Field Comparison of Sulfuryl Fluoride Susceptibility Among Three Termite Species (Isoptera: Kalotermitidae, Rhinotermitidae) During Structural Fumigation

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ABSTRACT Three termite species, *Incisitermes schwarzi* (Banks), *Cryptotermes cavifrons* (Banks), and *Coptotermes formosanus* Shiraki, were exposed in separate structures to sulfuryl fluoride dosages of ca. 3, 6, and 12 mg/liter. Termites, confined to vented petri dishes and sealed wooden enclosures, were removed from each structure at 2-h intervals for 20 h. Although in many cases initial mortality of *C. formosanus* in petri dishes was significantly lower than *I. schwarzi* and *C. cavifrons*, by 72 h mortality had stabilized and was the same for all three species. In wood enclosures, however, mortality at 72 h remained lower for *C. formosanus*. This effect was attributed to experimentally elevated wood moisture content in the *C. formosanus* enclosures acting as a gas barrier and possible physiological differences between this termite and the other two species. In all combinations except *C. formosanus* in wood enclosures, 72 h mortality followed a simple hyperbolic concentration versus time function and reached 100% mortality from accumulated dosages of 28–49 mg h/liter. *C. formosanus* in wood enclosures required dosages of ≥95 mg h/liter for 100% mortality. These results suggest that minimum fumigant concentration and time thresholds, in conjunction with higher initial dosage, must be achieved for successful control of *C. formosanus* under simulated field conditions.

KEY WORDS termite fumigation, sulfuryl fluoride, fumigant efficacy, *Coptotermes formosanus, Cryptotermes cavifrons, Incisitermes schwarzi*, accumulated dosage

FUMIGATION IS a common method for remedial control of extensive drywood termite (Kalotermitidae) infestations in wooden structures. Stewart (1957), who tested fumigants against *Incisitermes minor* (Hagen), concluded that both methyl bromide and sulfuryl fluoride, two compounds currently registered for termite control, are about equally toxic to this insect. Field efficacy of fumigants was monitored by Bess & Ota (1960) using *Cryptotermes brevis* (Walker) confined to wood block cages. They found that sulfuryl fluoride, for a minimum 1.5-h exposure at 32 mg/liter, rapidly penetrated 3.2 cm of wood and provided 100% mortality. The current label prescribed rate for drywood termites is ca. 6 mg/liter for 20 h at 27°C for sulfuryl fluoride (Anonymous 1982) and ca. 16–24 mg/liter for 12–24 h for methyl bromide (Anonymous 1981).

The expanding distribution of the Formosan subterranean termite, *Coptotermes formosanus* Shiraki, in the southeastern United States (Thompson 1985) coupled with its propensity for establishing aerial infestations, has placed increased reliance on fumigation to control this introduced pest. The current recommended dosage for sulfuryl fluoride against *C. formosanus* is ca. 24 mg/liter or 4-fold the drywood termite rate. A 4-fold rate produced 100% mortality of *C. formosanus* confined to wood boxes that were placed in fumigated structures (J. P. La Fage, personal communication). In a laboratory study, La Fage et al. (1983) showed that the acute rate for 100% mortality for sulfuryl fluoride at 30°C and 24-h exposure was ca. 4 mg/liter to unconfined *C. formosanus* workers. They concluded that the recommended label dosage may be excessive. However, M. Tamashiro (personal communication) found that 3-year-old incipient colonies of *C. formosanus*, housed in 19-liter steel cans capped with plywood, were often not killed at the 4-fold rate when placed inside fumigated structures. These results indicated a need for more research to identify an effective field dosage and to explain apparent differences in susceptibility of *C. formosanus* to sulfuryl fluoride as compared with drywood species.

In this study, we determined, under field conditions, the relative toxicity of sulfuryl fluoride to three termite species exposed directly to the fumigant or sealed in wood enclosures. We also compared termite mortality resulting from exposure to three fumigant concentrations as a function of time and concentration—i.e., accumulated dosage.

Materials and Methods

Termites. Foraging groups from three colonies of *C. formosanus* were taken from buried wooden traps located in Hallandale, Fla. Whole colonies

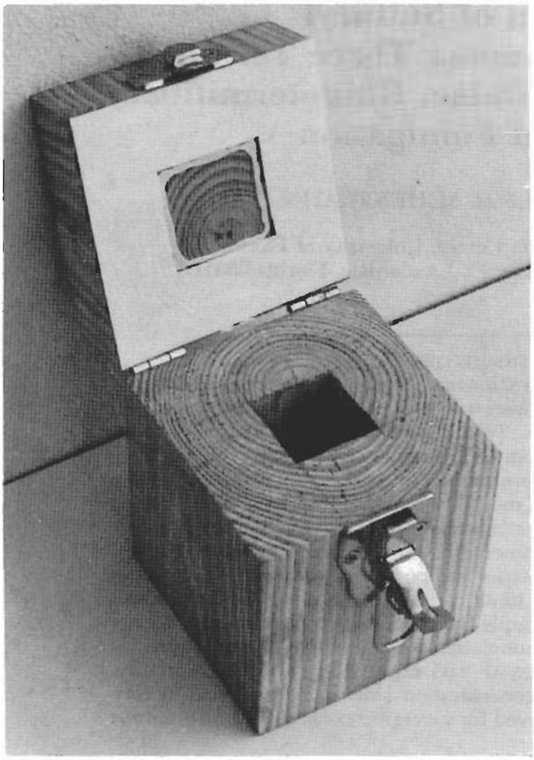

Fig. 1. Wooden enclosure used to confine termites during the fumigations.

of *C. cavifrons* (Banks) and *I. schwarzi* (Banks) were collected in dead wood logs from H. T. Birch Recreation Area, Ft. Lauderdale, Fla. Termites were excised from the wood, separated from debris, and stored in provisioned containers for <2 weeks before the experiment. An unknown number of colonies of each drywood species combined as logs often contained several reproductive pairs of undetermined age. The three *C. formosanus* colonies were kept separately. Termites were placed into test containers 1 day before fumigation.

Containers. Termites were confined to either petri dishes or wooden enclosures during sulfuryl fluoride exposure. Plastic petri dishes (3.5 cm diam by 1.0 cm high) were provisioned with single filter paper disks (2.5 diam, moistened with 0.1 ml deionized water for *C. formosanus*) and a small wood chip. Three venting ribs on the underside of the petri dish lids permitted unimpeded gas diffusion. The wooden enclosures (Fig. 1) were cut as 11.4-cm lengths from heartwood timbers (11.4 by 11.4 cm) of slash pine, *Pinus elliottii*. These cubes were drill-chiseled along the grain from one side to form rectangular hollows (3.8 by 3.8 by 7.6 cm) surrounded on all sides by 3.8-cm-thick walls. The 3.8-cm-thick lids were attached by dual rear hinges and a front snap latch to firmly compress a lid-mounted gasket when closed. Gaskets were cut from sheets of Nalgene closed-cell resilient polyethylene foam (3.2 mm thick; Fisher Scientific, N.J.), which provided a watertight seal. External cracks on some of the wood surfaces were filled with glue (Silicon II; General Electric, N.Y.). Each container (558 total) received one of the following: *C. formosanus* (one group from each colony per replicate), 44 undifferentiated larvae of at least third instar (3.99 mg per termite ± 1.07 [SE]) and 6 soldiers; *C. cavifrons*, 50 pseudergates or first-molt nymphs (3.22 ± 0.24); or *I. schwarzi*, 19 pseudergates and 1 soldier or 20 pseudergates (12.88 ± 0.53). Wood containers designated for *C. formosanus* were provisioned with 5 ml sand and 8 ml water before adding termites.

Fumigation. Three adjacent mobile homes mounted on a tarmac surface at the Ft. Lauderdale Research and Education Center served as experimental fumigation chambers. These encompassed volumes of ca. 368, 204, and 368 m^3 and were designated for sulfuryl fluoride dosages of 3, 6, and 12 mg/liter respectively. Flat ramps were constructed from the front entrance of each chamber down, which cardboard boxes holding the termite containers could be slid from inside the chambers during the fumigations. Each cardboard box contained nine petri dishes and nine wood enclosures, representing three replicates for each termite species in each container type. Ten cardboard boxes were lined up along the entrance hallway of each chamber and a labeled rope was attached to each box so they could be pulled from the chambers in correct sequence. One additional 18-unit cardboard box, containing the control group, was placed in a nearby untreated building maintained at 30°C and 80% RH. Hygrothermographs were placed in the mobile homes.

The structures were covered with tarpaulins secured with clamps and sealed along the ground with sand. A resealable seam was positioned at the bottom of each ramp through which the cardboard boxes could be removed. The 99% pure sulfuryl fluoride gas was introduced by weight for desired dosages through a hose which opened into a side room of each chamber. A calibrated thermal conductivity meter (Fumiscope, Hassler, Mammoth Lakes, Calif.) was used to measure fumigant concentrations. Gas samples were drawn by pump and measured successively from sampling hoses in entrance hallways before and after each cardboard box was removed. Once during the experiment (at 8 h) fumigant concentrations had declined ca. 1 mg/liter below initial rates, so additional gas was added to compensate for this loss.

After gas was introduced, a cardboard box was pulled from each chamber on a 2-h schedule for a total period of 20 h. Initial mortality was recorded immediately for each of the 54 termite containers removed for a given time period. Dead and moribund individuals were counted and removed from each container, and survivors were transferred to freshly provisioned petri dishes.

Mortality in the control group was tallied after the 20 h count. All surviving termites were stored in a 30°C incubation chamber for succeeding 24 h posttreatment counts which were suspended after no additional mortality was observed.

Statistical Analyses. Because the control units were only examined at 20 h, a linear control mortality was extrapolated for each bihourly count. Abbott's (1925) formula was used to correct for control mortality. The statistical design used for each 2-h series was a 3 × 2 factorial, with species and container type as the main effects and termite mortality as the response variable. Mortality percentages were transformed to the arcsine of their square root values and were subjected to analysis of variance. Significant differences were detected by Student-Newman-Kuels test ($\alpha = 0.05$, Steele & Torrie [1980]).

Changes in gas concentration between every 2-h monitoring period were assumed to be linear; thus the accumulated dosage (AD = mg h/liter) for each period was equal to the sum of the gas concentrations observed at the beginning and end of each sampling period: $AD = 2(ck + c'k)/2, = ck + c'k$ where ck = gas concentration at $2k$ h and $c'k$ = concentration at $2k + 2h$. Thus, the AD at time t (ADt) is:

$$ADt = \sum_{k=1}^{t/2} (ck + c'k).$$

Termite mortalities among the three concentrations were compared by plotting the accumulated dosage against corresponding mortalities.

Results and Discussion

Temperature within the fumigation chambers during the test period (1000 hours on 22 August to 0600 hours on 23 August 1985) was 27.2 ± 0.9°C with ca. 90% RH. Seventy-two hours was required after the exposure to sulfuryl fluoride to fully express its lethal effect on the termites. Initial mean mortalities of *C. formosanus* in petri dishes were significantly lower than the other species when elapsed exposure time was 10–14 h at 3 mg/liter and 8 h at 6 mg/liter. However, the 72-h mortalities (Table 1) showed no significant differences among species in the petri dishes. This delayed action suggested that *C. formosanus* had a different physiological response to sulfuryl fluoride than *C. cavifrons* and *I. schwarzi*, but not to the extent of affecting its ultimate survival at these rates. In wooden enclosures, initial mortalities for *C. formosanus* were also significantly lower than the drywood termites for 10–20 h at 3 mg/liter, 8–18 h at 6 mg/liter, and 4–12 h at 12 mg/liter. In contrast to the results with petri dishes, mortality in the wood enclosures was also significantly lower for *C. formosanus* after 8–10 and 14–20 h exposure at 3 mg/liter, 4–10 h at 6 mg/liter, and 4–6 h at 12 mg/liter. The only other significant mortality differences between container types was increased survivorship in wooden containers for *C. cavifrons* after 6 h at 3 mg/liter and 4 h at 6 mg/liter. The walls of the wooden enclosures, therefore, offered little or no barrier to sulfuryl fluoride penetration in the drywood termite replicates.

The water solubility of sulfuryl fluoride is low (750 ppm [wt/wt] at 25°C). We suspect that the addition of 8 ml water to the *C. formosanus* wood enclosures, intended to prevent termite desiccation, also impeded gas penetration. Higher wood moisture content in the *C. formosanus* containers, in conjunction with a possible differential physiological response to sulfuryl fluoride, may have contributed to the increased survivorship of *C. formosanus* under these conditions. Likewise, this may explain the failure to kill incipient can-reared colonies (M. Tamashiro, personal communication) and control field infestations where nests and foraging galleries are naturally enveloped in a moisture laden seal of carton material.

The relationships between termite mortality and corresponding accumulated dosage for the three dosages are presented in Fig. 2. Except for *C. formosanus* held in wooden enclosures, each dosage and condition resulted in closely coinciding mortality curves. This indicated that, for all termites in petri dishes and the two drywood species in wood enclosures, mortality was essentially the function of accumulated dosage: $M = f(t, c)$, where M = mortality, t = time, and c = concentration. Haber's formula (Busvine 1938) which gives the simple hyperbolic relationship $M = tc$, is applicable for these treatments as well as the results of Stewart (1957) for *I. minor*. The slope of the mortality curve for *C. formosanus* held in wooden enclosures exposed to 3 mg/liter of sulfuryl fluoride reached zero at ca. 75%. At this low concentration, the amount of gas diffusing through the moistened wood was insufficient to cause complete mortality. This was described by Busvine (1938) as a deviation at low concentration "due to neutralization or excretion of the poison" by the organism. Our results suggest such a concentration threshold phenomenon in termites. *C. formosanus* mortality, therefore, should be expressed as: $M = f[(c - c\phi), t]$, where $c\phi$ = the greatest tolerated concentration. Flury (1921) gave a similar formula resulting from his hydrogen cyanide fumigation study on insects. Our highest concentration tested, 12 mg/liter, resulted in a *C. formosanus* mortality curve that did not coincide with the 6 mg/liter curve. This prolonged deviation may be the result of a short exposure at high concentration phenomenon noted by Powers (1917) which assumes a time threshold as well. Therefore, we suggest that *C. formosanus* mortality in wood enclosures (akin to its nesting conditions) should be expressed as: $M = f[(c - c\phi), (t - t\phi)]$, where $t\phi$ is the exposure time required to induce lethality.

The AD values for 100% mortality (lethal accumulated dosage 100 [LAD_{100}]) for *C. cavifrons* and *I. schwarzi* in both container types varied from

Table 1. Termite mortality ($\bar{x} \pm$ SE) observed 72 h after exposure to sulfuryl fluoride at three dosages

Exposure (h)	Container[a]	Dosage								
		3 mg/liter			6 mg/liter			12 mg/liter		
		C. formosanus	*C. cavifrons*	*I. schwarzi*	*C. formosanus*	*C. cavifrons*	*I. schwarzi*	*C. formosanus*	*C. cavifrons*	*I. schwarzi*
2	W	0 ± 0aA	0 ± 0aA	5.0 ± 2.9aA	0 ± 0aA	4.6 ± 4.6aA	11.7 ± 11.7aA	0 ± 0aA	6.2 ± 1.4aA	58.3 ± 29.2aA
	P	0.2 ± 0.2aA	1.1 ± 0.8aA	6.7 ± 6.7aA	16.6 ± 14.1aA	4.0 ± 0.7aA	23.3 ± 4.4aA	19.2 ± 18.5aA	2.6 ± 2.0aA	26.7 ± 15.9aA
4	W	0 ± 0aA	1.8 ± 1.8aA	10.0 ± 10.0aA	0 ± 0aA	21.3 ± 6.7bA	88.3 ± 7.3cA	0 ± 0aA	76.7 ± 23.3bA	100 ± 0bA
	P	11.3 ± 9.8aA	1.6 ± 0.9aA	1.7 ± 1.7aA	86.1 ± 6.7aB	66.2 ± 11.8aB	93.3 ± 3.3aA	100 ± 0aB	100 ± 0aA	100 ± 0aA
6	W	0 ± 0aA	1.2 ± 1.2aA	10.0 ± 5.0aA	0 ± 0aA	99.3 ± 0.7bA	100 ± 0bA	24.1 ± 11.3aA	100 ± 0bA	100 ± 0bA
	P	11.5 ± 6.0aA	8.7 ± 2.0aB	43.3 ± 17.6aA	94.6 ± 2.8aB	99.3 ± 0.7aA	100 ± 0aA	100 ± 0aB	100 ± 0aA	100 ± 0aA
8	W	0 ± 0aA	91.1 ± 1.8bA	88.3 ± 9.3bA	45.6 ± 7.8aA	100 ± 0bA	100 ± 0bA	98.0 ± 2.0aA	100 ± 0aA	100 ± 0aA
	P	99.2 ± 0.8aB	98.0 ± 2.0aA	98.3 ± 1.7aA	99.2 ± 0.8aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
10	W	36.9 ± 2.1aA	100 ± 0bA	100 ± 0bA	47.9 ± 10.9aA	100 ± 0bA	100 ± 0bA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	97.7 ± 2.3aB	100 ± 0aA	100 ± 0aA	100 ± 0aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
12	W	70.5 ± 12.8aA	100 ± 0aA	100 ± 0aA	96.5 ± 2.2aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
14	W	72.0 ± 5.3aA	100 ± 0bA	100 ± 0bA	93.6 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	98.5 ± 0.8aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
16	W	77.0 ± 6.2aA	100 ± 0bA	100 ± 0bA	98.7 ± 1.3aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	100 ± 0aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
18	W	75.3 ± 3.9aA	100 ± 0bA	100 ± 0bA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	100 ± 0aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
20	W	74.3 ± 4.1aA	100 ± 0bA	100 ± 0bA	97.9 ± 1.1aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA
	P	100 ± 0aB	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA	100 ± 0aA

Data are means of three replicates. For each exposure time at each dosage, means followed by the same lowercase letter within a row, or means followed by the same uppercase letter within a column, are not significantly different ($\alpha = 0.05$; Student-Newman-Keuls test [Steel & Torrie 1980]).

[a] W, wooden enclosure, sealed; P, petri dish, vented.

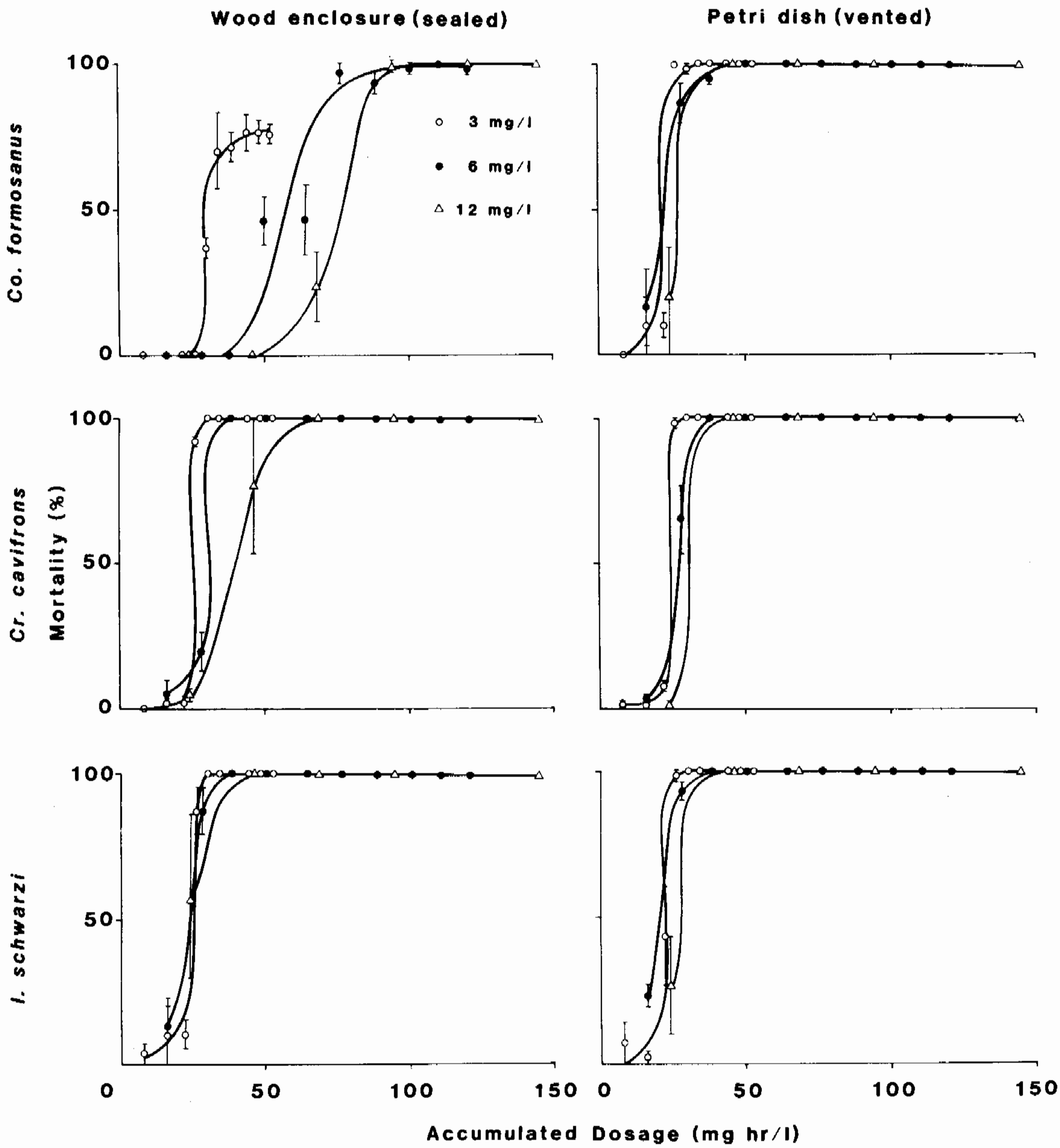

Fig. 2. Accumulated dosage versus percent mortality at 72 h for three termite species exposed to sulfuryl fluoride.

28 to 49 mg/liter (Fig. 2). This range compared favorably with LAD_{100} values calculated from the results of Stewart (1957) of ca. 40 mg h/liter at 30°C for *I. minor* and Bess & Ota (1960) of ≤48 mg h/liter for *C. brevis*. Latent mortalities, ≥3 days, were used as definitive data in both studies. The LAD_{100} values at 72 h for *C. formosanus* in petri dishes were ca. 30, 41, and 46 mg h/liter for 3, 6, and 12 mg/liter, respectively (Fig. 2), which agree with those of *C. cavifrons* and *I. schwarzi*. Immediate postexposure LAD_{100} values for *C. formosanus* in petri dishes, however, were 64–77 mg h/liter at 6 mg/liter and 70–93 mg h/liter at 12 mg/liter. At 3 mg/liter complete initial mortality was not attained with 51 mg h/liter of accumulation after 20 h. La Fage et al. (1983) considered only immediate mortality following 24-h exposures of sulfuryl fluoride to *C. formosanus* at 30°C and derived LAD_{100} values between 71 and 117 mg h/liter. Had 72-h counts been taken by La Fage et al. (1983), their values probably would have been lower. For *C. formosanus* in wood enclosures, our 72-h LAD_{100} values were ca. 95 mg h/liter for 6 and 12 mg/liter exposures; at the 3

mg/liter rate, an LAD_{100} was not attained. When the higher moisture content present in the *C. formosanus* wood enclosures is considered, the LAD_{100} values appear to be 2- to 3-fold greater than those of the drywood termites.

Our results suggest that, in field fumigations of *C. formosanus* where sulfuryl fluoride must penetrate moistened barriers or when exposure time must be greatly abbreviated, concentration and time thresholds should be incorporated into the *AD* calculation. Additional research is being conducted to determine the linear coordinates of $M = f[(c - c\phi), (t - t\phi)]$ under a variety of moisture, temperature, exposure time, and nesting conditions to establish corresponding LAD_{100} values for *C. formosanus*.

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