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INTRODUCTION

The West Indian drywood termite, *Cryptotermes brevis* (Walker), is a major pest of buildings, furniture, and other fiber products in many tropical and subtropical countries. In Hawaii many thousands of dollars are spent annually combating this pest.

Where the infestations are light and limited to a few local spots in furniture or buildings, treating these spots with a liquid insecticide or dust may be effective and feasible even though such treatment usually falls short of actually eliminating all infestations present. On the other hand, where infestations are extensive, it is likely to be more effective and practical to fumigate the infested furniture or buildings with a suitable gas such as sulfuryl fluoride. The biological, chemical, and physical properties of this fumigant have been investigated and compared with those of methyl bromide by Kenaga (1957) and Stewart (1957). For a number of reasons, sulfuryl fluoride is the fumigant commonly used in the control of drywood termites (Dow Chem. Co., 1969).

Termite-infested furniture is often fumigated in specially constructed fumigation chambers where there is relatively little gas leakage or change in temperature during the exposure period. Therefore, in these chambers, it is possible to use standardized dosages of fumigants with a high degree of confidence of success.

In contrast, where infested buildings are involved, the dosage needed is variable because the buildings are enclosed with tarpaulins or other coverings and many highly variable factors affect the rate of gas loss. The rate of loss and the dosage needed cannot be predicted with confidence prior to the introduction of the fumigant into a building. However, they may be estimated on the basis of several criteria (Dow Chem. Co., 1969; Stewart, 1962). Then gas concentration can be determined during the first few hours following the introduction of the fumigant, the actual rate of loss for that period can be calculated, and the needed dosage for the remainder of the fumigation period can be estimated more precisely. If needed, additional gas can be introduced. More recently a somewhat different approach to the art of fumigating buildings—referred to as "balanced fumigation"—has been suggested; the concepts on which it is based are the same as those presented earlier by Stewart (1962).

The studies reported here are actually a continuation of the investigations begun in 1957 when sulfuryl fluoride was first made available to the University of Hawaii Entomology Department for investigation. However, the gas was promptly withdrawn in the summer of 1957 and was unavailable for further testing until the summer of 1961. During the period from 1957 to 1960, investigations were continued using methyl bromide and ethylene dibromide (Bess and Ota, 1960).

The primary purpose of research since 1961 has been to determine the amount of sulfuryl fluoride in terms of ounce-hour-exposure required to kill *C. brevis* in infested buildings under conditions commonly encountered in Hawaii and to improve or develop recommendations for fumigation procedures which would increase the chances of reliable, effective control at minimal expense.

METHODS

The methods and procedures used in these investigations were essentially the same as those used and described by Bess and Ota (1960). A brief résumé of the major aspects of the methods and procedures used may be apropos.

Active, healthy, large nymphs of *C. brevis* and workers of *Coptotermes formosanus* Shiraki (Plates I, II) were used to obtain the termite exposure data. During exposure to the gas in the test, the termites were confined in petri dishes with a piece of filter paper on the inside bottom, plus some small pieces of wood as food. Or the termites were held in microscope slide cages made by cutting out a 1½ X ½-inch section of a piece of tongue depressor blade to form a cell, placing the blade with the cavity or cell between two microscope slides, and taping the ends together with a narrow strip of masking tape. Twenty-five termites were placed in a petri dish, but only 10 to 12 were placed in each microscope slide cage. The microscope slide cages containing the termites were exposed to the tests in a number of ways: in the open, inside 3½X3½X6-inch wooden blocks, inside ¼-inch plywood boxes, and inside wooden blocks encased with ¼-inch plywood (Plate III, page 9).

The blocks from which the cages were made were sawn from pieces of fir which were carefully selected for uniformity of grain and were free of knots. A hole slightly larger than 1 inch in diameter was bored into the center of each block from one end to a depth of 4½ inches, leaving a 1½-inch distance from the bottom of the hole to the other end of the block. The end of the block with the hole was covered with a piece of glass, and the edges

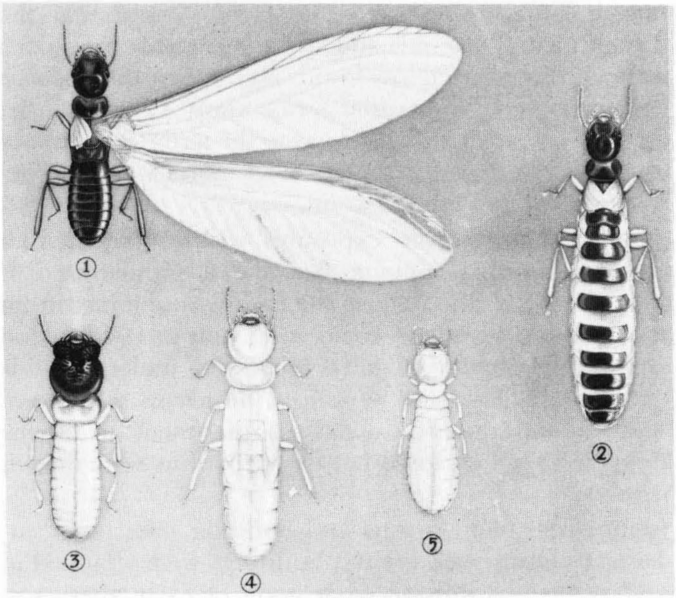

PLATE I *Cryptotermes brevis* (Walker)
1. Winged adult
2. Gravid queen
3. Soldier
4. Full-grown nymph
5. Young nymph

(Courtesy of Department of Entomology, State Department of Agriculture, and University of Hawaii Press.)

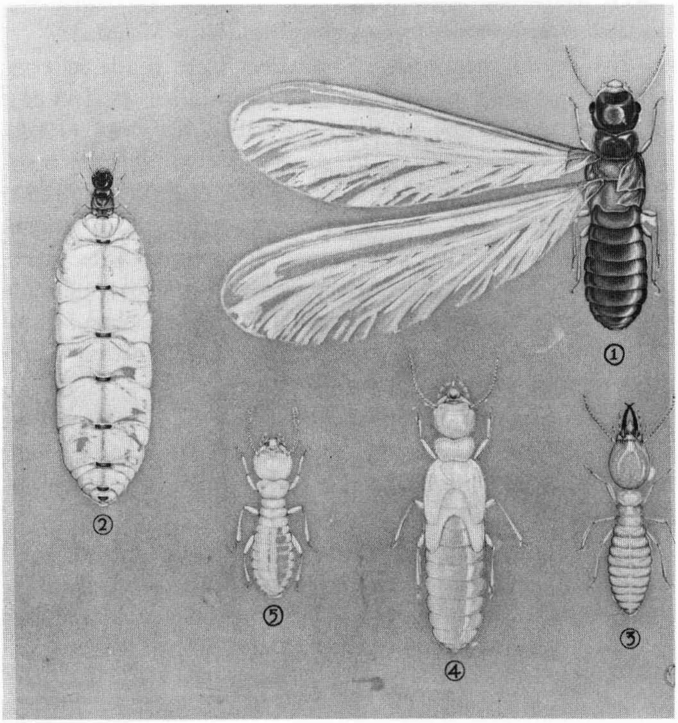

PLATE II *Coptotermes formosanus* Shiraki
1. Winged adult
2. Gravid queen
3. Soldier
4. Nymph of sexual form with developing wings
5. Worker

(Courtesy of Department of Entomology, State Department of Agriculture, and University of Hawaii Press.)

were sealed with melted paraffin. Bess and Ota (1960) found that the major penetration of both methyl bromide and sulfuryl fluoride into block cages was with the grain rather than across grain, even when the distance with the grain was approximately 3 times that across grain. Consequently, in the present investigations, the major access of gas to the termites in microscope slide cages within the chamber within the block cages was by penetration through 1½ inches of wood with the grain.

Some of the data were obtained from exposures within 10-cubic-foot fumigation chambers at controlled temperatures and a standardized 3-hour fumigation period. However, the bulk of the data was obtained from investigations within buildings which were enclosed or wrapped with nylon and/or polyethylene tarpaulins and fumigated overnight under variable temperatures and leakage rates. In a few instances, buildings were compartmentalized and gas was introduced into each compartment; in others, the roofs of the buildings were not enclosed but the tarpaulins were draped from the eaves of the roofs.

Routinely, both fumigation-chamber tests and building tests were arranged on a weekly basis. In most cases, the test buildings were wrapped in the forenoon on Monday, gas was introduced at noon or early afternoon, and the tarpaulins were removed soon after 8:00 o'clock the following morning. The fumigation-chamber exposures were made on Mondays.

The tests in the 10-cubic-foot fumigation chambers were made at controlled temperatures of 70 F and 80 F and a standard fumigation period of 3 hours. Dosages were measured by the method described by Doty (1961). Gas-concentration readings were taken with a thermoconductivity unit 5 to 10 minutes after introducing the gas and again at the end of the 3-hour fumigation period. Several series of *C. brevis* were exposed in open microscope slide cages and others were sealed within wooden block cages. Also, a number of series of *C. formosanus* were exposed in open microscope slide cages and in petri dishes. After treatment, the test termites, *C. brevis* and *C. formosanus,* were kept in the laboratory up to 5 days, examined daily, and their condition recorded as active, moribund, or dead.

The wrapping or preparation of the buildings for fumigation involved many details. To attain the primary objective of retaining the fumigant as well as was practical, in most cases the top and sides of the buildings were enclosed with nylon tarpaulins.

Immediately before introducing the gas into the test buildings, the following items were placed in each building: one or more gas introduction tubes, one or two electric fans which could be turned on and off from switches outside the buildings, four or more gas-sampling tubes, one or two hygrothermographs, two or more maximum-minimum thermometers, an extension cord to supply electric current to operate a thermoconductivity unit

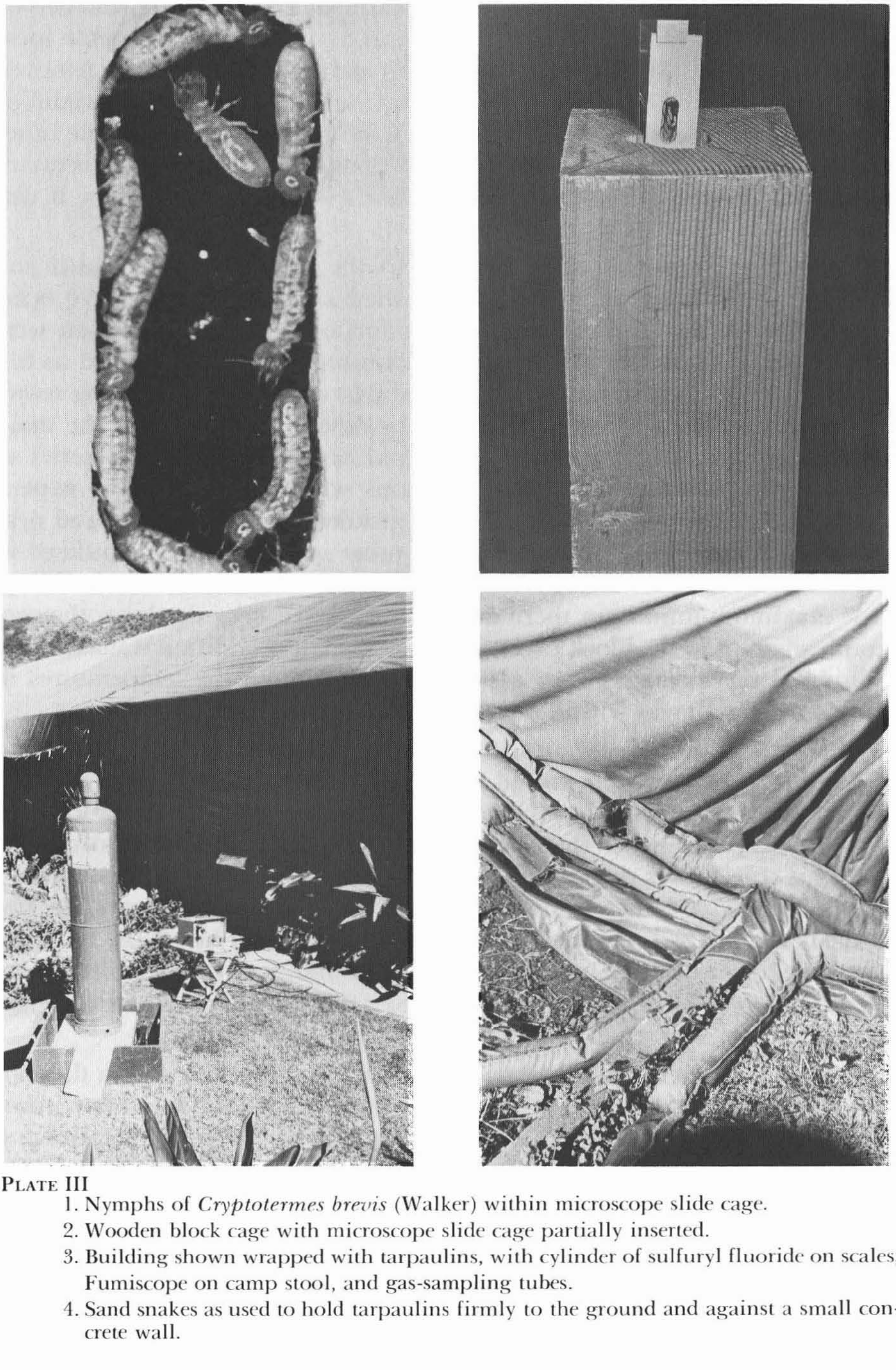

PLATE III

1. Nymphs of *Cryptotermes brevis* (Walker) within microscope slide cage.
2. Wooden block cage with microscope slide cage partially inserted.
3. Building shown wrapped with tarpaulins, with cylinder of sulfuryl fluoride on scales, Fumiscope on camp stool, and gas-sampling tubes.
4. Sand snakes as used to hold tarpaulins firmly to the ground and against a small concrete wall.

(Fumiscope) placed at a convenient location outside the building, and two or more series of block cages containing living termites at an accessible location near a seam. By removing tarpaulin clamps, cages could be removed or added as desired during the fumigation period. Outside the buildings, a reserve tank of gas and platform scales were left overnight near the outer ends of the gas-introduction tubes. If additional gas was deemed necessary to kill the termites in the natural infestations within the buildings, it was introduced.

Two tubes were usually used to introduce the gas; one led to the attic and the other to the basement or underneath the building. The fans were operated for one to two hours following introduction of the gas and then were turned off. A minimum of four plastic sampling tubes were placed as follows: one led to the attic, one to the central part of the house or living room, one to the under area or basement, and the other to a point near the main block cage station near a seam. Additional sampling tubes and series of block cages were placed at other locations within several of the experimental buildings. Usually one of the hygrothermographs was placed near the main test block cage station and the other one either in the attic or in the basement or other area thought to be the coolest area in the building. One maximum-minimum thermometer was placed near the hygrothermograph adjacent to the block cages. In a few instances additional maximum-minimum thermometers were also used to determine the temperatures in several different areas within certain buildings.

After the building was wrapped, the fumigator decided what ounce-hour-exposure (OHE) probably would be needed to kill the termites, based on the prevailing temperature and to some extent the unique conditions involved, such as whether there was infested plywood. The estimated half-loss-time (HLT) was then calculated with the aid of the criteria suggested by Stewart (1962). Next, on the basis of the OHE deemed necessary, the size of the buildings, the estimated HLT, and the number of hours the building was to be fumigated; the fumigator used a Fumiguide calculator to estimate the dosage needed to produce the desired OHE. He then introduced the gas.

In most buildings, gas-concentration readings were taken with a thermo-conductivity unit at hourly intervals for the first 5 to 8 hours after introducing the gas. Final readings were taken around 8:00 o'clock the following morning, immediately before opening the tarpaulins to ventilate the building at the end of the fumigation period, which was usually 16 to 21 hours in length. From these readings and the gas dosage applied to a building, it was possible to compute both the leakage rate in terms of HLT and the amount of gas exposure in terms of OHE for the entire fumigation period, and also for different segments of the period.

In a number of instances, the leakage rate during the first few hours was appreciably higher than estimated and additional gas was introduced. The amount needed was computed as described above, but there was now a more reliable estimate of the probable HLT to be expected during the remaining part of the fumigation period and the dosage required to obtain the desired OHE.

During fumigation of each test building, three or more series of block cages were used. Each series contained 3 block cages, with 2 microscope slide cages in each, giving a total of 20 to 24 living termites in each block cage, or 60 to 72 per series. One series was in the building throughout the fumigation period. Another series was in the building from the beginning (usually a Monday) until around 8:00 p.m. A third series was inserted when the second was removed; it remained until the building was unwrapped the following morning (usually a Tuesday) around 8:00 o'clock. Two or more additional series were often included. These provided data on specific aspects suspected of affecting mortality, such as out-of-the-way nooks or locations within the buildings and the time of opening the block cages after removal from the buildings.

The usual procedure was to open the block cages in the laboratory on a Tuesday morning around 9:00, remove the microscope slide cages, and examine the termites under a binocular dissecting scope to ascertain the number active, moribund, and dead. Termites classed as moribund were those unable to stand or crawl freely, but with some visible movement of segments of the legs and/or mouthparts. The termites were examined again between 3:00 and 5:00 that afternoon (Tuesday) and daily thereafter for 5 days, or until all individuals were dead. For each building fumigated, one or more series of unfumigated block cages containing termites were retained as checks.

To supplement the data obtained during and immediately following fumigation, several of the test buildings were inspected periodically for 2 years or more following fumigation. In addition, the Fumiseal Company made its files available for study of its records, including complaints and gas readings, on several hundred buildings which had been fumigated with sulfuryl fluoride or methyl bromide over the past several years.

DATA AND RESULTS

1. Fumigation Chamber Experiments

Exposures of *C. brevis* to different dosages of sulfuryl fluoride within the 10-cubic-foot fumigation chambers at controlled temperatures and a standard 3-hour fumigation period yielded data showing that at similar dosages mortality was greater at 80 F than at 70 F and was greater in unsealed micro-

TABLE 1. Mortality of *C. brevis* exposed to sulfuryl fluoride for 3 hours in temperature-controlled fumigation chambers

Dosage (ounces per 1000 cubic feet)	Exposed in microscope slide cages			Exposed in sealed block cages		
	No. of termites in tests	No. of termites dead after 5 days	Mortality (percent)	No. of termites in tests	No. of termites dead after 5 days	Mortality (percent)
			Exposure data at 80 F			
7.5	247	7	3	20	1	5
9.0	348	79	23	49	11	22
10.5	248	191	77	80	16	20
11.5	100	89	89	30	6	20
12.0	247	238	96	80	37	46
14.0	98	97	99	30	18	60
			Exposure data at 70 F			
8.0–10.0	198	4	2			
11.5–12.0	198	37	19			
13.0–13.5	199	102	51			
15.5–16.0	299	178	60			
17.5–19.0	200	197	98			
0 (controls)	348	5	1	206	5	2

scope slide cages than in sealed block cages (Table 1). In the unsealed microscope slide cages at 80 F, gas at the approximate rate of 10 ounces per 1000 cubic feet was required to produce a mortality of 50 percent (LD_{50}), while at 70 F approximately 13 ounces per 1000 cubic feet was required. To kill all termites exposed in unsealed slide cages at 80 F, a dosage of 15 ounces was required and at 70 F a dosage of 19 ounces was needed. Termites confined in sealed block cages at 80 F required approximately 13 ounces to produce a mortality of 50 percent in contrast to 10 ounces in the unsealed microscope slide cages.

Data from similar tests with *C. formosanus* confined in unsealed microscope slide cages at 80 F indicate that this species was as susceptible as *C. brevis* to sulfuryl fluoride (Table 2).

2. Fumigation Tests in Buildings

The fumigation tests in the buildings were entirely different from the tests in the fumigation chambers: instead of uniform temperatures, dosages, and exposure periods in gas-tight chambers similar in size, there were a multiplicity of variables involved with the buildings. Each building was different and each received a somewhat different treatment. Data were ob-

TABLE 2. Comparative mortality of *Cryptotermes brevis* and *Coptotermes formosanus* exposed to sulfuryl fluoride for 3 hours at 80 F

Elapsed time after removal from fumigation chambers (hours)	Termite species	Dosage (ounces per 1000 cubic feet)			
		7.5	9.0	10.5	12.0
		Mortality (mean percent dead)			
6	*C. brevis*	0	1.0	2.0	11.1
	C. form.	0	0	0	2.0
24	*C. brevis*	2.0	9.1	37.8	81.8
	C. form.	0	4.0	18.0	42.0
48	*C. brevis*	2.0	17.1	49.0	83.8
	C. form.	0	20.0	54.0	80.0
72	*C. brevis*	3.1	21.2	57.1	85.9
	C. form.	16.0	50.0	76.0	92.0
96	*C. brevis*	6.1	27.3	66.3	93.9
	C. form.	64.0	80.0	86.0	94.0

tained on the temperature during the fumigation period, and on the gas concentration at hourly intervals for the first several hours and at the end of the fumigation period. From these data and the mortality data, useful dosage-mortality relationships were established.

Temperatures within experimental buildings. In spite of the equitable climate in Hawaii, there were appreciable differences in the temperature among the experimental buildings fumigated. Differences were associated with type of construction, size of building, and night hours versus daylight hours. There were also differences between sunny dry days versus cloudy rainy days, as well as different seasons. Furthermore, within a wrapped building temperature differences of more than 10 degrees were found between the temperature in the attic and that in the basement, and these temperatures also differed from the air temperatures outside (Figure 1). Continuous-recording thermograph data obtained within many buildings, plus maximum-minimum temperature records from various locations within several of the

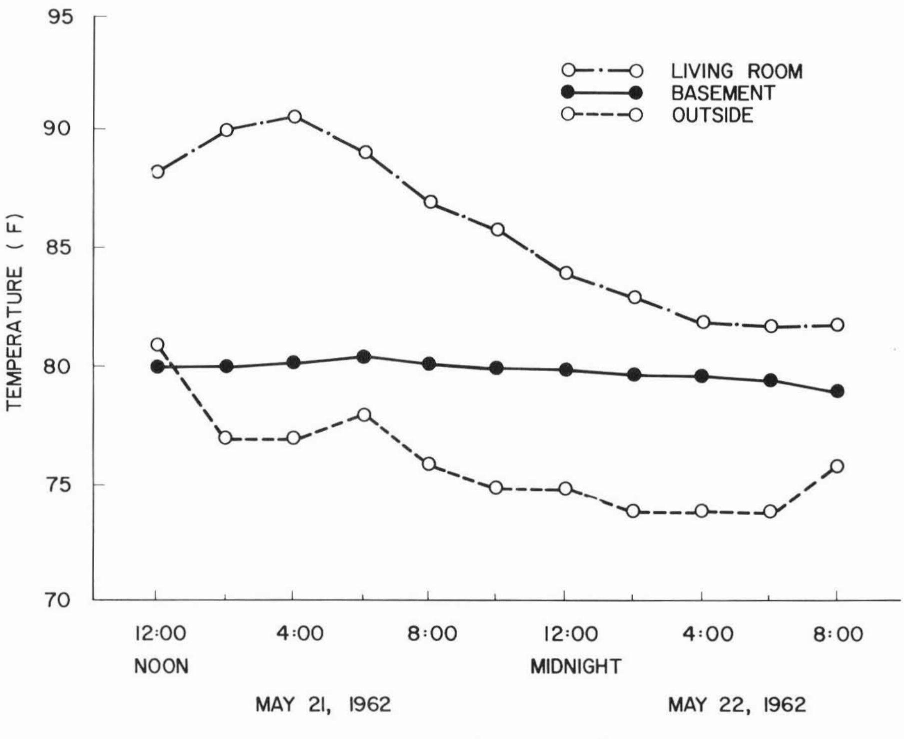

FIG. 1. Temperature within the living room and basement of an experimental building during fumigation shown with the outside air temperature during the same period.[1]

[1] Outside temperature from official U.S. Weather Bureau readings.

buildings, indicate that in the Honolulu area a mean air temperature of possibly 80 to 85 F might be expected in the cooler areas of buildings fumigated during the summer months and a mean of perhaps 70 to 75 F in those fumigated during the winter months. However, the actual temperatures within the block cages and termite-infested timbers were not determined.

Length of fumigation period. Although the experimental buildings were usually fumigated for a period of 16 to 21 hours, many series of test termites were exposed for shorter periods in order to obtain mortalities throughout the range from 0 to 100 percent. The length of these shorter exposures was determined to some extent by the predicted gas concentration during the exposure; it varied from a minimum of 3 hours during the first portion of the fumigation period—when the gas concentration and temperature were usually highest—to a maximum of 15 hours during the later portion of the fumigation, which was usually at night when both the gas concentration and temperature were lower.

Gas concentration within the test buildings. The initial gas dosage introduced into the test buildings varied from a low of 5 ounces per 1000 cubic feet to 16 ounces per 1000 cubic feet. In all the buildings the gas concentration, as determined from Fumiscope readings, decreased at a relatively

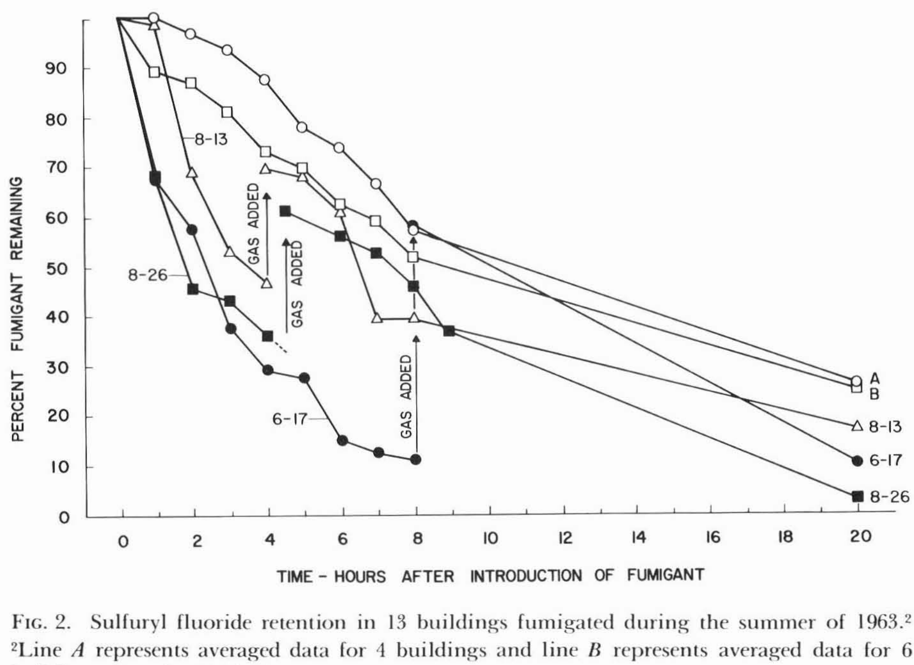

FIG. 2. Sulfuryl fluoride retention in 13 buildings fumigated during the summer of 1963.[2]

[2]Line *A* represents averaged data for 4 buildings and line *B* represents averaged data for 6 buildings. *See also* Table 3.

rapid rate; in approximately one-fourth of the buildings, the rate of decrease exceeded by at least 25 to 50 percent the anticipated rate. This necessitated the introduction of additional fumigant to obtain the ounce-hour-exposure, OHE, deemed necessary. The marked decrease in the concentration of the fumigant within buildings is illustrated by the gas determinations from 13 buildings fumigated during the summer of 1963 (Figure 2). In each of these buildings, the fumigant was introduced between 11:00 a.m. and 2:30 p.m. Gas readings were made at hourly intervals for the first 8 hours and final readings were made the next morning between 8:00 and 9:00 o'clock, immediately prior to unwrapping and ventilating the buildings.

Rate of gas loss within the test buildings. Stewart (1962) expressed the rate of gas loss in terms of half-loss-time, HLT, and used it with the aid of the Fumiguide to compute dosages and fumigant exposures, referred to as ounce-hour-exposure, OHE,* expected or received from a specific treatment. On the basis of the gas-concentration measurements and the length of time between them, the HLT's can be determined by computation or by referring to a chart on the Fumiguide which is similar to Figure 3.

*Stewart called this OH.

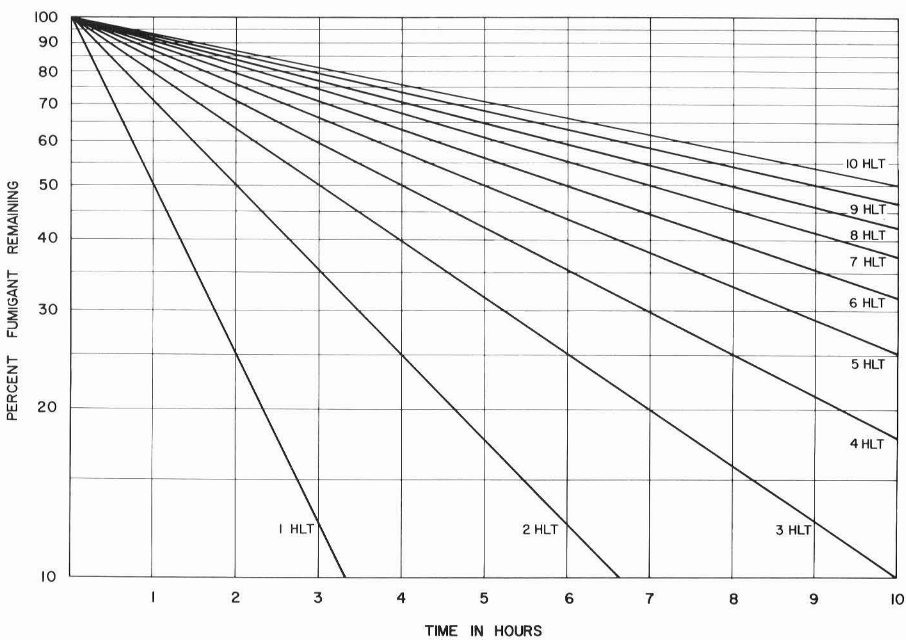

FIG. 3. Chart showing interrelationships among remaining fumigant, elapsed time, and gas-loss rate.

TABLE 3. Rates of gas loss for 13 test buildings fumigated during the summer of 1963

Building No.	Rate of gas loss (HLT)[1]			
	0–4th hour[2] A	1st–4th hour B	4th–8th hour C	8th–21st hour D
8– 5–3	64	50	6.2	8.4
9–23–3	22	16.5	7.8	9.4
9–30–3	16.5	12.4	10.4	7.4
9– 3–3	15.8	11.8	8.6	9.4
7– 1–3	10.8	9.2	10.5	6.4
6–24–3	9.2	48	6.8	14.0
9–10–3	9.2	8.2	10.2	9.6
9–16–3	8.6	15.5	11.9	9.0
8–20–3	8.4	6.5	3.6	40
7– 8–3	8.2	10.2	14.0	14.1
8–13–3	3.6	3.0	3.8	9.9
8–26–3	2.7	3.4	6.6	3.0
6–17–3	2.5	2.5	2.8	5.1

[1] HLT, or half-loss-time, is an expression of gas-loss rate used with the Fumiguide in the calculation of ounce-hour-exposure.

[2] Each building received an initial dosage between 11:00 a.m. and 2:30 p.m. This dosage was used as the gas concentration at 0 hour. Gas readings were obtained hourly for the first 8 hours and at the end of the fumigation just before removing the tarpaulins.

The HLT's varied among the test buildings. This could be expected due to the many variable factors: the condition of tarpaulins or cover, seal of tarpaulins with the ground or base, porosity of underseal material (sand, clay, concrete slab, etc.), volume of building, and wind velocity—all influenced the HLT. For 13 buildings fumigated in the summer of 1963, HLT's are given in some detail in Table 3 to illustrate both the variabilities and similarities among buildings and parts of the fumigation period within the individual buildings. HLT's for the first 4 to 5 hours for an additional 55 buildings fumigated during the summer of 1962 may be summarized as follows:

3 buildings with HLT's of 1.5 to 2.2
14 buildings with HLT's of 3.3 to 4
14 buildings with HLT's of 5 to 7
16 buildings with HLT's of 8 to 12
8 buildings with HLT's of 13 to 18.

In 12 of these buildings, the HLT during the night was essentially the same as for the first 4- to 5-hour period after the fumigant was introduced; in 40 of them the HLT increased during the night and in 3 it decreased.

In addition to the usual procedure of enclosing buildings with tarpaulins, some innovations were investigated. One of these was to wrap the building only from the eaves down and to rely on the roofs with the underlying tar paper to retain the gas above the tarpaulins. Another, tried with reinforced concrete buildings, was to seal only the windows and doors with tarpaulins or polyethylene sheeting. In most cases, fair HLT's were obtained by the first method and good to excellent HLT's by the second. A third innovation, used on several occasions, was to compartmentalize the building into separate units and fumigate each as if it were a separate building. Often the major area under a building was on a concrete slab but with the remainder of the underseal sand, coral fill, or some other material of high porosity. Consequently, compartmentalization of such buildings often made it possible to have a good HLT for the major portion of a building even though the HLT was poor for the remaining portion. In one case, a building in excess of 100,000 cubic feet in volume was compartmentalized into five units. The HLT was extremely low in one unit and a total dosage of 46 ounces per 1000 cubic feet was used in it. In another unit, the HLT was 18 and the 8-ounce dosage used produced an OHE in excess of 100. All test termites exposed in block cages in each of the five units were killed, but it is evident from the above information that more than 5 times the dosage of fumigant was required in the unit with the poorest HLT and that more gas was used than needed in the unit with the lower dosage.

TABLE 4. Gas exposure-mortality relationships within fumigated buildings[1]

Exposure (OHE)[2]	No. of termites in tests	Mortality (percent)
0	1,441	3.3
9	127	8.7
11-20	878	23.0
21-30	1,121	61.8
31-40	1,662	94.0
41-50	1,116	98.8
51-60	421	99.8
61-150	2,162	100

[1] The mean temperatures for the exposure periods were probably between 75 and 90 F in all cases. However, continuous-recording thermograph data were available for only 60 percent of these exposures.

[2] OHE, or ounce-hour-exposure, is an expression of the intensity of exposure to the fumigant over a period of time, and was determined with the aid of the Fumiguide.

TABLE 5. Gas exposure-mortality relationships within buildings at different temperatures

	Exposures at 76–80 F[1]		Exposures at 81–85 F[1]		Exposures at 86–90 F[1]	
Exposure (OHE)[2]	No. of termites in tests	Mortality (percent)	No. of termites in tests	Mortality (percent)	No. of termites in tests	Mortality (percent)
11–20	447	7.6	164	26.2	209	35.0
21–30	286	40.4	277	46.3	278	92.9
31–40	326	83.2	355	96.8	529	84.9
41–50	224	99.6	168	100	140	100
51–100	198	100	645	100	216	100

[1] Mean air temperature near block cages during exposure period.

[2] OHE, or ounce-hour-exposure, is an expression of the intensity of exposure to the fumigant over a period of time, and was determined with the aid of the Fumiguide.

Ounce-hour-exposure (OHE)-mortality relationships. Recommendations for the use of sulfuryl fluoride for the control of drywood termites in buildings have been developed on the basis of OHE requirements rather than dosage *per se* as in the case of fumigation chamber fumigation. Consequently, a primary concern or goal in these investigations was to obtain OHE and mortality data for the exposure periods of the test termites within wooden block cages placed inside the experimental buildings, so that OHE-mortality relationships could be established. Since the buildings were fumigated on a commercial basis and received an OHE of 60 or more, and since 60 OHE was sufficient to kill essentially all termites within the wooden block cages, as well as those in most of the naturally occuring infestations within the buildings, our principal interest was in the OHE and mortality data for the various series of termites exposed for only a portion of the fumigation period.

The exposures produced a wide range of mortalities. The mortalities were directly correlated with OHE's (Table 4). However, temperature had an appreciable influence on the effectiveness of the fumigant and at specific OHE's the mortalities increased with temperature (Table 5).

As would be expected, the time required for termites to die after receiving a lethal exposure was inversely related to the OHE they received. For example, at OHE's of 30 to 40, the majority of the termites were moribund, unable to walk, but showed some movement of appendages at the time the block cages were opened to remove them. At OHE's of 80 and above, there were few or no individuals that showed movement. On the other hand, at lower exposures, many of the individuals were active at the time of removal from the block cages and the majority of them survived the usual 5-day holding period (Figure 4). There was relatively little additional mortality among active termites retained for 3 to 4 weeks.

On the basis of the above data, it was possible to ascertain the approximate OHE that would be effective with mean temperatures of 75 to 90 F. Through the use of the Fumiguide, it is possible to calculate the amount of fumigant needed with different HLT's and periods of time to obtain the OHE sought. Furthermore, by the use of a graph such as that shown in Figure 3, it is possible to determine the concentration of fumigant that will be present during different intervals of time if the desired OHE is to be reached within the specified fumigation period. It is also possible to determine the HLT from the graph. The fumigator may be somewhat surprised to find that when the proper dosages are used, that by the end of the 4th or 5th hour after introduction the concentration of the fumigant will be relatively the same, even though the HLT's and dosages were widely different (Table 6). The fumigant-concentration figures in the last four columns may be viewed as minimal concentrations required to accomplish a goal of 70 OHE in 16 hours. Consequently, if at the end of 3, 4, or 5 hours the concentration is less than that shown, immediate steps should be

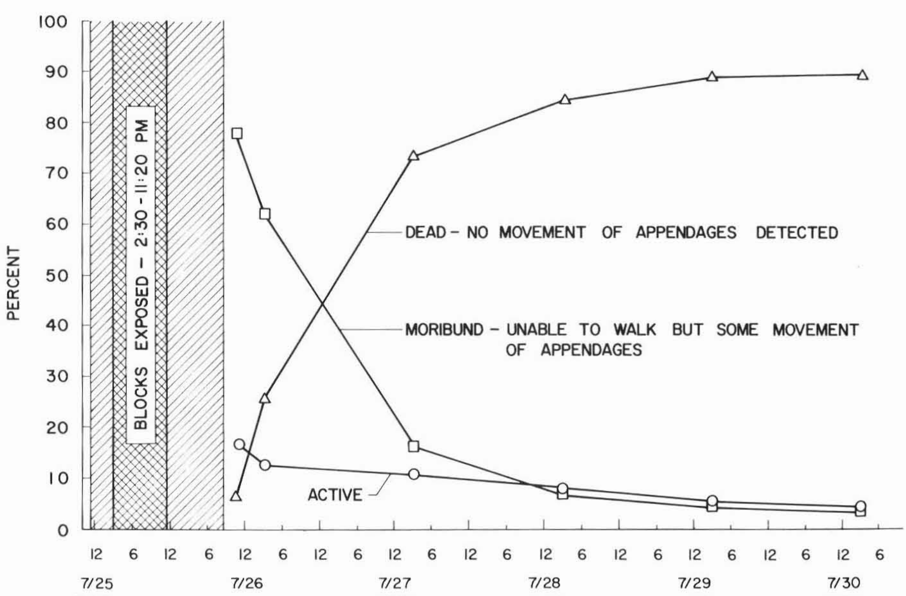

FIG. 4. Condition of termites following exposure to sulfuryl fluoride.[3]

[3]The wooden block cages were held for 12 hours after removal from the building before they were opened and the termites removed. The temperature varied from a high of 90 F to a low of 80 F; the ounce-hour-exposure, OHE, totalled approximately 30.

Table 6. Expected concentrations after 3, 4, 5, and 16 hours where an ounce-hour-exposure of 70 is to be reached within a 16-hour period

	Concentration of gas (ounces per 1000 cubic feet)				
Gas-loss rate (HLT)[1]	Required initial dosage	Reading after 3 hours	Reading after 4 hours	Reading after 5 hours	Reading after 16 hours
2	24.0	8.6	6.0	4.3	—
3	16.0	8.0	6.3	5.1	0.4
4	13.0	7.7	6.5	5.5	0.9
5	11.0	7.3	6.3	5.5	1.2
6	9.8	7.0	6.1	5.5	1.5
7	9.0	6.7	6.1	5.5	1.8
8	8.2	6.3	5.8	5.3	2.0
9	7.5	6.0	5.5	5.1	2.2
10	7.1	5.8	5.4	5.0	2.3
12	6.8	5.7	5.4	5.1	2.7
16	6.1	5.4	5.1	4.9	3.1

[1] HLT, or half-loss-time, is an expression of gas-loss rate used with the Fumiguide in the calculation of ounce-hour-exposure.

taken to cope with the problem. Additional fumigant may be introduced. Some other efforts may be made, such as extending the fumigation period or reducing the leakage rate of the fumigant by adding more sand snakes, loose sand, or water to make a better seal between the tarpaulins and the ground.

In addition to temperature, a number of other factors or conditions were suspected or found to affect the OHE-mortality relationships. Among these were location of the block cages or infestations within the buildings, moisture content of the wood, kind and size of plywood panels or other timbers, varnished or unvarnished surface finish, and length of time between removal of the block cages. Special investigations were made on some of these aspects, and observations and deductions were drawn about others where pertinent information became available.

Early in the investigations a few of the block cages proved to be conspicuously "soft" and others "hard" as evidenced by the mortalities obtained when they were included in tests with other blocks. This was corrected by carefully selecting for uniformity in the grain of the 3¾ × 3¾-inch timbers from which the cages were constructed, exposing test termites within several cages at the same time, and eliminating any unusually soft or hard blocks.

In one series where 23 block cages containing termites received the same treatment (an OHE of 30 at a mean temperature of 86 F) the mean mortality, inactive plus moribund, at the time the cages were opened was 85 + 10 percent, with a range of 71 to 96 percent among the individual cages. Therefore, good reproducibility of results with the block-cage exposures was possible, as evidenced by the data presented in Tables 4 and 5. However, there would probably be wide variations in the OHE-mortality relationships based on natural infestations within buildings, should dosages be sufficiently low to give a wide range of mortalities.

Bess and Ota (1960) found that both sulfuryl fluoride and methyl bromide penetrated the wooden block cages more readily with the grain than across grain and in several instances survival within fumigated furniture and buildings was associated with plywood. Special tests were made to investigate the resistance of plywood to penetration of the fumigant. Some of the regular block cages were encased with ¼-inch plywood and the joints sealed with paraffin. The results were in the direction predicted, as can be seen from the following data:

	Percent mortality of termites exposed in block cages	
Intensity of exposure (OHE)*	**Regular exposure technique**	**Plywood case technique**
48–55	36.7	10.0
64–70	99.6	75.8
76–93	100	95.5

*Ounce-hour-exposure.

At OHE's of 64 to 93, only 1 out of 16 of the regular block cages had survivors, while 7 out of 16 of those encased in plywood had survivors. Included in the tests were also block cages encased in plywood to which two coats of varnish were applied. There were survivors in 11 of the 12 varnished cages and there was no mortality in 8 of the cages.

Survival of termites within relatively wet wood was observed on a few occasions, but was not specifically investigated quantitatively. In two of the test buildings, a few of the block cages inadvertently became partially wet; very low mortality occurred among the termites in these cages. Furthermore, in a few cases where nontest buildings were involved, there were some survivors in natural infestations within wet wood and refumigation was necessary.

At relatively low OHE exposures, mortality was considerably less among termites exposed outside block cages than among those exposed within block cages and mortality was less when the cages were opened and the termites removed immediately after exposure than when the cages were left sealed for several hours (Figure 5). It would be logical to expect both

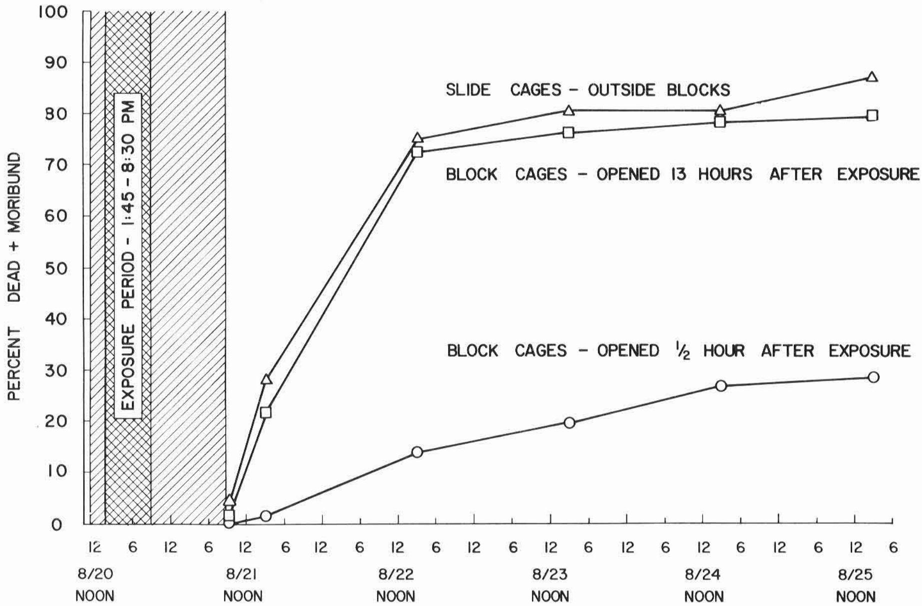

Fig. 5. Comparative mortality of termites exposed in open slide cages and in wooden block cages.[4]

[4]The temperature varied from a high of 89 F to a low of 85.5 F; the ounce-hour-exposure, OHE, totalled approximately 20. Some block cages were opened and the termites removed ½ hour after exposure and others 13 hours after exposure.

these results. The wooden walls were a hinderance to the fumigant in penetrating the block cages, so that the termites within the block cages received a lower OHE than those outside, especially when the exposure period was relatively short and the cages were opened immediately after exposure. Perhaps after the fumigant had penetrated into the block cages, the wooden walls hindered its escape, thus prolonging to some extent the exposure of the termites within the sealed block cages.

DISCUSSION

Structural fumigation with sulfuryl fluoride to control drywood termites is effective and practical. However, in determining the quantity of sulfuryl fluoride needed to eliminate *C. brevis* effectively from various kinds of buildings, under variable site and weather conditions found in Hawaii, many factors were found to affect the efficiency of the fumigation operations. These variables make it virtually impossible to establish standardized fumigation dosages in the same manner as is commonly done for insecticidal dusts and sprays used in the control of agricultural pests. Instead, the quantity or dosage of gas needed to be effective was found to depend to a large extent on three factors: (i) the temperature within the building, particularly where the termites were located; (ii) the gas concentration, which was influenced both by dosage and the gas-leakage rate; and (iii) the length of the fumigation period. Adequate data on these three factors made it possible to measure the intensity of the fumigation in terms of ounce-hour-exposure (OHE). Through many tests the OHE-mortality relationships were established, so that fumigation recommendations could be developed on the basis of OHE requirements rather than dosages *per se*. However, during these investigations many variable and complex factors were found either to adversely affect or to facilitate the attainment of a specific OHE, and also to reduce or increase OHE recommendations. Many of these factors were related to gas-leakage rate but others are worthy of mention.

The temperature-mortality data presented in an earlier section clearly show that mortality increased with temperature. Also, the temperature may be several degrees higher in the attic, or a room exposed to the sun, than in the basement. This means that less fumigant or a lower OHE may be needed in the attic than in the basement, but the critical consideration is to insure that an effective exposure, OHE, be obtained in all parts of a building, including the coolest or least vulnerable part. As a result of these findings, some fumigators adopted the general policy of using at least two shooting tubes and introducing about two-thirds of the dosage in the lower cooler part of the building and the remainder in the attic. Naturally, differences in temperature within and between buildings were influenced by many factors, including kind and size of structures, exposure, weather, and seasons. Under the conditions that prevailed in the buildings on Oahu, night temperatures, especially in the cooler part of the buildings, were not too different even between seasons. Often attic temperatures varied greatly, as would be expected.

In general, it would appear that an OHE of 70 to 82 could be set as a goal for most buildings fumigated during the summer months, and an OHE of 82 to 96 as a goal for those fumigated on cooler days during the winter months. Exceptional conditions might justify somewhat lower or higher OHE's but these should be good guide lines, which are comparable to those suggested on the Fumiguide.

In actually carrying out a fumigation, the first major operation is to wrap the building with tarpaulins to retain the fumigant as well as possible. Next, the shooting tubes, sampling tubes, and one or more electric fans are placed in strategic positions. In carrying out these initial activities, the fumigator makes a thorough study of the situation from many angles, especially aspects known to contribute to gas-leakage rate. His next step is to set his OHE goal—which may be more or less arbitrarily set at 70, 82 or possibly 96—and then estimate, with the aid of the Fumiguide, the amount of gas that will probably be needed to obtain the OHE sought.

A major problem is to estimate the rate of gas loss in terms of half-loss-time (HLT), and there are many factors that enter into it. Stewart (1962) has suggested criteria and procedures for estimating the probable HLT for a building before introducing the gas. Major contributing influences or factors suggested are: condition of tarpaulins or cover, seal of tarpaulins with the soil or base, porosity of underseal material (such as sand, clay or concrete slab) volume of building, and wind velocity. Values between 0.25 and 4.0 were assigned for the factors, which were then multiplied together and used with an assumed basic HLT of 12 to obtain the estimated HLT.

Estimates of the HLT made before introducing the gas were often considerably lower than the actual HLT's. On the basis of the HLT's obtained in the present studies, it was suspected that the factors above 1.0 suggested by Stewart (1962) for underseal and volume may need revision downward. There was no clear-cut HLT-volume relationship at volumes between 20,000 and 100,000 cubic feet, but relatively low HLT's were obtained at volumes below 10,000 cubic feet. The HLT's obtained indicate that probably the factor for slab on sand should be no higher than for clay without slab, but this was not confirmed under controlled conditions. Where there is sand under a building, the volume of sand above the water table may be an important consideration, especially near the seashore. Gas readily penetrates dry sand. Unless the volume of dry sand is included, the Fumiscope readings will be much lower than expected. This suggests that a sizeable quantity of the gas enters the sand, as occurred when methyl bromide was used (Bess and Ota, 1960). In reality the volume fumigated in such cases includes not only the buildings but also the sand above the water table. Consequently, on these dry, sandy sites, the initial dosage was calculated on the basis of the volume of sand above the estimated water table and the volume of the building, rather than of the building alone. It was also found that HLT's obtained on the basis of the Fumiscope readings alone were much higher than would have been predicted by the suggested factor of 0.25 for sand as the underseal.

The usual procedure in the investigations was to take gas readings at hourly intervals in the buildings during the first 5 to 8 hours after the initial gas introduction, and a final set of readings immediately before opening the tarpaulins at the end of the fumigation period. Usually 1 hour was sufficient for the fan or fans to mix the gas thoroughly, so that the concentration was relatively uniform throughout the main sections of a building. By the end of the 4th or 5th hour, the HLT for that initial segment of the fumigation period was determined. On the basis of that HLT, the dosage introduced, and the length of the fumigation period, it was possible with the aid of the Fumiguide to determine readily whether sufficient fumigant had been introduced initially to produce the desired OHE—providing, of course, that the volume of the building had been correctly estimated and that the HLT did not deteriorate during the remainder of the fumigation period. If additional gas was needed, the amount was determined with the aid of the Fumiguide and introduced.

After the fumigation was completed, HLT's for different segments of the fumigation period were computed on the basis of the gas readings and the time elapsed between readings. It was also possible to compute an HLT for a specific segment or the entire period on the basis of an assumed gas concentration, derived by computation from the amount of gas introduced and the estimated volume of the building. If additional gas was introduced after the initial introduction, consideration of this factor also was necessary. In most cases, the HLT's for the first 3 to 5 hours obtained by the 2 methods were approximately the same; in a few instances there were wide differences between them. These differences or discrepancies between the 2 types of HLT's could have been due to an incorrect estimation of the volume of the building itself, a miscalculation in the amount of gas required, an error in weighing the gas, excessive loss of gas around the introduction tubes, or possibly a large volume of dry sand or other porous material underneath the building. Other possible causes might be suggested, but all of those mentioned occurred or were suspected during these tests. This suggests that the actual dosage per 1000 cubic feet may often be questionable or unknown prior to determination by Fumiscope readings after equilibrium is reached. Those readings could be used as an index of dosage in the computation of OHE's. Another approach would be to use the introduced dosage with the Fumiscope readings to calculate the HLT for the initial period, which is of key importance in a fumigation job.

The HLT's were not only different for the different buildings; they also varied throughout a fumigation. In many buildings the lowest HLT's—which means the most rapid loss of gas—occurred during the initial few hours after the gas was introduced around noon. There were several exceptions. Of the 15 test buildings fumigated during the summer of 1963, 3 had unexpectedly low HLT's and required additional gas (Figure 2, page 15). Rapid loss of gas continued in these 3 buildings following the 2nd introductions.

Tables showing the gas concentrations that would be required at the end of 4 hours and/or possibly other specified times following introduction can provide useful information to fumigators (Table 6). Readings equal to or greater than those shown indicate that the estimated HLT has been realized and therefore that the dosage introduced was sufficient to produce the desired OHE goal. Readings lower than those shown can act as a "red light" or warning indicating that the fumigator should be notified promptly. He can then return to the job and take the necessary steps to assure that an adequate OHE will be obtained. This will probably include the introduction of additional gas. The fumigator may deem it wise to take other steps, depending on the difference between the expected and actual HLT and also on the alternatives at his disposal in the particular case. An unexpectedly low HLT will indicate that the tarpaulins should be carefully reexamined for possible tears and for openings at the seams, between sections, or between the tarpaulins and the underseal surface. However, it should be emphasized that troubles of this kind which cause low HLT's can often be avoided altogether, or greatly reduced, through the perseverance of the fumigator in attending to these matters properly before introducing the initial dosage of fumigant.

The data presented in a previous section show that where buildings are involved, there is ample justification for recommending a specified ounce-hour-exposure (OHE) rather than a specified dosage as is commonly done with fumigation in chambers. However, some fumigators continue to rely on a dosage of 1 pound, or possibly less, per 1000 cubic feet and do not obtain Fumiscope readings. Our investigations show, as have others, that the effectiveness of the fumigant is influenced by temperature. Therefore, it has been found necessary to recommend different dosages and OHE's, depending on the different temperatures involved during the fumigation period. As a general rule, a mean temperature for the cooler parts of buildings might approximate 70 to 75 F on cool days during the cooler months and possibly 75 to 80 F on cool days during the warmer months. Suggested minimal OHE goals are 82 at 75 F and 70 at 80 F. These recommendations agree with those indicated for similar temperatures on the Fumiguide calculator, which appear to be conservative but also justified. Possibly even higher OHE's should be sought if there are unusual conditions.

Since the OHE itself is determined by three factors—the gas dosage, the leakage rate or HLT, and the length of the exposure period—the desired OHE can be reached by adjustments of any factor. Perhaps the adjustment will be the addition of fumigant after the initial 3 to 4 hours, when the HLT has been determined; significant improvement in the HLT has often been possible. Also, when feasible from the standpoint of the client, extension of the fumigation period may be a practical solution. The cost of additional gas could be an important consideration where the structure is of considerable size, especially where an HLT of 4 or less is involved.

For example, to produce an OHE of 70 within an exposure period of 16 hours, 3 times as much gas would be needed with an HLT of 2 as with an HLT of 8. This would mean that to obtain an OHE of 70 with an HLT of 2, a 100,000-cubic-foot building would require 150 pounds of gas, while with an HLT of 8, only 50 pounds would be needed: a difference of 100 pounds of gas and over $300 at present market price. Thus steps taken to reduce the leakage rate when the HLT is 5 or less may be conspicuously worthwhile in reducing the dosage needed, but when the HLT is above 10 or 12, the reduction would be appreciably less important.

It would also follow that extending the exposure period beyond 16 hours would contribute relatively little to the OHE when the HLT is 4 or less. However, this would make an appreciable contribution when the HLT is above 10 or 12. The reason for this is obvious: with an HLT of 4, after 16 hours only 6 percent of the dosage would remain, while with an HLT of 12, 40 percent of the gas would still be present.

CONCLUSIONS

Apparently most, if not all, buildings can be successfully fumigated with sulfuryl fluoride to control *C. brevis*. The fumigator can guarantee that an effective job can be (or was) done, provided gas readings are obtained so that the OHE can be determined and an adequate exposure assured. A dosage of 1 pound per 1000 cubic feet was sufficient to provide an adequate OHE in approximately 90 percent of the test buildings, but in several buildings this dosage was inadequate. One-half this dosage, 8 ounces per 1000 cubic feet, was adequate to kill all test termites in the block cages in approximately 50 percent of the test buildings and this represents a considerable saving. Therefore, gas readings are essential for an enlightened scientific approach to the fumigation of buildings, with confidence that an effective job is done.

There are exceptional conditions, such as where infestations may be located in damp timbers, within wood which has been recently painted, or perhaps in plywood; where the usually effective OHE may be insufficient. Gas leakage may be the key factor in structural fumigation, for in many cases the HLT was found to be appreciably different from what was estimated or expected. The use of gas-tight tarpaulins and the careful wrapping of the buildings are extremely important in obtaining good HLT's.

The mortality of the test termites was found to be positively correlated with the OHE obtained within the buildings. Therefore, the OHE is considered to be a feasible measure or index of the fumigant dosage needed. Buildings fumigated in the Honolulu area during the summer and fall should probably receive a minimal OHE of 70 to 82. Those fumigated during the winter and spring should receive a minimal OHE of 82 to 96. Higher OHE's may be justified under unusual circumstances such as extensive quantities of plywood paneling, cabinets, or moist timbers. To cope with these, in some cases it may be feasible to compartmentalize the buildings and use additional fumigant in the units where it is needed.

SUMMARY

The experimental investigations discussed in this paper were of two kinds: (1) the exposure of *Cryptotermes brevis* (Walker) and *Coptotermes formosanus* Shiraki to sulfuryl fluoride for 3 hours at either 70 or 80 F within fumigation chambers where the gas concentration was relatively stable, and (2) the exposure of *C. brevis* in buildings wrapped with tarpaulins where the temperature, gas concentration, and length of the fumigation period were variable.

The fumigation-chamber test results showed that, with similar dosages, mortality was greater at 80 F than at 70 F and that with *C. brevis* the LD_{50} was lower for sulfuryl fluoride than for methyl bromide where the exposures were within unsealed slide cages. As anticipated, mortality was greater in unsealed slide cages than in wooden block cages and sulfuryl fluoride was more effective than methyl bromide where block cages were used.

In unsealed cages, *C. formosanus* was as susceptible as *C. brevis* to sulfuryl fluoride. The building tests in which *C. brevis* was exposed within wooden block cages showed that there was a direct relationship between mortality and ounce-hour-exposure (OHE). Consequently OHE is considered to be a usable index of the actual dosage of fumigant received by the termites or buildings. However, with the many variables involved, only an approximation of the OHE could be obtained.

More than 100 buildings were used in these tests. Data were obtained on temperatures and gas concentrations for the periods when the test termites were exposed in the buildings, and on the mortalities produced by different OHE's. One of the key factors involved in calculating the OHE was the rate of loss in the concentration of the fumigant during the fumigation operation, which usually extended over a period of 16 to 21 hours. The rate of loss, or half-loss-time (HLT), was calculated from the periodic gas-concentration readings obtained with a thermoconductivity instrument. It was used with the dosage of fumigant and length of the exposure to calculate the OHE through the aid of a Fumiguide calculator. In all of the experimental buildings, two or more series of test termites were exposed for only a portion of the fumigation period, so that a wide range of mortalities could be obtained to determine the desired OHE-mortality relationships.

Mortality was directly related to the OHE involved. This means that in structural fumigation, fumigant requirements may be stated in terms of

OHE needs, rather than dosages *per se* as in chamber fumigation. On the basis of the information obtained, it is suggested that in the Honolulu area, minimal dosages of 70 to 82 OHE be obtained during the summer and fall months, and that dosages be raised to 82 to 96 OHE during the winter and spring months. It is important that all timbers within the structures receive at least these minimal dosages.

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