# IPM for Drywood Termites (Isoptera: Kalotermitidae)[1]

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**Abstract** The foundation of IPM for drywood termites (Isoptera: Kalotermitidae) has academic and industry origins some extending back several decades. Regardless of the origin, the underlying philosophy of IPM for drywood termites is consistent and includes correct identification of the pest, monitoring its activity, and use of a variety of treatment methods including chemical, nonchemical, and prevention. Species diversity and adaptive biology can make the detection and treatment of drywood termites challenging and difficult. Advances in detection technology now make it feasible to determine whether drywood termites are active within wood. Recent advances have also made it feasible to non-chemically treat for drywood termites. Efficacy testing is incomplete for many of the newer detection and treatment options especially field trials. In addition, pest control legislation and regulations have not kept up with the technological changes, particularly for detection devices and nonchemical treatment options. The interplay of drywood termite biology, detection, management options, and changes needed in public perception of termites and treatments are reviewed.

**Key Words** Integrated Pest Management (IPM), detection, management, control, Isoptera, Kalotermitidae, drywood termite

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The origin of our modern definition of Integrated Pest Management (IPM) for drywood termites has its roots in academia and the structural pest control industry. For academia, the earliest mention of what became IPM was in the 1920's and pertained to boll weevil control on cotton (Flint and van den Bosch 1981). The academic recognition of IPM for structural pests including drywood termites did not appear until the 1970's and 1980's (Ebeling 1978, Katz 1982). However, practicing pest control companies have been using some components of IPM (i.e., inspections, prevention, chemical, and nonchemical methods) for many decades (Brown et al. 1934, Kofoid and Chase 1934, Mallis 1945, Potter 1997). In fact, for California in the early 1930s, the first drywood termite control method was not a chemical; it rather was wood replacement based on inspection (Hennessy 1993). Regardless of the origin, the essence of the philosophy underlying all IPM definitions is to correctly identify the pest, monitor its activity, and use a variety of treatment methods including chemical, nonchemical, prevention, and even no action. In the sections that follow, I will review how species diversity, economic importance, and adaptive biology impact drywood termite detection, monitoring, and management.

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There are a number of disclaimers the reader should consider when reading the sections in this paper on detection and management. First, the names of products, devices, and techniques mentioned are not exhaustive. Additions and deletions of products and devices occur frequently. Availability for many of the detection and management methods also is highly variable across the U.S. The approval process, federal and state, for termite detection and nonchemical methods also is variable and can be confusing when seeking availability and efficacy information. Product or devices mentioned in this paper do not represent an endorsement by the author. Lastly, terms like drywood termite abatement, elimination, and prevention should be used with extreme caution. The more appropriate and realistic term that should be used is drywood termite management that includes regular building maintenance and inspection.

## Diversity in the U.S.

Drywood termites are very adaptive and occur on most continents. All species are contained in the single Family Kalotermitidae. There are about 500 recognized species (Su and Scheffrahn 2000). These are moderately-sized insects (10 to 13 mm) and pale to dark brown in color (Fig. 1). The family is recognized by alates (winged primary reproductives) having ocelli on the head, 2-segmented cerci, and 2 marginal teeth on the left mandible (Kambhampati and Eggleton 2000). For North American

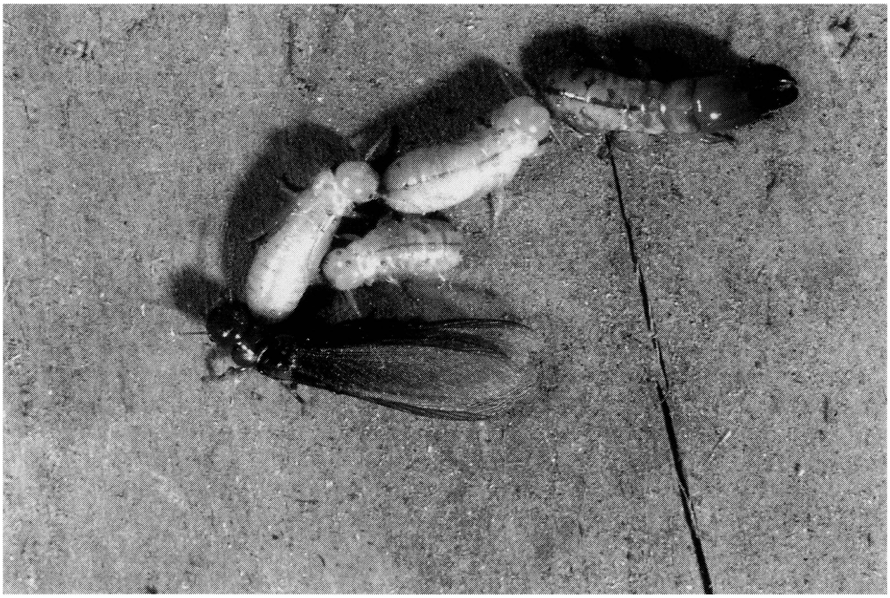

Fig. 1. Drywood termite, *Incisitermes minor* (Hagen) (Isoptera: Kalotermitidae). Castes represented include winged reproductive (top), several psuedergate workers (middle), and soldier (bottom). Photographer Jack Kelly-Clark, University of California, Davis.

species, alates characteristically have 3 or more heavier veins beyond the wing scale and spines at the apex of the tibia (Weesner 1965). Another characteristic that can be found among some species of this family is the presence of a phragmotic head for soldiers. There are 8 genera and 19 species of drywood termites named from North America exclusive of Mexico and Caribbean (Su and Scheffrahn 1990). The last drywood termite species named was *Incisitermes fruticavus* Rust from California (Rust 1979).

## Economic Importance

Most experts agree on the global economic importance of drywood termites and their damage to structures. Interestingly, there are few published reports that quantify the economic importance in monetary units. The few published reports that exist involve surveys from California, Texas, and a group of 11 southern states (Ebeling and Wagner 1964, Williams and Smythe 1979, Granovsky 1983, Brier et al. 1988).

In California, by law, termite inspections must be reported to the Structural Pest Control Board. Two studies have reported findings from these inspection reports. Ebeling and Wagner (1964) have reported 35.7% of 240,926 inspections as having infestations of drywood termites. For southern California, the infestation rate was slightly higher, 46.8%, although it was unclear how the sampling was conducted. Brier et al. (1988) randomly selected 573 inspection reports from a total sample of 2.6 million filed with the state from 1985 to 1986. Information collected included type of wood-destroying pest, treatment, damage repairs, and associated costs for each. Depending on geographic area and locations within homes, the percentage of homes found to have infestations of drywood termites ranged from 0% to 44% (Brier et al. 1988).

Williams and Smythe (1979) reviewed more 32,000 state-filed reports and treatment records for 11 southern states. Type of wood-destroying pest was noted in the reports. From a total of 160,438 records of treatment, 70 homes from Arkansas and Georgia were randomly selected for further visual inspection to verify data in filed reports. The authors determine their findings to be at least 87% correct. Granovsky (1983) using a different procedure, conducted direct interviews of 24 pest control companies in Corpus Christi, TX. The author asked the companies if they inspected, treated, and conducted damage repairs for termites including drywood termites.

Summarizing these surveys, there is considerable variation in economic impact attributed to drywood termites. However, the consensus appear to be that economic expenditures attributed to drywood termites represent about 5 to 20% of the >$1.5 billion spent on wood-destroying pest control each year (Lewis et al. 2000).

## Adaptive Biology

Drywood termites have a number of behavioral and physiological adaptations that can make their detection and treatment difficult. Most species of drywood termites inhabit and nest in wood (Su and Scheffrahn 1990, Su and Scheffrahn 2000). Infestations tend to consist of multiple, small-to-moderately sized colonies that number to several thousand, that are scattered throughout the structure (Su and Scheffrahn 1990). Colony growth and development has been reported as slow, <500 individuals after 5 yrs starting from primary reproductives (Harvey 1934). However, alates have been produced from laboratory colonies within 2 yrs (Grassé and Noirot 1958, Thorne et al. 2002) and as few as 20 live nymphs can lead to colony survival after treatment

(Smith 1995). They can tolerate desiccation (Pence 1956), avoid light (Cabrera and Rust 1996), move from extremes in temperature (Rust et al. 1979, Cabrera and Rust 1994, 1996, 2000), and modify their cuticle in response to changes in temperature and humidity (Woodrow et al. 2000). Their feeding preference also reflects their adaptations to varied cellulose food sources including hardwoods and softwoods (Rust and Reierson 1977) as well as cacti (Myles 1997). Wood consumption rates vary depending on temperature and relative humidity (Cabrera and Rust 1994). The adaptive ability of drywood termites to their environment may help to explain their success as an economic pest in the warmer climates across the U.S. and invasions into cooler locations including Canada (Grace et al. 1991, Myles 1995).

## Detection and Monitoring

Visual searching and probing of wood including the use of flashlight and metal probe for evidence of alate wings, fecal pellets, and damage is the dominant means of inspecting for drywood termites (Scheffrahn et al. 1993). The effectiveness of visual searches ranges from 87 to 100%; however, these data represent only visual and accessible areas in 70 homes surveyed in Arkansas and Georgia (Williams and Smythe 1979). Field studies that include the effectiveness of visual searches for inaccessible areas in homes have not been conducted (V. Lewis, unpubl. data). Fecal pellets produced by drywood termites also are diagnostic for their presence and frequently looked for during inspections (Smith 1995). Pellet counts have been used to demonstrate efficacy of treatment for some chemical treatments (Scheffrahn et al. 1997a). However, there are no published reports on the presence of chemicals in pellets that relate to whether a drywood termite colony is active or not.

Other drywood termite detection methods are listed in Table 1. There are at least 7 detection methods other than visual searchers mentioned in the table. All detection methods and devices claim high levels of successful detection of termites. Optical borescopes use visual light passing through a hollow tube as a means to view termites and damage hidden away behind walls. A small hole may be drilled into walls to add viewing. Fire blocking, installation, and viewing through a fish-eye lens may impede the inspector's view. Optical borescopes are currently marketed; however, their efficiency in the detection of drywood termites has yet to be scientifically tested. Canines (*Canis familiarius* L. = *Canis lupus* L. (Nowak 1999) are being used to assist on termite inspections. TADD Services in California and BEACON DOGS in Maryland provided trained beagles; however there may be others. The mode of action used by dogs in finding termites, audition, olfaction, or both still needs further research (Lewis et al. 1997). Based on laboratory trials, the success rate for canines (beagle and German shepherd) in identifying plastic containers containing drywood termites (*Cryptotermes cavifrons* Banks and *Incisitermes snyderi* (Light)) was 88.8% (Brooks 2001). False positives, canines response to containers without drywood termites, were <1% (Brooks 2001). Electronic odor detectors (e.g., TERMITECT II and SENSIT®) were, and still may be, commercially available to assist on termite inspections. Their mode of action includes detecting methane gas, commonly produced by termites (Lewis et al. 1997). One device (TERMITECT II) was tested on subterranean termites and produced highly variable detection rates from 20 to 100% (Lewis et al. 1997). There have been no reports on the use of electronic odor detectors in successfully identifying drywood termites.

Termites produce vibrations in wood while feeding and by alarm calls from the

**Table 1. Detection methods for drywood termite IPM**

| Methods | Successful detection (%) | Selected references |
|---|---|---|
| Visual Searches | 87 to 100% | Williams and Smythe 1979[1] |
| Optical borescope | * | Potter 1997[2] |
| Odor | | |
| Canine | 20 to 100% | Lewis et al. 1997[3], Brooks 2001[3] |
| Electronic | 0 to 100% | Lewis et al. 1997[3] |
| Sound (including electronic stethoscope) | * | Emerson and Simpson 1929[3], Pence et al. 1954[3] |
| Acoustic Emission | 80 to 94% | Scheffrahn et al. 1993[3], Lewis and Haverty 1996a[4], Scheffrahn et al. 1997a[5] |
| Infrared | * | Lewis 1997[2] |
| Laser | * | Lewis 1997[2] |
| Microwave | 86 to 90% | Evans 2002[3], Peters and Creffield 2002[3] |

[1] Visual searches of exposed and accessible wood for 70 randomly selected homes in Arkansas and Georgia that were treated for termites.

[2] Review paper.

[3] Laboratory studies

[4] Simulated field study.

[5] Field study.

* Little or no published information.

head banging of soldiers. Some of these vibrations can be heard by humans or amplified by microphone (Emerson and Simpson 1929, Pence et al. 1954, Wilson 1971, Stuart 1988, Kirchner et al. 1994). Audible sounds are also produced among genera in the Kalotermitidae (Emerson and Simpson 1929). At least one recording device was made commercial (INSECTA-SCOPE II). No data are available on its performance. Newer technologies, i.e., acoustic emission (AE), allow for the amplification of these vibrations. Surface and subsurface probes are available, successful detection of drywood termites in laboratory settings is at least 80% (Lewis and Lemaster 1991, Lewis et al. 1991, Scheffrahn et al. 1993, 1997a, Lewis and Haverty 1996a, Lemaster et al. 1997). Wall covering may impede sensor and AE performance. Distance in detection is limited to ≈80 cm along the length of a board and <8 cm across the grain (Scheffrahn et al. 1993). Excessive background sounds can also result in false positive results for active termites. AE detection equipment is commercially available, although its availability is very limited.

Newer devices that may allow for the nondestructive searching of entire walls include laser, infrared, and microwave technologies (Lewis 1997). Several years ago a proto-type laser detector was built to nondestructively detect termite motion inside walls. However, results conducted by the developer from a laboratory demonstration were never presented (V. Lewis, unpubl. data). Similarly, several infrared devices have been built to detect termites (e.g., TERMICAM). It is believed that infrared uses changes in temperature to detect termites in wood. To date, there have been no published reports on the success of infrared in detecting drywood termites. Of the newer detection devices, only the microwave device has been tested on drywood termites as well as other termite species (Evans 2002, Peters and Creffield 2002). Microwaves detect termite movement in wood. Success in detection of drywood termites (*Crytotermes brevis* (Walker)) using microwaves (TERM_A_TRAC$^{TM}$) was 86% based on laboratory studies (Peters and Creffield 2002). Detection distance was 35 mm along the long axis of test boards and 25 mm deep below the surface (Peters and Creffield 2002). However, water in wood or wall coverings and excessive wind and motion can lead to false positive results for active termites.

All detection technologies have limitations, and care must be shown in their selection (Potter 1997). Field investigations that report successful detection for naturally-occurring infestations behind walls and other inaccessible areas in homes are lacking for drywood termites. The best strategy to detect and monitor for drywood termites may be a combination of detection methods and techniques (Thorne 1993).

## Management

Treatment option is a critical step in the IPM process. For drywood termites, treatment options are varied and efficacy testing incomplete. Options available include chemical, nonchemical, biological control, and preventive construction (Table 2). Drywood termite treatment options can be broadly classified as whole-structure or localized. Whole-structure treatment is defined as the simultaneous treatment of all wooden members; whereas, localized treatment is restricted to a group of boards or locations within boards (Lewis and Haverty 1996a).

Before reading the following sections on drywood termite treatment options, I want to mention another disclaimer. For most people the important variable in selecting for a drywood termite treatment option is efficacy, often cited as percent mortality or kill. Unfortunately, after reviewing efficacy rates (mostly laboratory studies some field) and 10 yrs troubleshooting field failures in California, I have concluded that most treatment options have the same range of efficacy, 0 to 100% (Table 2). The point being, when applied correctly and under “best case conditions” any treatment can result in high efficacy. Conversely, when not applied correctly and at less than optimal dosages or amounts, treatments will fail. Another way to view “how well a treatment works” is robustness. Since species of drywood termite, geographical location, and structural design vary greatly, robustness of treatment is the most important variable to consider during field applications. Most researchers and pest management practitioners will admit whole-house treatment with fumigants or heat are more robust than local treatment (e.g., penetrates better into concealed locations without the need for destructive sampling and large volumes of wood are treated more efficiently per unit time). Unfortunately there is no consensus or standard definition for robustness. One of the reasons for this discrepancy is the need for pest management regulatory and industry input, along with sound science. There are probably many more reasons and hurdles to overcome before a consensus definition for robustness is agreed upon. Lastly, treatment efficacy and robustness will both improve with detection, especially those detection methods that can state whether an infestation is active or not.

**Table 2. Summary of drywood termite IPM treatment options**

| Treatment | Efficacy range | Selected references |
|---|---|---|
| | | Whole-structure |
| Fumigation | 0 to 100% | Randall et al. 1934a[1,2], Stewart 1957[1], 1966[1], Bess and Ota 1960[2], Su and Scheffrahn 1986[2], Osbrink et al. 1987[1], Peters 1990[2], Scheffrahn and Su 1992[1], Thoms and Scheffrahn 1994[1], Scheffrahn et al. 1995[1], Lewis and Haverty 1996a[2], Mueller 1997[4], Scheffrahn et al. 1997a[2] |
| Asphyxiant gases | * | Paton and Creffield 1987[1], Delate et al. 1995[1], Rust et al. 1996[1] |
| Heat | 0 to 100% | Randall and Doody 1934a[1]; Forbes and Ebeling 1987[2], Ebeling 1994[2]; Lewis and Haverty 1996a[2]; Woodrow and Grace 1997[2], 1998 a[1], b[2], c[1]; Rust and Reierson 1998[1]; Scheffrahn et al. 1997b[1] |
| | | Localized treatments |
| Chemical | | |
| Liquids and dusts (topical and injected) | 0 to 100% | Smith 1930[3], Randall and Doody 1934b[1,3], Randall et al. 1934b[1], Snyder 1950[4], Ebeling and Wagner 1959 a[2,3],b[1], 1964[4], Ebeling 1978[4], Scheffrahn et al. 1979[1], Scheffrahn and Su 1994[4], Moein and Farrag 1997[1], Scheffrahn et al. 1997a[1,2], Su and Scheffrahn 2000[4], Ferster et al. 2001[1], Scheffrahn et al. 2001[1], Lewis 2002[4] |
| Baits | * | Scheffrahn and Su 1994[4] |
| Foams | * | Su and Scheffrahn 2000[4] |
| Liquid nitrogen | 0 to 100% | Forbes and Ebeling 1986[2], Lewis and Haverty 1996a[2], Rust and Reierson 1998[1], Rust et al. 1997[1] |
| Nonchemical | | |
| Microwaves | 0 to 100% | Lewis and Haverty 1996a[2], Lewis et al. 2000[1] |
| Electrocution | 0 to 100% | Ebeling 1983[1,3], Lewis and Haverty 1996a[2], Creffield et al. 1997[1], Lewis and Haverty 2001[1] |
| Heat, local | 0 to 100% | Same as listed for heat and whole-structure |

*(Table continues)*

**Table 2. Continued.**

| Treatment | Efficacy range | Selected references |
|---|---|---|
| Biological, fungi, virus, and nematodes | * | Grace 1997[4]; Moein and Farrag 1997[1], Moein and Nasr 1998[1]; Su and Scheffrahn 2000[4] |
| Light & sticky traps | * | Su and Scheffrahn 2000[4] |
| Preventive Construction | | |
| Termite resistent woods | * | Rust and Reierson 1977[1], Scheffrahn and Rust 1983[1], Scheffrahn 1991[4] |
| Pressure-treated wood | 0 to 100% | Randall and Doody 1934a[1,3], Mallis 1945[4], Snyder 1950[4], Rust and Scheffrahn 1982[1], Su and Scheffrahn 2000[4] |
| Noncellulose materials | * | Su and Scheffrahn 2000[4] |
| Screens, caulk & pain | * | Randall et al. 1934c[1], Mallis 1945[4], Snyder 1950[1], Rust and Scheffrahn 1982[1], Scheffrahn and Su 1994[4], 2000[4] |

[1] Laboratory study.
[2] Simulated field study.
[3] Field study.
[4] Review paper.
* Little or no published information.

## Whole-Structure Treatments

Fumigation has a long history as a whole-structure treatment option (Table 2). The earliest report was from the 1930s and included the 8 fumigants of benzene, carbon bisulfide, carbon tetrachloride, chloropicrin, hydrogen cyanide, para dichlorobenzene, naphthalene, and turpentine (Randall et al. 1934a). Today, only methyl bromide (MB) (BROM-O-GAS®) and sulfuryl fluoride (SF) (VIKANE®) are currently registered as structural fumigants in the U.S. (Mueller 1997, Su and Scheffrahn 2000). However, MB is an ozone-depleting substance and, by international treaty, will be phased out by 2010 (Mueller 1997). Chloropicrin, a third fumigant, is used only as a warning agent to discourage human reentry into fumigated structures.

Structural fumigation requires that the entire building be sealed or enclosed in tarpaulins to confine the gas for a predetermined concentration and time depending on the target pest, weather, and physical size of the building. Fumigants are introduced via plastic tubing as a gas within a space confined by vinyl-coated nylon tarpaulins. Tarpaulins are wrapped entirely around a structure and held together with metal clamps. Water or sand filled plastic tubes are also laid on tarpaulins at the base of the structure being fumigated to help prevent fumigant leaks. Care must be taken to limit the escape of gas from underneath the tarpaulins before the required effective dose is achieved to kill drywood termite infestations. Electric fans are also used to help the movement of fumigant resulting in the quick equilibrium of gas throughout the structure. A commonly used dosage to kill drywood termites under field conditions is 16g/$m^3$ for MB and 8 g/$m^3$ for SF (Scheffrahn et al. 1992a). However, treatment time and dosage can vary depending on target pest, temperature, wind, soil type, and quality of tarpaulins (Mueller 1997). All living organisms must be removed from the structure prior to fumigating since MB and SF have similar toxicities in disrupting glycolysis, and are lethal to living organisms (Meikle et al. 1963, Scheffrahn et al. 1990). Structural fumigation is highly regulated due to risks of accidental human mortality and explosion from the buildup and ignition of natural gas underneath tarpaulins (Su and Scheffrahn 2000, Annon. 2002a)

High efficacy levels (100%) have been reported for both MB and SF for at least 8 species of drywood termites (Bess and Ota 1960, Su and Scheffrahn 1986, Peters 1990, Scheffrahn and Su 1992, Thoms and Scheffrahn 1994, Lewis and Haverty 1996a). Most efficacy reporting represents laboratory investigations (Stewart 1957, Osbrink et al. 1987, Thoms and Scheffrahn 1994, Scheffrahn et al. 1995). One study has reported field failures, efficacy values of 0% to 10% for 2 buildings containing test blocks with live *C. brevis* fumigated with MB (Bess and Ota 1960).

Fumigation per label directions has been reported to completely eradicate all infestations, even those concealed or in inaccessible areas (Su and Scheffrahn 2000). This proposition is based on monitoring fumigant gas levels in structures undergoing fumigation. It is doubtful that the field failure rate is the same for both monitored and non-monitored fumigations. In Australia, 25% of 199 buildings fumigated with MB for *C. brevis* required additional fumigant when monitored (Peters 1990). Similar studies are needed for the U.S.

The ability of a material or commodity to retain a fumigant after fumigation is called 'desorption.' At 5 ppm, a fumigated structure is safe for reentry (Anon. 2000). Some materials and commodities retain fumigants for a longer duration, up to 40 d measured in ppb (Scheffrahn et al. 1987). Desorption was greatest for unprotected fatty commodities (high oil peanut butter and margarine) packaged in "leaky" containers and for polyester fiber and polystyrene installation (Scheffrahn et al. 1987, 1992b). However, food and commodities packed in double-nylon film bags and aeration times of >7 h eliminated or significantly reduced desorption of fumigants (MB and SF) for all foods and commodities tested (Osbrink et al. 1988, Scheffrahn et al. 1990, 1992b, 1994). Worst-case condition of desorption for sulfuryl fluoride (F residue) is <1 ppm, less than 8 ppm which is considered normal and safe and can be found in some drinking water (Scheffrahn et al. 1989a,b). Fluoride supplements of 1 ppm have been recommended and added to municipal water supplies to reduce dental cavities (Scheffrahn et al. 1989b).

Other whole structure treatment options include asphyxiant gases and heat (Table 2). The use of asphyxiant gases is limited to laboratory investigations (Paton and Creffield 1987, Delate et al. 1995, Rust et al. 1996). Gases investigated include nitrogen ($N_2$) and carbon dioxide ($CO_2$). Large-scale use of asphyxiant gases for wooden structures is not technically feasible at this time due to limitation in the containment of high concentrations of gas (>95%) and long exposure times >72 h needed for whole-structure treatments (Delate et al. 1995).

Temperatures exceeding 51.5°C are lethal to drywood termites as was demonstrated six decades ago (Randall and Doody 1934a). Commercial applications using propane heaters rated at ≈400,000 BTUs to heat structures are more recent, with the first reports appearing in the 1980s (Forbes and Ebeling 1986, 1987). Current commercial offerings include, but are not limited to, THERMAPURE®, ISOTHERMICS®, and THERMAL PEST ERADICATION®. Preparations for whole-structure heating are similar to fumigation. Tarpaulins are wrapped around a structure, however, unlike fumigation, the tarpaulins have holes to aid the rapid exchange of heated air for cooler air. Electric fans are also used to aid the movement of heated air to cooler locations in the structure. A number of thermocouples are installed throughout the structure to aid in monitoring temperature changes in wood undergoing treatment. Treatment time is variable depending of the size of the structure. Several hours to one day may be needed to complete the treatment process (Ebeling 1994, Woodrow and Grace 1997).

Laboratory, simulated-field, and field investigations on using heat to kill infestations from structures have included at least five species of drywood termites (Lewis and Haverty 1996a, Rust and Reierson 1998, Scheffrahn et al. 1997b, Woodrow and Grace 1997, 1998a,b,c). Some construction features (e.g., wood touching concrete) can be difficult to heat to lethal temperatures resulting in treatment failures (Lewis and Haverty 1996a). Damage to a test structure, minor warping of wood, doors sticking and warping of an ABS wastewater pipe have been reported (Lewis and Haverty 1996a,b). An entire home was recently burned and destroyed from a heat treatment (Annon. 2002a). Additional testing of whole-structure heat treatments will be needed on safety from fire and studies that include efficacy testing for multi-storied structures containing drywood termite infestations.

## Local Treatments

**Chemicals.** Local treatments with chemicals and inert dusts have dominated the drywood termite control market for decades. Applications for controlling drywood termites include liquid (e.g., DURSBAN®, TIM-BOR®, BORA-CARE®), dust (e.g., KALI-DUST, TIM-BOR®), paste (e.g., WOODTREAT-TC) or foam (e.g., TIMBOR®, PREMISE®, DRAGNET®, and others) applied to the surface of wood or injected into termite galleries. Exact estimates on the market share of chemicals for controlling drywood termite infestations are difficult; however, in California at least 70% of all drywood termite treatments involve local applications of chemicals (Potter 1997, Lewis et al. 2000). Published efficacy testing on active ingredients is very extensive and includes at least 52 chemical compounds (Randall and Doody 1934b, Randall et al. 1934b, Mallis 1945, Snyder 1950, Moein and Farrag 1997, Scheffrahn et al. 1979, 1997a, 1998, 2001, Ferster et al. 2001). At least one natural product consisting of *d*-limonene (POWER PLANT®) is commercially available for localized treatments (Su and Scheffrahn 2000). Currently, the mode of action and active ingredient for the more commonly used chemicals for drywood termite control include stomach poison and absorber of insect cuticle wax (disodium octaborate tetrahydrate-DOT); coagulation of proteins (arsenicals in pressure treated wood); and nerve poisons (e.g., fipronil, bifenthrin, cyfluthrin, imidacloprid, methyl bromide, permethrin, and sulfuryl fluoride) (Ware 2000). Describing the mode of action for the dozens of chemicals used for drywood termite control is beyond the scope of this paper and the reader is referred to the material safety data sheet information required for all federally registered chemicals. An excellent review on mode of action for many commonly used chemicals also can be found in Ware (2000).

Collectively, reports on chemical efficacy in controlling infestations are highly variable, ranging from 0 to 100% depending on active ingredient, application technique, and species of drywood termite (Randall and Doody 1934b, Moein and Farrag 1997, Scheffrahn et al. 1979, 1997a, 2001). Currently, all chlorinated hydrocarbons, arsenicals, and organophosphate compounds have been banned or restricted in the U.S. due to excessive human toxicity, residues, or carcinogenicity (Su and Scheffrahn 2000, Rambo 2002).

Efficacy testing of insecticidal foam injected into galleries or topically applied to wood has not been reported for drywood termites; however, reports for subterranean termites exist (Potter 1997). The practice of foaming wall voids for drywood termites is increasing in some states (V. Lewis, unpubl. data). Intragallery injections with liquids (spinosad, chlorpyrifos) and dusts (Ca-arsenate, spinosad) have been reported to have higher efficacy (>90%) than topical applications with liquids (14% for DOT) (Scheffrahn et al. 1998, Ferster et al. 2001). Labels that include chemical baits are not commercially available for drywood termites in the U.S. (V. Lewis, unpubl. data), although arsenic dusts were reported as having a "bait-like" action when injected into drywood termite galleries (Kofoid and Williams 1934).

Liquid nitrogen is another local-treatment chemical option for drywood termites. The sole commercial offering is called BLIZZARD SYSTEM®. The mode of action of liquid nitrogen includes cellular and tissue membrane damage and shock from extreme cold resulting in death (Rust and Reierson 1998). Pseudergate workers for *Incisitermes minor* (Hagen) were all dead when exposed 5 min or longer to temperatures of −18.5°C or colder (Forbes and Ebeling 1986, Rust et al. 1997). Laboratory and field efficacy testing has been conducted using liquid nitrogen (Forbes and Ebeling 1986, Lewis and Haverty 1996a, Rust and Reierson 1998, Rust et al. 1997). Applications of liquid nitrogen resulted in mortality $\geq$99.8% at dosages of 381.8 and 122.7 kg/m$^3$; however, mortality for the 57.3 kg/m$^3$ dosage was significantly lower (74%) (Lewis and Haverty 1996a). Efficacy is best when using high dosages (>57.3 kg/m$^3$), achieving temperatures of < −18.5°C, and having a compartment and installation blanket to contain and maintain the cold liquid (Lewis and Haverty 1996b,c, Rust et al. 1997, Rust and Reierson 1998). However, drilling holes in walls for injection of liquid nitrogen can be damaging to wall coverings.

**Nonchemical.** There are at least 5 nonchemical options for drywood termite IPM. They include microwaves, electric shock, excessive heat, biological control, and traps (Table 2). Microwaves of 2.4 GHz frequency oscillations kill termites by causing fluids inside their cells to boil, which destroys cell membranes (Lewis and Haverty 1996a,b, Lewis 2002). The lethal effects of microwaves to drywood termites have been reported for laboratory and simulated-field studies (Lewis and Haverty 1996a,b, Lewis et al. 2000). Effectiveness (98%) was greatest when using at least 700 W of power and exposure time of >8 min for at 311 cm$^2$ treated spot within test boards during simulated-field studies (Lewis and Haverty 1996a). However, 6 boards were burned, 2 severely resulting in charred wood and smoke (Lewis and Haverty 1996a).

High voltage electricity (90,000 volts, <0.5 amps) kills termites. The probable mode of action includes death to cells from excessive heat and destruction of protozoa in the gut of termites (Ebeling 1983, Lewis 1997). Application may be applied to wood by waving the probe end over the surface or by drilling small holes for insertion of metal pins to aid in the transmission of current below the surface (Ebeling 1983, Lewis and Haverty 1996a). Electric shock treatments using the ELECTRO-GUN® for drywood termites have been reported (Ebeling 1983, Lewis and Haverty 1996a, 2001, Creffield et al. 1997, Lewis and Haverty 2001). Efficacy results were mixed and ranged from 44% to 100% depending on application technique (surface vs drilling and inserting a metal pin), treatment time per test board (7 min vs 22 min) and species of drywood termite (*I. minor* and *Cryptotermes primus* (Hill)) tested. Damage to test boards and structures included minor burn marks and drill holes for metal pin insertion (Lewis and Haverty 1996a, 2001).

Local treatment with heat has already been discussed in the whole-structure treatment section, and high levels of efficacy >96% at temperatures >49°C held for at least 30 min have been reported (Randall and Doody 1934a, Forbes and Ebeling 1987, Lewis and Haverty 1996a,b, Rust and Reierson 1998, Scheffrahn et al. 1997b, Woodrow and Grace 1997, 1998a,b,c).

Published reports on using biological agents to control drywood termites have been limited and incomplete (Grace 1997, Su and Scheffrahn 2000). The few published papers that exist include nuclear polyhedrosis virus successfully infecting *Kalotermes flavicollis* F. (Grace 1997); bacteria *Bacillus thuringiensis* Berliner and *B. sphaericus* (Meyer and Neide) infecting *K. flavicollis* and *C. brevis* (Moein et al. 1996, Grace 1997, Moein and Nasr 1998); and the nematode *Heterorhabditis spp.* has been reported to infect *Glyptotermes dilatatus* (Bugnion and Popoff) (Su and Scheffrahn 2000). The fungus *Metarhizium anisopliae* (Strain ESC 1) is registered for *Incisitermes* spp. in the U.S. (Su and Scheffrahn 2000). However, more research will be needed before the potential and commercial acceptance of biological control as an IPM treatment option for drywood termites can be assessed. There have been no reports on the efficacy of light or sticky traps as a viable IPM treatment option (Su and Scheffrahn 2000).

Lastly, the availability for all nonchemical treatment options is very limited. Their greatest usage appears to be in California where at least 10% of the drywood termite treatment market is represented by alternatives to fumigation and localized treatments with chemicals (Potter 1997). Additional studies for many nonchemical treatment options, as well as a more thorough understanding of the limitations of their application, will be needed before realistic efficacy levels can be determined.

## Prevention

Preventive construction is the best long-term IPM treatment option (Table 2). For many decades resistant species of wood (old growth redwood) and pressure-treated wood (creosote, pentachlorophenol, and chromated copper arsenate) have been used as preventative determents to drywood termite infestations in new construction and post-construction repairs (Randall and Doody 1934b, Mallis 1945, Snyder 1950, Hunt 1959, Rust and Scheffrahn 1982, Scheffrahn 1991, Su and Scheffrahn 2000). Chemical and inert dusts also have been applied to attic spaces as deterrent to drywood termite alates (Randall and Doody 1934a, Ebeling and Wagner 1959a,b, Hunt 1959, Wagner and Ebeling 1959, Ebeling 1978, Potter 1997, Scheffrahn et al. 1998, 2001). Published efficacy results for pressure-treated wood and topically applied liquids and inert dusts were similar and ranged from 0% to 100% (Randall and Doody 1934a,b, Randall et al. 1934b, Rust and Scheffrahn 1982, Scheffrahn et al. 1979, 1997a, Ferster et al. 2001).

Regulatory concerns over the indoor use and environmental hazards of chlorinated hydrocarbons (pentachlorophenol, WOODTREAT-TC) and creosote resulted in the removal of these chemicals from the market (Rambo 1997). More recently, a commonly used preservative, chromated copper arsenate (CCA), has been voluntarily withdrawn due to perceived danger surrounding its disposal (Annon. 2002b).

Replacement chemicals include ammoniacal copper quat (ACQ; PRESERVE®, NATUREWOOD®, and WOLMANIZED NATURAL SELECT® wood), copper boron azole (CBA), and disodium octaborate tetrahydrate (DOT, TIM-BOR®). However, except for DOT, little has been published on the success of these replacement wood preservatives in preventing drywood termite infestations.

Little is known from laboratory or field studies on how noncellulose materials, screens, caulks, and paints prevent the establishment of new drywood termite infestations (Randall et al. 1934c, Mallis 1945, Rust and Scheffrahn 1982, Su and Scheffrahn 1990, 2000). However, preventing new infestations is very short term and, for existing infestations deep inside wood, these physical barriers used alone are ineffective.

## Future Prospects

Using IPM as a philosophy to manage drywood termites does not represent a change of tactics by the structural pest control industry. Some components of IPM have been used for the industry for decades (Brown et al. 1934, Kofoid and Chase 1934, Mallis 1945, Hennessy 1993, Potter 1997). What has changed is greater regulatory control over pesticide use due to air and water quality issues and hazards to humans (Su and Scheffrahn 2000).

In the past, chemicals have dominated IPM treatment options. The federal registration and patent processes have favored chemical development and marketing. For nonchemical alternatives, the process is not as clear. There are no federal drywood termite efficacy standards for detection or treatment options, including chemical and nonchemical. Perhaps legislative and regulatory groups should consider efficacy criteria along with safety in new laws they propagate. Perhaps new legislation should also consider the demonstration of drywood termite infestations being active before treatment and left alone if not active, even though pellets and damage are present.

The prospects for IPM for drywood termites are very good. There are many detection and management options available. More will be developed and evaluated. With the continued technological advances, more effective detection options and safer treatments will be offered on the marketplace. Localized treatments will continue to dominate the drywood termite control market. Whole-structure treatments, especially with fumigants, will be more regulated due to perceived public risk (Su and Scheffrahn 2000). Greater emphasis will be placed on newer technologies that will include combination treatments and perhaps baits. However, for baits to be effective, research will be needed on the foraging behavior of drywood termite colonies which is currently unknown (Scheffrahn and Su 1994). All treatments may someday be verified with detection options other than visual searches by inspectors.

What is not clear is how the public will perceive new detection and treatment options that may invoke some apprehension, for example, microwaves, lasers, and treatments that include microbial pathogens and molecular altered agents. Also uncertain is whether the public will accept and pay for a service that manages drywood termites, not eliminates or eradicates them. Some agency or entity will be needed to better educate the public to the changes needed to truly make all components of IPM for drywood termites realistic.

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