ambient conditions without attempting to control moisture content. We employed both biological assays and chemical analyses to evaluate the resulting boron concentrations and penetration in the wood and the efficacy of the treatments after 1-wk and 10-wk diffusion periods. Rather than allowing termites to contact only the treated face of the board, as was the case in our earlier study (Grace & Yamamoto 1992), they were allowed access to both the treated face and the interior wood.

To address the second question of whether surface applications of sodium borate to lumber could help to control existing termite infestations, we designed a field test, in which dimensional Douglas-fir lumber treated on one face with multiple applications of borate solutions was placed directly into *C. formosanus* foraging sites in the vicinity of a field colony with a foraging population of ≈1.3 million. We hypothesized that termites tunneling into the lumber through the untreated face would elevate the moisture content of the wood and enhance the borate diffusion rate, with their tunnels possibly serving as wicks. High concentrations of boron in the gallery lining would lead to termite mortality and retreat of the foragers from the lumber. At the conclusion of the 10-wk field exposure, we, thus, would expect to observe few, if any, termites in the borate-treated lumber and reduced feeding damage in comparison with untreated control lumber.

Materials and Methods

Laboratory Assays. A clear Douglas-fir board (38 by 180 mm by 3 m [nominal 2 by 8 inches]) was purchased from a local retail outlet (Kaimuki Ace Hardware, Honolulu) and cut into six lengths of 452 mm each. To prevent spray drift and application to the ends and sides, each length of board was placed within a frame constructed of 18- by 85-mm lumber.

Disodium octaborate tetrahydrate solutions were prepared in distilled water as a 10% aqueous solution (95.8635 g TIM-BOR per 800 ml water) and as a 23.5% ethylene glycol solution (1:1 BORA-CARE in water). Control solutions consisted of distilled water and 1:1 (by volume) ethylene glycol (Sigma, St. Louis, MO) in water.

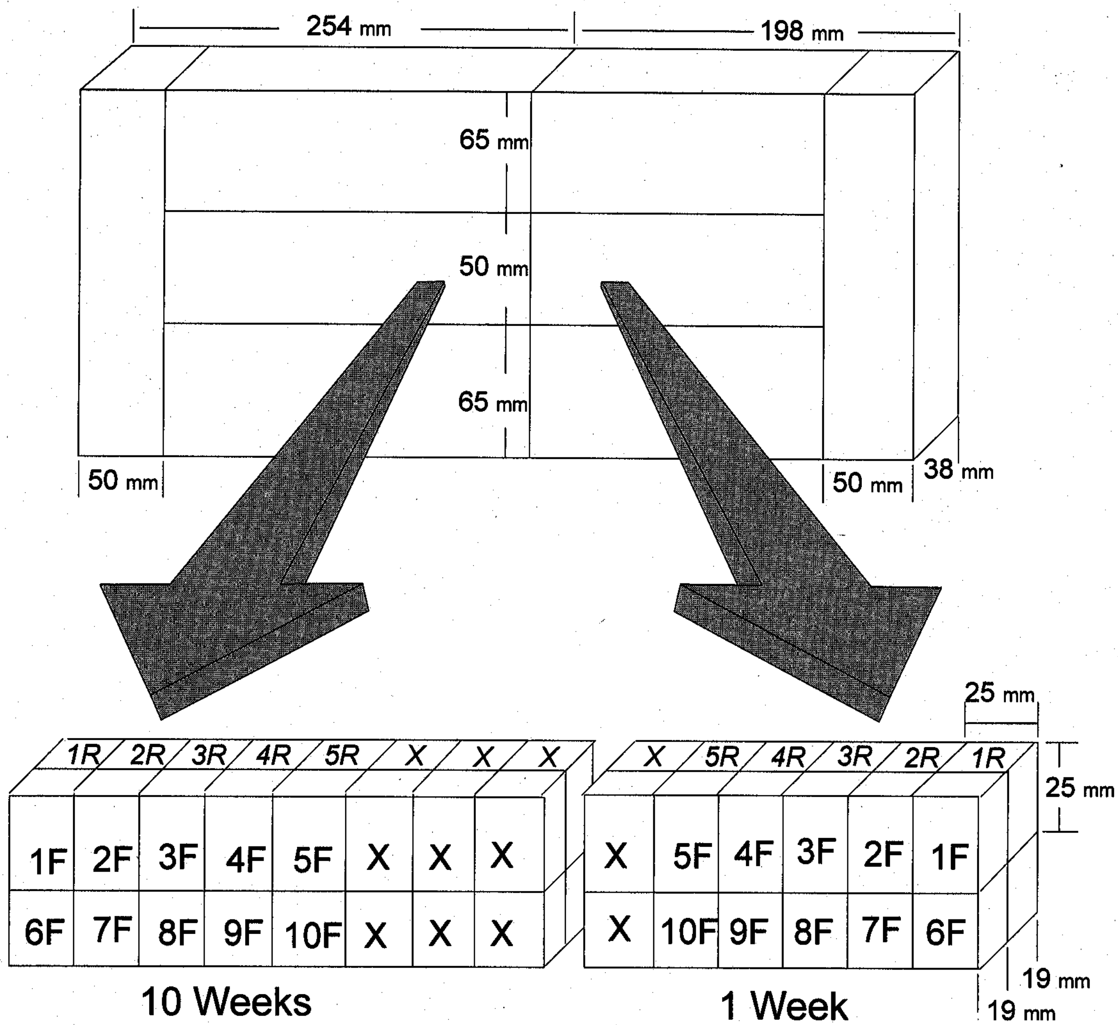

Fig. 1. Positions of test blocks cut from the front (F) borate-teated face and rear (R) untreated face of vertically oriented Douglas-fir boards for laboratory assays. Even-numbered blocks were assayed for boron content and penetration, and odd-numbered blocks were bioassayed for susceptibility to *C. formosanus*.

With the lengths of board standing on edge within their perimeter frames, one vertical face was sprayed to runoff with a fine spray from a hand-pressurized (by squeezing the trigger) 0.95-liter plastic spray bottle. Each board either received one application of sodium borate in water or ethylene glycol or received two applications separated by an 18-h drying period. The ethylene glycol and water control solutions each were applied twice. After spraying, the boards were stored in the same vertical position for 1 wk at ambient conditions in an unair-conditioned room (24–27°C, 54-95% RH).

After 1 wk, each length of board was cut into two sections (Fig. 1), and one of the sections was stored for an additional 9 wk. The other section was reduced to a single center strip (50 mm wide). This center strip was split into front (treated face) and rear halves, and each half was cut into ten 25-by-25-by-29-mm test blocks. Even-numbered blocks were assayed for boron content and penetration, and odd-numbered blocks were bioassayed for susceptibility to termite feeding (Fig. 1). At the end of 10 wk, the remaining board section was cut and assayed in the same manner.

All chemical analyses were performed at U.S. Borax. To measure borate penetration, selected blocks were sliced normal to the exterior face and sprayed sequentially with alcohol solutions of curcumin and salicylic acid in a colorimetric test sensitive to ≈0.25% boric acid equivalents (Anonymous 1984). Boron content was determined by planing a 6-mm slice from the exterior face of each block, ashing the slice at 500°C, extracting the residue with hydrochloric acid, and analyzing the extract for boron content with inductively coupled plasma spectroscopy (Docks et al. 1990, Robinson & Barlow 1993).

Laboratory bioassays of 4-wk (28-d) duration were performed to determine the susceptibility of the test blocks to termite feeding (Grace & Yamamoto 1992, Grace et al. 1993) and were based on methods used in the wood-preservation industry (American Society for Testing and Materials 1991, American Wood-Preservers' Association 1991). Immediately before their use in assays, Formosan subterranean termite workers (pseudergates, [undifferentiated individuals older than the third instar]) were collected from a field colony on the Manoa campus of the University of Hawaii (Tamashiro et al. 1973). The test containers were screw-top plastic jars (8 cm diameter by 10 cm high), each containing ≈150 g washed and oven-dried crushed coral sand (sieved to pass a U.S. 14-mesh [1.4 mm] screen) and 30 ml distilled water. A single test block was placed with the exterior face upward on a 50-by-50-mm square piece of aluminum foil on the surface of the sand, and 400 termites (360 workers and 40 soldiers, to simulate normal caste proportions) were added to each jar. The jars (five replicates per treatment) were incubated in an unlighted temperature-controlled cabinet (29 ± 0.5°C) for 4 wk. Blocks were oven dried (45°C, 3 d) before and after the test period to determine their mass loss caused by termite feeding, and termite mortality was recorded.

To determine the effects of spray pattern (fine, coarse) and application method (light or heavy runoff) on boron content of the treated wood, we also purchased two additional Douglas-fir boards and sprayed cut sections of both boards with either the 0.95-liter plastic spray bottle (fine spray, to either light or heavy runoff) or a 7.57-liter steel sprayer (Sears; coarse spray with heavy runoff). After a 1-wk diffusion period, the board sections were trimmed and reduced to two center strips from each section, each measuring ≈215 by 70 by 38 mm. Using an electric planer, one strip was sampled to a depth of 6 mm, and the slice was ashed and analyzed for boron content by inductively coupled plasma spectroscopy. The other slice was sampled in two slices, each 3 mm thick, to evaluate borate penetration.

Wood mass loss, percentage boric acid equivalents, and termite-mortality data (transformed by the arcsine of the square root) were subjected to analysis of variance (ANOVA) and means were separated by the Ryan–Einot–Gabriel–Welsch multiple *F* test (SAS Institute 1987).

Field Study. This study was designed to simulate field applications to lumber in structures infested by *C. formosanus*. Termite feeding sites were established using the methods described by Tamashiro et al. (1973) for establishing collection traps in the field. Initially, Douglas-fir stakes (2.5 by 3.3 by 25.5 cm) were driven into the ground, with ≈10 cm protruding, at a location on the Manoa campus from which subterranean termites have been collected for ≈18 yr. As measured by mark–release–recapture methods (Grace 1992), this colony has a foraging population of ≈1.3 million.

After ≈1 mo, small open-ended boxes (4 by 5 by 25 cm) constructed of plywood (6 mm thick) were placed over 12 of the infested stakes. We then constructed larger open-ended boxes (Tamashiro et al. 1973), measuring 8.2 by 8.7 by 25 cm, from construction-grade Douglas-fir lumber (18 mm thick [nominal 1-inch]). Before construction, each piece of wood was oven dried (90°C, 4 d) and weighed. Each test box weighed ≈600 g.

We allowed 2 wk for termites actively to infest the plywood boxes at the field site. Each test box then was placed upright with a cap of Douglas-fir (18 mm thick) placed over the upper end, and the sides were thoroughly treated to runoff with a fine spray from a 0.95-liter plastic spray bottle containing either a 10% aqueous solution (95.8635 g TIM-BOR per 800 ml water) or a 23.5% ethylene glycol solution (1:1 BORA-CARE in water) of disodium octaborate tetrahydrate or distilled water (controls). Borate treatments consisted either of two or four applications of the 10% aqueous solution or of two applications of the ethylene glycol solution. Successive applications were made at 24-h intervals, and the boxes were held under laboratory conditions (≈25°C, 60% RH) for 2 d before being placed in the field. A sheet of 6-mil polyethylene was placed around the base of each plywood box to protect the test boxes, or sleeves, from soil contact, and one of the test boxes was placed over each plywood box. Each treatment was replicated three times, and each replicate was protected from rainfall by a 19-liter metal can with the bottom removed and a sheet metal cover over the upper end (Tamashiro et al. 1973).

After 10 wk of field exposure, the wooden boxes were dismantled carefully and cleaned of termites and carton material, and the wood was oven dried and weighed to determine mass loss caused by termite feeding. Wood mass-loss data were subjected to ANOVA (SAS Institute 1987).

Results and Discussion

We expressed the boron concentration in the treated Douglas-fir boards in terms of the percentage boric acid equivalents (weight:weight) in the outer 6 mm of wood (Tables 1 and 2). However, the colorimetric test did not indicate any borate penetration below 2 mm from the surface. Similarly, very limited penetration was recorded when thin sections of the boards treated with sodium borate in water were analyzed by inductively coupled plasma spectroscopy, with no boron detected above background levels (<0.02% boric acid equivalents) below 3 mm from the surface (Table 3). Greater borate diffusion was reported in southern pine (Puettmann & Williams 1992, Su & Scheffrahn 1991b),

Table 1. Boron content and Formosan subterranean termite feeding and mortality in Douglas-fir boards sprayed to runoff with disodium octaborate tetrahydrate (DOT) in water or ethylene glycol solutions after a 1-wk diffusion period

Category	Treatment	% DOT in solution (wt:vol)	No. sprays	% BAE[a] in outer 6 mm	Wood mass loss		% Termite mortality
					g	%	
Front (sprayed) board surface	DOT/water	10	1	0.18 ± 0.06c	0.94 ± 0.41b	24.48 ± 10.50	55.40 ± 28.79b
			2	0.34 ± 0.06b	0.87 ± 0.32b	23.40 ± 8.53	73.95 ± 26.59b
	DOT/glycol	23.5	1	0.74 ± 0.13a	0.08 ± 0.03c	2.13 ± 0.87	100.00 ± 0.00a
			2	0.86 ± 0.16a	0.11 ± 0.07c	2.84 ± 1.78	100.00 ± 0.00a
	Ethylene glycol	0	2	<0.02d	1.44 ± 0.30a	36.32 ± 8.40	17.55 ± 7.74c
	Water	0	2	<0.02d	1.62 ± 0.23a	40.62 ± 6.33	12.60 ± 5.43c
Rear (unsprayed) board surface	DOT/water	10	1	<0.02a	1.44 ± 0.07a	36.72 ± 2.13	16.40 ± 4.52a
			2	<0.02a	1.37 ± 0.20a	34.90 ± 5.51	17.60 ± 6.51a
	DOT/glycol	23.5	1	<0.02a	1.59 ± 0.10a	41.01 ± 3.34	13.75 ± 2.12a
			2	<0.02a	1.58 ± 0.16a	40.40 ± 4.04	14.60 ± 7.82a
	Ethylene glycol	0	2	<0.02a	1.49 ± 0.29a	36.00 ± 7.50	19.30 ± 3.95a
	Water	0	2	<0.02a	1.53 ± 0.08a	37.83 ± 3.87	16.20 ± 4.41a

Mean (±SD) of five replicates. Means within each column and within each catagory (front, rear) followed by the same letter are not significantly different ($P \leq 0.05$ [ANOVA and Ryan–Einot–Gabriel–Welsch multiple F test]; df = 5, 24).
[a] Percentage boric acid equivalents (wt:wt).

although penetration results of Robinson & Barlow (1993) showed considerable variability in the slope of the boron concentration gradient from 0 to 3 mm below the wood surface.

Although we found no evidence that ethylene glycol aided diffusion (and thus penetration) of borate into wood below the surface, the surface concentrations obtained with one application of sodium borate in ethylene glycol were >2-fold greater than those obtained with two applications of the aqueous solution (Tables 1 and 2). These high surface concentrations may have been a result of the greater viscosity of the ethylene glycol solution, as opposed to water, when applied to runoff on the smooth vertical face of the boards used in our study. Spray applications of aqueous sodium borate solutions to rougher Douglas-fir board faces may produce borate concentrations in the wood closer to the 1:2.4 ratio of sodium borate in the water and ethylene glycol solutions (M. D. Noirot, U.S. Borax, personal communication).

With both aqueous and ethylene glycol solutions of sodium borate, boron was detected only on and immediately beneath the treated face of the boards. We observed no diffusion nor surface migration (creep) of sodium borate from the treated face to the rear untreated portions of the boards (Tables 1 and 2). This was confirmed in our bioassays by the susceptibility of the rear portion of the boards to termite feeding.

The boron concentrations of 0.18% (Table 1), 0.16% (Table 2), and 0.14% boric acid equivalents (Table 3) obtained with one application of sodium borate in water were well below the concentrations needed to protect wood from Formosan subterranean termite attack, although continual feeding on those levels does lead to gradual termite mortality (Grace et al. 1992, Williams et al. 1990). Thus, termite responses to wood

Table 2. Boron content and Formosan subterranean termite feeding and mortality in Douglas-fir boards sprayed to runoff with disodium octaborate tetrahydrate (DOT) in water or ethylene glycol solutions after a 10-wk diffusion period

Category	Treatment	% DOT in solution (wt:vol)	No. sprays	% BAE[a] in outer 6 mm	Wood mass loss		% Termite mortality
					g	%	
Front (sprayed) board surface	DOT/water	10	1	0.16 ± 0.05c	1.45 ± 0.21a	34.93 ± 6.63	23.65 ± 6.15b
			2	0.20 ± 0.02c	1.39 ± 0.25a	34.00 ± 5.99	29.00 ± 6.13b
	DOT/glycol	23.5	1	0.53 ± 0.12b	0.39 ± 0.20b	9.31 ± 4.62	96.35 ± 8.16a
			2	0.80 ± 0.16a	0.26 ± 0.07b	6.67 ± 1.99	100.00 ± 0.00a
	Ethylene glycol	0	2	<0.02d	1.55 ± 0.16a	37.39 ± 2.62	19.85 ± 6.04b
	Water	0	2	<0.02d	1.52 ± 0.11a	36.77 ± 2.12	16.70 ± 3.06b
Rear (unsprayed) board surface	DOT/water	10	1	<0.02a	1.46 ± 0.22a	33.71 ± 5.25	18.90 ± 3.92a
			2	<0.02a	1.61 ± 0.18a	36.78 ± 3.76	16.60 ± 4.41a
	DOT/glycol	23.5	1	<0.02a	1.67 ± 0.18a	37.47 ± 3.88	21.20 ± 3.50a
			2	<0.02a	1.69 ± 0.16a	39.41 ± 3.71	16.20 ± 3.55a
	Ethylene glycol	0	2	<0.02a	1.70 ± 0.04a	38.14 ± 1.70	15.40 ± 1.97a
	Water	0	2	<0.02a	1.73 ± 0.07a	38.16 ± 1.85	14.10 ± 3.60a

Mean (±SD) of five replicates. Means within each column and within each catagory (front, rear) followed by the same letter are not significantly different ($P \leq 0.05$ [ANOVA and Ryan–Einot–Gabriel–Welsch multiple F test]; df = 5, 24).
[a] Percentage of boric acid equivalents (wt:wt).

sprayed with either one or two applications of sodium borate in water were variable. The greater termite mortality noted after 1 wk than after 10 wk diffusion of sodium borate applied as an aqueous solution may have been caused by termite contact initially with a higher concentration of boron at the surface of the treated wood and dilution of this gradient effect as diffusion occurred in the first 2–3 mm. Variations in the wood within the treated boards or in applicator technique could contribute also to variation in boron content among the test blocks. In a field test of Douglas-fir lumber diffusion treated with disodium octaborate tetrahydrate in water, Archer et al. (1991) were also unable to obtain sufficiently high boron concentrations by diffusion to provide protection from Formosan subterranean termites.

Two applications of the 23.5% (wt:vol) solution of sodium borate in ethylene glycol were needed to obtain boron concentrations in the first 6 mm of wood close to the 1% boric acid equivalents needed to protect wood adequately from Formosan subterranean termite feeding (Grace et al. 1992). As in our previous investigation of ethylene glycol borate treatments (Grace & Yamamoto 1992), termites died rapidly after contact with the treated wood surface, even after a 10-wk diffusion period (Table 2). Applications of the dilute ethylene glycol solvent alone did not elicit termite mortality nor reduction in feeding. This suggests that treatment with the ethylene glycol solution deposited a persistently high concentration of sodium borate on the wood surface and that contact with this treated surface, and possibly subsequent termite grooming activities, caused rapid ingestion of a lethal dose of boron.

Although we followed label instructions to "thoroughly wet" (TIM-BOR) the wood surface with sodium borate in water and apply to the "point of runoff" (BORA-CARE) with sodium borate in ethylene glycol, our solution usage indicated that we actually applied about one-half of the 26.5–37.9 liters/92.9 m^2 (7–10 gal/1000 square feet) recommended on the TIM-BOR label and twice the 3.8 liters/1.9 m^3 (1 gal/800 board feet) recommendation of BORA-CARE. Thus, at least with application to a smooth vertical board face, there were discrepancies with both materials between their recommended application rates and the visual cues to the applicator indicating a successful treatment. With sodium borate in water, we found that application to a heavier degree of runoff increased solution usage to that recommended by the label but did not result in greater boron concentrations or better diffusion of borate in the treated wood (Table 3).

Our field results also indicated that borate treatments, even with multiple applications meeting and exceeding the label recommendations, do not penetrate deeply into Douglas-fir wood, at least within the first 3 mo after treatment. At the conclusion of the 10-wk field exposure, large numbers of active termite foragers were found tunneling in all of the borate-treated and control Douglas-fir boxes, providing no evidence that enhanced borate migration resulting from termite tunneling led to retreat by the colony. There was considerable variation in the amount of damage among the replicates, with the weight losses from termite feeding on individual boxes ranging from 82 to 429 g. However, there were no significant differences in wood weight losses among the treatments, and none of the borate treatments differed significantly in termite damage from the control boxes (Table 4). Tunneling was extensive in all treatments, and tunnels were visible to within a few millimeters of the treated surfaces. Termites did not penetrate the treated surfaces, although there were also very few penetrations of the exterior wood surfaces in the control boxes.

Our results lead us to conclude that application of borate solutions to the surface of Douglas-fir lumber results in a shell, or envelope, treatment. Spray treatment can protect the treated surface from termite penetration, but disodium octaborate tetrahydrate should not be expected to diffuse more than a few millimeters beneath that surface. Even if the internal concentrations of borate in the treated lumber continue gradually to increase as a result of the diffusion process, this process appears to be too slow to prevent damage from termite attack on areas other than the treated face. As previously mentioned, Douglas-fir is considered generally resistant to preservative treatment, and greater

Table 3. Boron content of Douglas-fir boards treated with spray applications of disodium octaborate tetrahydrate in a 10% aqueous solution after a 1-wk diffusion period

Equipment	Spray	Coverage	Application rate		% BAE[a] in zones below wood surface		
			ml/m^2	gal/1,000 ft^2	0–3 mm	3–6 mm	0–6 mm
Plastic bottle (0.95 liter [1 qt])	Fine	Light runoff	82	2	0.28 ± 0.09	<0.02	0.14 ± 0.03
		Heavy runoff	285	7	0.38 ± 0.11	<0.02	0.14 ± 0.03
Steel sprayer (7.57 liter [2 gal.])	Coarse	Heavy runoff	448	11	0.28 ± 0.08	<0.02	0.11 ± 0.03

Mean (±SD) of four samples (two each from two boards). Means within each column are not significantly different ($P \leq 0.05$ [ANOVA]; df = 3).

[a] Percentage boric acid equivalents (wt:wt).

Table 4. Mass loss of Douglas-fir boxes sprayed to run-off with disodium octaborate tetrahydrate (DOT) in water or ethylene glycol solutions after a 10-wk field exposure to Formosan subterranean termites

Treatment	% DOT in solution (wt:vol)	No. sprays	Wood mass loss	
			g	%
DOT/water	10	2	224.27 ± 115.43	36.74 ± 18.65
		4	174.77 ± 40.32	30.03 ± 6.72
DOT/glycol	23.5	2	208.43 ± 125.37	36.60 ± 20.80
Water	0	4	316.63 ± 117.04	54.31 ± 19.19

Mean (±SD) of three replicates. Mean mass losses are not significantly different ($P \leq 0.05$ [ANOVA]; df = 3).

borate penetration may indeed be achieved in spray treatments of other wood species, such as *Pinus* spp. (Puettmann & Williams 1992). However, because Douglas-fir is extremely common in building construction in Hawaii and the western United States and because pine is not, this illustrates that pest-control methods developed under a particular set of conditions cannot be assumed to apply to other geographic regions.

Under the worst-case scenario of our laboratory study, more than two, and perhaps as many as four, applications of sodium borate in water (10% by weight) would be required to provide protection from termite penetration of the treated surface. Once the wood surface was wet with the aqueous solution of sodium borate, neither a coarser spray pattern nor application of excess solution increased boron concentrations or diffusion rate.

The higher concentration (23.5%) of disodium octaborate tetrahydrate dissolved in ethylene glycol solution and the greater viscosity of the ethylene glycol solution reduced the need for multiple reapplications. However, we found no evidence that ethylene glycol contributed to increased diffusion of borate in Douglas-fir, nor did it lead to any migration of borate on the wood surface to surface areas not sprayed directly with the solution. In our laboratory assays, termites confined in close proximity to wood treated with sodium borate in ethylene glycol solutions contacted the treated wood surface and died much more rapidly than occurs from exposure to aqueous sodium borate solutions. However, under field conditions simulating application to wood in an infested structure, the ethylene glycol solvent did not contribute to any reduction of termite activity in the treated wood.

Despite the limitations noted in our study, applications of disodium octaborate tetrahydrate to the surface of wood in service may be helpful in controlling wood-boring insects. Such applications impart at least some toxicity to the treated wood, and sufficiently high boron concentrations should prevent insect penetration of the treated surface. This is particularly useful in preventing infestation by wood-boring beetles (Robinson & Barlow 1993) but may also inhibit termite foragers or alates (winged primary reproductives) attempting to penetrate the treated surface. Moreover, as long as the treated surface is not exposed to running water, this protection is virtually permanent, which represents a distinct advantage over surface applications of organic insecticides. The fungistatic activity of sodium borate is also advantageous in protecting structural wood. However, pest control operators should be well aware of the limitations of surface spray applications and the need for multiple applications of disodium octaborate tetrahydrate solutions to attain boron concentrations that are effective against Formosan subterranean termites. One should not expect surface sprays with borate solutions to provide protection to board surfaces that were not treated directly nor expect deep diffusion of borates applied to the surface of Douglas-fir boards.

Acknowledgments

We thank M. J. Manning and M. D. Noirot (U.S. Borax) for chemical analyses, T. G. Shelton (University of Hawaii) for figure illustration, J. R. Yates III (University of Hawaii) for helpful comments on the manuscript, and Nisus (Knoxville, TN) and U.S. Borax for providing materials and helpful information. Financial support was provided by McIntire–Stennis funds and USDA–ARS Specific Cooperative Agreement 58-6615-9-012. This is journal series no. 3954 of the Hawaii Institute of Tropical Agriculture and Human Resources.

References Cited

American Society for Testing and Materials. 1991. ASTM D3345–74 (reapproved 1986): standard method of laboratory evaluation of wood and other cellulosic materials for resistance to termites. Annual Book of ASTM Standards, vol. 04.09, Wood. American Society for Testing and Materials, Philadelphia, PA.

American Wood-Preservers' Association. 1991. AWPA E1–72: standard method for laboratory evaluation to determine resistance to subterranean termites. AWPA Book of Standards. American Wood-Preservers' Association, Woodstock, MD.

Anonymous. 1984. TIMBOR preservatives: plant operators' manual of recommended practice. Borax Holdings, London.

Archer, K. J., D. A. Fowlie, A. F. Preston & P. J. Walcheski. 1991. A termite field test with diffusion treated lumber, pp. 1–13. *In* Document No. IRG/WP/3648, International Research Group on Wood Preservation, Stockholm, Sweden.

Dickinson, D. J. 1990. Remedial treatment: in-situ treatments and treatments of historical structures, pp. 87–90. *In* Proceedings 47355, First International Conference on Wood Protection with Diffusible Preservatives. Forest Products Research Society, Madison, WI.

Docks, E. L., Y. S. Chiu & N. T. Carey. 1990. Developing quality control procedures and standards for diffusible preservatives, pp. 115–117. *In* Proceedings 47355, First International Conference on Wood Protection with Diffusible Preservatives. Forest Products Research Society, Madison, WI.

Grace, J. K. 1991. Response of eastern and Formosan subterranean termites (Isoptera: Rhinotermitidae) to borate dust and soil treatments. J. Econ. Entomol. 84: 1753–1757.

1992. Termite distribution, colony size, and potential for damage, pp. 67–76. *In* Proceedings, National Conference on Urban Entomology, 23–26 February 1992. University of Maryland, College Park, MD.

Grace, J. K. & A. Abdallay. 1990. Termiticidal activity of boron dusts (Isoptera, Rhinotermitidae). J. Appl. Entomol. 109: 283–288.

Grace, J. K., & R. T. Yamamoto. 1992. Termiticidal effects of a glycol borate wood surface treatment. For. Prod. J. 42(11/12): 46–48.

1994. Repeated exposure of borate-treated Douglas-fir to Formosan subterranean termites in an accelerated field test. For. Prod. J. 44(1): 65–67.

Grace, J. K., A. Abdallay & J. M. Sisson. 1990. Preliminary evaluation of borate baits and dusts for eastern subterranean termite control, pp. 1–7. *In* Document no. IRG/WP/1433, International Research Group on Wood Preservation, Stockholm, Sweden.

Grace, J. K., R. T. Yamamoto & M. Tamashiro. 1992. Resistance of borate-treated Douglas-fir to the Formosan subterranean termite. Forest Prod. J. 42(2): 61–65.

Grace, J. K., P. E. Laks & R. T. Yamamoto. 1993. Efficacy of chlorothalonil as a wood preservative against the Formosan subterranean termite. For. Prod. J. 43(1): 21–24.

Harlow, W. M., E. S. Harrar & F. M. White. 1979. Textbook of dendrology. McGraw–Hill, New York.

Jones, S. C. 1991. Field evaluation of boron as a bait toxicant for control of *Heterotermes aureus* (Isoptera: Rhinotermitidae). Sociobiology 19: 187–209.

Morrell, J. J. & S. T. Lebow. 1991. Borate treatment of seasoned western hemlock and Douglas-fir lumber. For. Prod. J. 41: 27–29.

Puettmann, M. M. & L. H. Williams. 1992. Penetration of southern pine floor joists by borate/glycol formulations. Wood Prot. 2(1): 29–34.

Robinson, W. H. & R. A. Barlow. 1993. Diffusion of disodium octaborate tetrahydrate into southern yellow pine to control wood-infesting beetles, pp. 187–191. *In* Proceedings, First International Conference on Insect Pests in the Urban Environment, St. John's College, Cambridge, UK ISBN 0–9521824–0-8.

SAS Institute. 1987. SAS/STAT user's guide for personal computers, version 6 ed. SAS Institute, Cary, NC.

Su, N.-Y. & R. H. Scheffrahn. 1991a. Laboratory evaluation of disodium octaborate tetrahydrate (TIM-BOR[r]) as a wood preservative or a bait-toxicant against the Formosan and eastern subterranean termites (Isoptera: Rhinotermitidae), pp. 1–12. *In* Document no. IRG/WP/1513, International Research Group on Wood Preservation, Stockholm, Sweden.

Su, N.-Y. & R. H. Scheffrahn. 1991b. Remedial wood preservative efficacy of BORA-CARE™ against the Formosan subterranean termite and eastern subterranean termite, pp. 1–7. *In* Document no. IRG/WP/1504, International Research Group on Wood Preservation, Stockholm, Sweden.

Tamashiro, M., J. K. Fujii & P. Y. Lai. 1973. A simple method to observe, trap and prepare large numbers of subterranean termites for laboratory and field experiments. Environ. Entomol. 2: 721–722.

Wilcox, W. W. 1984. Observations on structural use of treated wood in Hawaii. For. Prod. J. 34: 39–42.

Williams, L. H., T. L. Amburgey & B. R. Parresol. 1990. Toxic thresholds of three borates and percent wood weight losses for two subterranean termite species when feeding on treated wood, pp. 129–133. *In* Proceedings 47355, First International Conference on Wood Protection with Diffusible Preservatives. Forest Products Research Society, Madison, WI.

Received for publication 26 July 1993; accepted 29 June 1994.